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WEFPRESS™
For the Water Quality Professional

Water Environment Federation®
Preserving & Enhancing the Global Water Environment

Operation of Municipal Wastewater Treatment Plants

Volume I: Management and Support Systems
SIXTH EDITION

Water Environment Federation® (WEF®)

MANUAL OF PRACTICE No. 11

OPERATION OF MUNICIPAL WASTEWATER TREATMENT PLANTS

Volumes in Manual of Practice No. 11

Volume I **Management and Support Systems**
Chapters 1–16

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OPERATION OF MUNICIPAL WASTEWATER TREATMENT PLANTS

Manual of Practice No. 11

Sixth Edition

Volume I Management and Support Systems

Prepared by
Operation of Municipal Wastewater Treatment Plants Task Force
of the Water Environment Federation

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Task Force

Prepared by the Operation of Municipal Wastewater Treatment Plants Task Force of the Water Environment Federation

Michael D. Nelson, *Chair*

Douglas R. Abbott
George Abbott
Mohammad Abu-Orf
Howard Analla
Thomas E. Arn
Richard G. Atoulikian, PMP, P.E.
John F. Austin, P.E.
Elena Bailey, M.S., P.E.
Frank D. Barosky
Zafar I. Bhatti, Ph.D., P. Eng.
John Boyle
William C. Boyle
John Bratby, Ph.D., P.E.
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James H. Clifton
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James L. Daugherty
Viraj de Silva, P.E., DEE, Ph.D.
Lewis Debevec
Richard A. DiMenna
John Donnellon
Gene Emanuel
Zeynep K. Erdal, Ph.D., P.E.
Charles A. Fagan, II, P.E.
Joanne Fagan
Dean D. Falkner
Charles G. Farley
Richard E. Finger
Alvin C. Firmin
Paul E. Fitzgibbons, Ph.D.
David A. Flowers
John J. Fortin, P.E.
Donald M. Gabb
Mark Gehring
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Charlene K. Givens
Fred G. Haffty, Jr.
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Carl R. Hendrickson
Webster Hoener
Brian Hystad
Norman Jadczak
Jain S. Jain, Ph.D., P.E.
Samuel S. Jeyanayagam, Ph.D., P.E., BCEE
Bruce M. Johnston
John C. Kabouris
Sandeep Karkal
Gregory M. Kemp, P.E.

Justyna Kempa-Teper
Salil M. Kharkar, P.E.
Farzin Kiani, P.E., DEE
Thomas P. Krueger, P.E.
Peter L. LaMontagne, P.E.
Wayne Laraway
Jong Soull Lee
Kurt V. Leininger, P.E.
Anmin Liu
Chung-Lyu Liu
Jorj A. Long
Thomas Mangione
James J. Marx
Volker Masemann, P. Eng.
David M. Mason
Russell E. Mau, Ph.D., P.E.
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William R. McKeon, P.E.
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Darrell Milligan
Robert Moser, P.E.
Alie Muneer
B. Narayanan
Vincent L. Nazareth, P. Eng.
Keavin L. Nelson, P.E.
Gary Neun
Daniel A. Nolasco, M. Eng., M. Sc., P. Eng.
Charles Norkis
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Jesse Pagliaro
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Barbara Paxton
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Keith A. Radick
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Ed Ratledge
Melanie Rettie
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Joel C. Rife
Jim Rowan
Hari Santha
Fernando Sarmiento, P.E.
Patricia Scanlan
George R. Schillinger, P.E., DEE
Kenneth Schnaars
Ralph B. (Rusty) Schroedel, Jr., P.E., BCEE
Pam Schweitzer
Reza Shamskhorzani, Ph.D.
Carole A. Shanahan
Andrew Shaw
Timothy H. Sullivan, P.E.
Michael W. Sweeney, Ph.D., P.E.
Chi-Chung Tang, P.E., DEE, Ph.D.
Prakasam Tata, Ph.D., QEP
Gordon Thompson, P. Eng.
Holly Tryon
Steve Walker
Cindy L. Wallis-Lage
Martin Weiss
Gregory B. White, P.E.
George Wilson
Willis J. Wilson
Usama E. Zaher, Ph.D.
Peter D. Zanoni

Under the direction of the MOP 11 Subcommittee of the Technical Practice Committee

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For information on membership, publications, and conferences, contact

Water Environment Federation
601 Wythe Street
Alexandria, VA 22314-1994 USA
(703) 684-2400
http://www.wef.org

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Chapters 11, 23, and 32 were not updated for this edition of MOP 11. Chapters 11, 23, and 32 included herein are taken from the 5th edition of the manual, which was published in 1996.

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The WEF Technical Practice Committee (formerly the Committee on Sewage and Industrial Wastes Practice of the Federation of Sewage and Industrial Wastes Associations) was created by the Federation Board of Control on October 11, 1941. The primary function of the Committee is to originate and produce, through appropriate subcommittees, special publications dealing with technical aspects of the broad interests of the Federation. These publications are intended to provide background information through a review of technical practices and detailed procedures that research and experience have shown to be functional and practical.

Water Environment Federation Technical Practice
Committee Control Group
B. G. Jones, *Chair*
J. A. Brown, *Vice-Chair*
S. Biesterfeld-Innerebner
R. Fernandez
S. S. Jeyanayagam
Z. Li
M. D. Nelson
S. Rangarajan
E. P. Rothstein
A. T. Sandy
A. K. Umble
T. O. Williams
J. Witherspoon

Acknowledgments

This manual was produced under the direction of Michael D. Nelson, *Chair*.

The principal authors and the chapters for which they were responsible are

George Abbott (2)
Thomas P. Krueger, P.E. (2)
Thomas E. Arn (3)
Greg Ramon (3)
Gregory M. Kemp (4)
Roger A. Migchelbrink (5)
Melanie Rettie (6)
Michael W. Sweeney, Ph.D., P.E. (6)
David Olson (7)
Russell E. Mau, Ph.D., P.E. (8)
Peter Zanoni (9)
Louis R. Germanotta, P.E. (10)
Norman Jadczak (10)
James Kelly (11)
Richard Sutton, P.E. (12)
Alicia D. Gilley, P.E. (13)
Jorj Long (14)
Keavin L. Nelson, P.E. (15)
Ed Ratledge (16)
Kathleen M. Cook (17)
Frank D. Barosky (17)
Jerry C. Bish, P.E., DEE (18)
Ken Schnaars (19)
Donald J. Thiel (20, Section One)
William C. Boyle (20, Section Two)
Donald M. Gabb (20, Section Three)
Samuel S. Jeyanayagam (20, Section Four)
Kenneth Schnaars (20, Section Five)
Alan J. Callier (20, Section Six)
Jorj Long (20, Appendices)
Howard Analla (21)
John R. Harrison (22)
Anthony Bouchard (23)
Sandeep Karkal, P.E. (24)
Daniel A. Nolasco, M. Eng., M. Sc., P. Eng. (25)
Donald F. Cuthbert, P.E., MSEE (26)
Carole A. Shanahan (27)
Kim R. Riddell (28)
Peter L. LaMontagne, P.E. (29)
Patricia Scanlan (30)
Webster Hoener (30)
Gary Neun (30)
Jim Rowan (30)
Hari Santha (30)
Elena Bailey, M.S., P.E. (31)
Rhonda E. Harris (32)
Peter L. LaMontagne, P.E. (33)
Wayne Laraway (33)

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Contributing authors and the chapters to which they contributed are

David M. Mason (3)
David W. Garrett (9)
Earnest F. Gloyna (23)
Roy A. Lembcke (23)
Jerry Miles (23)
Michael Richard (23)
John Bratby, Ph.D., P.E. (29)
Curtis L. Smalley (32)

Michael D. Nelson served as the Technical Editor of Chapters 10 and 25.

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Abbott & Associates, Chester, Maryland
Alberta Capital Region Wastewater Commission, Fort Saskatchewan, Alberta, Canada
Allegheny County Sanitary Authority, Pittsburgh, Pennsylvania
Alliant Techsystems, Lake City Army Ammunition Plant, Independence, Missouri
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Burns and McDonnell, Kansas City, Missouri
Capitol Environmental Engineering, North Reading, Massachusetts
Carollo Engineers, Walnut Creek, California
CDM, Albuquerque, New Mexico; Manchester, New Hampshire
CH2M Hill, Cincinnati, Ohio; Santa Ana, California
City of Delphos, Delphos, Ohio
City of Edmonton, Alberta, Canada
City of Fairborn Wastewater Reclamation District, Fairborn, Ohio
City of Frankfort, Frankfort Sewer Department, Frankfort, Kentucky
City of Phoenix Water Service Department, Phoenix, Arizona
City Of Tulsa Water Pollution Control Section, Tulsa, Oklahoma
City of Tulsa, Tulsa, Oklahoma
Clayton County Water Authority, Jonesboro, Georgia
Consoer Townsend Envirodyne Engineers, Nashville, Tennessee
Consolidated Consulting Services, Delta, Colorado
CTE Engineers, Spokane, Washington
David A. Flowers, Cedarburg, Wisconsin
DCWASA, Washington, D.C.
Department of Biological Systems Engineering, Washington State University, Pullman, Washington
Earth Tech Canada, Inc., Markham, Ontario, Canada
Earth Tech, Sheboygan, Wisconsin
East Norriton-Plymouth-Whitpain Joint Sewer Authority, Plymouth Meeting, Pennsylvania

EDA, Inc., Marshfield, Massachusetts
Eimco Water Technologies Division of GLV, Austin, Texas
El Dorado Irrigation District, Placerville, California
Electrical Engineer, Inc., Brookfield, Wisconsin
EMA, Inc., Louisville, Kentucky; St. Paul, Minnesota
Environmental Assessment and Approval Branch, Ministry of the Environment, Toronto, Ontario, Canada
Eutek Systems, Inc., Hillsboro, Oregon
Fishbeck, Thompson, Carr & Huber, Inc., Farmington Hills, Michigan; Grand Rapids, Michigan
Floyd Browne Group, Delaware, Ohio
Gannett Fleming, Inc., Newton, Massachusetts
Givens & Associates Wastewater Co., Inc., Cumberland, Indiana
Grafton Wastewater Treatment Plant, South Grafton, Massachusetts
Greater Vancouver Regional District, Burnaby, British, Columbia, Canada
Greeley and Hansen, L.L.C., Chicago, Illinois; Philadelphia, Pennsylvania; Phoenix, Arizona
Hazen and Sawyer, PC, New York, New York; Raleigh, North Carolina
HDR Engineering, Charlotte, North Carolina
Hillsborough County Water Department, Tampa, Florida
Hubbell, Roth, & Clark, Inc., Detroit, Michigan
Infrastructure Management Group, Inc., Bethesda, Maryland
ITT/Sanitaire WPCC, Brown Deer, Wisconsin
Kennedy/Jenks Consultants, San Francisco, California
Los Angeles County Sanitation Districts, Whittier, California
MAGK Environmental Consultants, Manchester, New Hampshire
Malcolm Pirnie, Inc., Columbus, Ohio
Massachusetts Institute of Technology, Cambridge, Massachusetts
Metcalf & Eddy, Inc., Philadelphia, Pennsylvania
Metro Wastewater Reclamation District, Denver, Colorado
Mike Nelson Consulting Services LLC, Churchville, Pennsylvania
Ministry of Environment, Toronto, Ontario, Canada
MKEC Engineering Consultants, Wichita, Kansas
MWH, Cleveland, Ohio
New York State Department of Environmental Conservation, Albany, New York
NOLASCO & Assoc. Inc., Ontario, Canada
Nolte Associates, San Diego, California
Northeast Ohio Regional Sewer District, Cleveland, Ohio

Novato Sanitary District, Novato, California
NYSDEC, Albany, New York
Orange County Sanitation District, Fountain Valley, California
Parsons Engineering Science, Inc., Tampa, Florida
Pennoni Associates, Inc., Philadelphia, Pennsylvania
Peter LaMontagne, P.E., New Britain, Pennsylvania
Philadelphia City Government, Philadelphia, Pennsylvania
Philadelphia Water Department, Philadelphia, Pennsylvania
PSG, Inc., Twin Falls, Idaho
R.V. Anderson Associates, Limited, Toronto, Ontario, Canada
Red Oak Consulting—A Division of Malcolm Pirnie, Inc., Phoenix, Arizona
Research and Development Department, Metropolitan Water Reclamation District of Greater Chicago, Cicero, Illinois
Rock River Water Reclamation District, Rockford, Illinois
Rohm and Haas Co., Croydon, Pennsylvania
Sanitary District of Hammond, Hammond, Indiana
Seacoast Environmental, L.L.C., Hampton, New Hampshire
Siemens Water Technologies, Waukesha, Wisconsin
Simsbury Water Pollution Control, Simsbury, Connecticut
Tata Associates International, Naperville, Illinois
Thorn Creek Basin Sanitary District, Chicago Heights, Illinois
Trojan Technologies Inc., London, Ontario, Canada
U. S. Environmental Protection Agency, Philadelphia, Pennsylvania
U.S. Filter Operating Services, Indian Harbour Beach, Florida
United Water, Milwaukee, Wisconsin
University of Wisconsin, Madison, Wisconsin
USFilter, Envirex Products, Waukesha, Wisconsin
USFilter, Inc., Norwell, Massachusetts
Veolia Water North America, L.L.C., Houston, Texas; Norwell, Massachusetts
West Point Treatment Plant, Seattle, Washington
West Yost & Associates, West Linn, Oregon
Weston & Sampson Engineers, Inc., Peabody, Massachusetts

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Chapter 1

Introduction

This sixth edition of *Operation of Municipal Wastewater Treatment Plants* (MOP 11), an update of the edition published in 1996, aims to be the principal reference for the superintendent or chief operator of municipal wastewater treatment plants (WWTPs) and thereby helps maintain compliance. Based on the practices, experiences, and innovations of many who have operated the thousands of plants built or upgraded since 1996, this updated manual reflects the state of the art in plant management and operation. It emphasizes principles of treatment plant management, troubleshooting, and preventive maintenance and recognizes that the plant's success over the long run depends largely on sound management.

The revised version of Chapter 2 discusses the evolution of the Clean Water Act from a point source approach to a holistic watershed strategy, changes in wastewater treatment plant financing, and the positive trend of beneficial use of biosolids and treated effluent. This chapter also discusses improvements in toxicity testing and advances in wastewater treatment technology, which include membrane filtration (e.g., microfiltration and ultrafiltration). The Environmental Management System approach is also discussed; in particular, the way it can be used to improve management practices and outcomes of utility operations.

Chapter 3 was reorganized with extensive editing throughout to reflect new headings and topics. It contains extensive new text, figures, and tables in all subject areas. The new version's perspective includes a shift from programmatic content (e.g., a compendium of "how to") to more of an overview (broader discussion on general management considerations and things to think about for covered topics).

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Chapter 4 has been updated to focus on the U.S. Pretreatment Program requirements defined in 40 *CFR* 403. The chapter offers a brief history of the National Pretreatment Program, an overview of the program requirements, and a brief discussion of the program responsibilities for publicly owned treatment works (POTWs) and industrial users. New information briefly discusses local limits, including maximum allowable headworks loading and removal credits. References are provided that offer more-in-depth discussion of the program and its requirements for POTWs and industrial users.

The revised version of Chapter 5 contains basic safety for the operations, maintenance, and administration of wastewater treatment plants and collection systems. It includes new material on parasites and updated information on regulations.

Because wastewater utilities rely on vast amounts of historical, transactional, and real-time information to efficiently operate and maintain various systems, to ensure compliance with regulations, and to make informed decisions, Chapter 6 comprehensively explores the various areas comprising information management that are unique and vital to utilities and their customers. They include operations, administration, laboratory, process control, and recordkeeping and other functional area perspectives. While the entire chapter has been updated from the previous edition, the areas of risk management, regulation updates (e.g., the capacity, management, operations, and maintenance rule), and information technology integration and security have been expanded to reflect current requirements.

The revised version of Chapter 7 provides information on sensors and incorporates a new section on facility personnel protection and security, including fire, card access, intrusion detection, closed-circuit television, and page party systems.

Chapter 8 provides a brief review of pump and pumping fundamentals, then presents operation and maintenance (O&M) guidance for liquid and solids pumping, and finally discusses pumping station considerations. The revised version of this chapter has been updated to reduce the repetitiveness of the O & M considerations listed in previous version (i.e., general O&M considerations that are applicable to all pumps are presented first in a dedicated section, then more specific O&M practices are outlined under each type of pump or pumping system). Also, the revised version of this chapter provides updated O&M information, recognizing improvements in pump driver and control technologies, and includes more information about computerized O&M systems.

The revised version of Chapter 9 is a complete overview and guide to the handling, storage, and feeding of various chemicals used in wastewater treatment. The chapter can serve as a refresher to anyone experienced in chemical handling, as well as an introduction to those who have little or no knowledge in this area. This revised ver-

sion has updated references, tables, and figures. One new table includes chemical feeding information (e.g., feed concentrations, feeding methods, and equipment type). Methods for choosing the appropriate storage system are also discussed. New text additions include a discussion of the U.S. Environmental Protection Agency's Risk Management Regulations and Spill Prevention Considerations. Technical additions, which are applicable to both small and large treatment plants, feature discussions on sodium hypochlorite storage and feed systems, including onsite generation. Lastly, a "Helpful Hints" section has been added that provides a checklist of items for use by operations personnel and design engineers.

Chapter 10 provides information about the electrical distribution system and its components. A section on basic terminology has been added to increase reader understanding of electrical topics. Sections on "Staffing and Training", "Maintenance and Troubleshooting", and "Cogeneration" have been expanded. The chapter has been restyled to increase readability and selected references have been updated.

Chapter 11, which was not updated for this edition, outlines the vital support role performed by in-plant utilities in the operation of wastewater treatment facilities. Some utilities assist with equipment and process operations, and others support the safety and welfare of plant personnel. Some utilities (e.g., water supplies; compressed air; communications systems; heating, ventilating, and air conditioning systems; fuel supply systems; and roadways) continuously serve as an integral part of the plant's daily functions. Others (e.g., fire protection, storm drainage, and flood protection) serve on an occasional, seasonal, or emergency basis. Loss of any of these services can impair operations, cause facility failure, or impose risks and discomfort on plant staff.

The revised version of Chapter 12 abandons calendar-based maintenance strategies in favor of condition-based practices. This paradigm shift occurred long ago in world-class maintenance groups in industries of all kinds. Additionally, emphasis is placed on basic maintenance fundamentals over computer tools.

Chapter 13 is intended to be a reference of practice for operators involved in managing air emissions from wastewater conveyance and treatment facilities. This chapter provides information on odor measurement and characterization, as well as the mechanisms of odor generation in both the collection system and treatment processes. Significant changes in the revised version of this chapter include the discussion of appropriate odor-control methods and technologies, because many innovative treatment technologies have been introduced in the past several years. Operation and maintenance requirements for control equipment are also included. Finally, odor-control strategies for operators are discussed, providing a sequence of steps to consider when approaching an odor-control problem.

In the revised edition of Chapter 14, the process-control section now includes two examples of standard operating procedures (SOPs). The list-style SOP provides information for certified operators. The narrative-style SOP provides a detailed description of the procedures to be followed. This approach is good for full documentation and training, and utilities that use cross-training. In addition, the process-control section now contains a detailed explanation of how to read and apply a process and instrumentation diagram.

This update of Chapter 15 has been crafted to review the current state of the outsourcing industry and present the options that have evolved over the past decade. It is not intended to be complete in every detail because every outsourcing opportunity presents unique requirements and goals. Rather, it is intended as a guide, providing a broad overview of the various options available, critical issues that should be considered, and strategies to make an outsourcing effort successful. The outsourcing market is a dynamic one, affected by many considerations, and it is continually evolving. Municipal or private entities considering outsourcing their treatment facility or utility operations are encouraged to openly explore existing options with various service providers and consultants in the industry to define which solution is best for each individual case.

The revised version of Chapter 16 offers a different approach to training development, a simple yet comprehensive look at training and the role of the trainer in an organization, and answers such questions as: What makes training work, and what common mistakes guarantee that it will fail? Why is skill stratification an issue now, and what can be done about it? What can a trainer really do for the organization, and what should trainers never be expected to do? What are policies, procedures, and operating manuals, and how should these very different documents be organized and written? How can a trainer know what kind of training will work? Are there substitutes for training that can achieve the same results?

As detailed in Chapter 17, it is important for facility operators to understand the physical and chemical characteristics of wastewater and the way to properly sample and test it to provide the treatment necessary to discharge clean water to the environment. Chapter 17 gives an overview of the composition of wastewater; explains the different types of sampling needed, how to collect and preserve samples, what equipment is needed, and why the chain of custody is important; and briefly discusses airspace monitoring relative to worker safety and odor control. In particular, sampling and testing are important to provide the data that operators need to treat the wastestream properly to meet legal requirements. The revised version of this chapter provides more detail and adds tests that were not included in the previous edition of MOP 11. The

added material will help operators better understand wastewater and how to provide effective treatment.

Chapter 18 has been revised and expanded to include more descriptions of commonly used equipment and systems and important O&M aspects involved in keeping those systems in good working order. It also includes equipment and systems, such as vortex grit chambers and screening presses, that are currently used to treat raw wastewater that were not included in the last version. The chapter serves as a practical guide to understanding important O&M issues and concerns related to good operations, maintenance, and management practices related to preliminary treatment systems.

This edition of Chapter 19 includes several full-scale and current operational modifications and improvements that have been made to the primary treatment process since 1996. The chapter includes expanded discussions on primary sludge fermentation, enhanced primary treatment, dissolved air flotation primary systems, and combined grit removal/primary treatment processes. The chapter also provides a brief description about the ways that computer systems can assist with the operation of the primary treatment process. The primary treatment process appears to be a simple process to operate compared with other processes in a wastewater treatment plant; however, new advances to the primary treatment process are being made to improve both removal efficiencies in primary tanks and process reliability in downstream biological processes. For example, modifying the primary treatment process to a primary sludge fermentation system can increase the production of volatile fatty acids, which are known to play an important role in the success of the biological phosphorus removal process.

As outlined in Chapter 20, the activated sludge process is the most widely used biological process for reducing the concentration of organic pollutants in wastewater. Although well-established design standards based on empirical data have evolved over the years, poor process performance can still present problems for many municipal WWTPs. The objective of this chapter is to help operators and other wastewater treatment professionals better understand the process, solve performance problems, and improve operations. It describes activated sludge process variations and focuses on operation, addressing pertinent process theory, alternative process control strategies, energy conservation, and troubleshooting. This chapter doubles as the stand-alone manual, *Activated Sludge* (Manual of Practice No. OM-9). This chapter/manual now serves as the Water Environment Federation's primary reference for operating the activated sludge process.

As detailed in Chapter 21, tricking filters, biotowers, and rotating biological contactor (RBC) processes are generally known as fixed-film treatment processes. Of these three processes, the trickling filter predates biotowers, RBCs, and combined fixed-film and suspended growth (FF/SG) processes. New types of filter media are now used; therefore, rock media systems are labeled *trickling filters*, and plastic media systems are labeled *biotowers*. The trickling filter process is being incorporated in wastewater utilities using new methods or process modes, and many rock filters are being refurbished for continued use. This chapter aids both operators and engineers in grasping the O&M requirements of trickling filters in both existing and new systems. This chapter discusses many of the changes in the design and operation of RBCs. It includes discussions of predicting operating problems or plant overload and emphasizes methods of upgrading or improving the operation of RBCs. Combined processes [i.e., coupling trickling filters, biotowers, or RBCs (fixed-film) with suspended-growth (activated sludge) processes] are attempts to take advantage of the strengths and minimize the weaknesses of each process. In many cases, the practice is used to reduce construction costs by avoiding the building of additional tankage. This chapter addresses O&M concerns associated with combining of biological processes.

The revised version of Chapter 22 on biological nutrient removal (BNR) incorporates the best training information available from recent workshops or texts on nitrogen and phosphorus removal. It is intended to provide operators, managers, and engineers with both the fundamentals and practical examples of design and operation of BNR facilities. Chapter 22 is a complete rewrite on nutrient removal and contains figures and examples never before published.

Chapter 23, which was not updated for this edition, emphasizes that stabilization lagoons and land-treatment processes are natural systems commonly used to treat the municipal wastewater of small communities (populations less than 20,000). Stabilization lagoons typically provide secondary treatment; land-treatment systems often provide higher levels of treatment. This chapter provides information that will enable operators of lagoons and land treatment systems to prevent problems, solve them, and improve the performance of these natural systems.

Chapter 24 provides information on physical and chemical treatment processes. Examples of chemical processes are heavy metal precipitation, phosphorus precipitation, acid or alkali addition for pH control, and chlorine or hypochlorite disinfection. Physical processes include flow measurement, grit removal, primary and secondary clarification/sedimentation, filtration, and centrifugation. At the time of this writing, most WWTPs in the United States provide preliminary, primary, and secondary levels of wastewater treatment, where the focus is on reducing carbonaceous

biochemical oxygen demand (CBOD) and total suspended solids (TSS) to meet discharge permit parameters. However, to further enhance the quality of receiving waters, regulators are increasingly targeting reductions in nitrogen, phosphorus, metals, and non-biodegradable soluble organics in addition to the conventional BOD, TSS, and fecal coliform parameters. Another area of regulatory and environmentalist focus is in providing additional (tertiary) treatment to secondary effluent so it can be recycled for applications traditionally served by potable water (e.g., irrigation and industrial uses). Both objectives can be addressed by physical and chemical processes. Chemical addition can be used to enhance the reduction of conventional parameters, such as suspended solids, or new processes can be added to reduce the levels of such parameters as phosphorus and soluble, non-biodegradable chemical oxygen demand (COD). Accordingly, this chapter addresses the use of physical and chemical treatment as it relates to (a) enhanced suspended solids reduction in primary treatment, (b) further reduction of solids in advanced treatment processes following conventional treatment, and (c) reductions in such parameters as phosphorus and soluble, non-biodegradable COD.

Chapter 25 outlines the steps of process performance improvement. An important relevant topic, flow meter accuracy, is discussed. Next, tools used to define the process performance of the existing facility are presented. They include hydraulic capacity analysis, tracer testing, and aeration system analysis. Embedded in the tools are approaches to improve process performance. A section then follows on chemical addition. Chemical selection steps are detailed, in addition to examples of process performance improvements. Next, a section on bioaugmentation is presented. Appendices are included to fully explain flow meters and aeration system analysis, and present a tracer case history.

While the understanding of fundamental wastewater disinfection mechanisms has changed little over the years, applications of the technologies have evolved considerably. Chapter 26 has been revised to include current industry trends associated with the post-September 11, 2001, emphasis on security and safety when selecting technologies; the recent focus on receiving water effects caused by disinfection byproducts; the challenges associated with wet weather treatment applications; and new and evolving technologies.

The revised version of Chapter 27 has been expanded to include a discussion of the final disposition of biosolids and associated costs. Emphasis is placed on cooperating with regulators, networking with organizations, and developing information about biosolids constituents, quality control, and public education.

Chapter 28 describes the types of residuals present in wastewater. It details where the residuals are found and their typical percentages in each stage of the wastewater

treatment process. The chapter also presents information on the biological and chemical makeup of the different types of residuals. The chapter further describes how to obtain samples of these residuals and what typical tests must be performed from regulatory and process-control perspectives. Testing procedures are described and referenced for further information and reasoning is given as to which test should be performed and what information it can provide. The tables have been updated to reflect the latest regulatory requirements. This chapter is a good general reference regarding the types of residuals typically found in wastewater and the types of testing procedures typically used to analyze them.

For the 6th edition of Chapter 29, the sections on centrifuges and dissolved air flotation have been completely rewritten to be more specific and user friendly.

Chapter 30 serves as a resource for plant staff to increase their knowledge of anaerobic digestion for biosolids treatment. While this chapter focuses on operational and troubleshooting guidance, it also includes a general discussion of digestion theory, such as information on available digestion process equipment and the common benefits and drawbacks that can affect the digestion process or its O&M. Significant changes and additions to the text include information on digestion pretreatment technologies, advanced digestion processes, regulatory issues associated with anaerobic digestion, and an expanded section on gas-cleaning technologies. Discussions of all technologies and equipment have been updated to reflect most recent developments.

As addressed in Chapter 31, aerobic digestion was initially used in plants that typically treated waste activated sludge from treatment systems that did not have a primary settling process—only waste activated or trickling-filter sludge, or mixtures of waste activated or trickling-filter sludge. Typically, if a primary settling process was included, anaerobic digestion was the process of choice because reliable techniques to thicken and aerobically digest flows containing more than 4% solids were not established at the time. Because of tighter effluent nitrogen and phosphorus standards in the United States in the late 1990s, primary clarifiers have slowly been eliminated from the process train to preserve the good carbon-to-nitrogen ratio typically required to achieve successful biological nitrogen removal. Both the new effluent limits and new techniques for controlling aerobic digestion processes and accurately predicting system performance have made aerobic digestion attractive once again. A number of anaerobic digesters have been converted to aerobic digesters because of their relatively easy operation, lower equipment cost, and ability to produce a better quality supernatant with lower nitrates and phosphorus (that protects the liquid side upstream). Another benefit of aerobic digestion is fact that these systems can achieve comparable volatile solids reduction with shorter retention periods, they have less hazardous cleaning and

repairing tasks, and they do not produce an explosive digester gas. The revised chapter was prepared in response to the new performance requirements of the rules and regulations for beneficial reuse, resulting in the identification of techniques that improved the process performance of aerobic digestion. These techniques are grouped into the following categories: (1) pre-thickening, (2) staged operation, (3) aerobic–anoxic operation, and (4) temperature control. These techniques are explored in depth in this chapter.

As described in Chapter 32 (which was not updated for this edition), because WWTPs have become more efficient at producing high-quality effluents, more solids are being generated. Solids treatment processes—thickening, dewatering, stabilization, and disposal—represent a significant portion of the cost of wastewater treatment. Stabilization processes further treat solids to reduce odors or nuisances, reduce the level of pathogens, and facilitate efficient disposal or reuse of the product. This chapter focuses on the following stabilization methods:

- Composting,
- Lime stabilization,
- Thermal treatment,
- Heat drying, and
- Incineration.

All of these stabilization methods (other than incineration) are widely used for treating sludge to Class A or Class B levels for beneficial reuse and disposal, as referenced in the U.S. Environmental Protection Agency's 40 *CFR* 503 regulations.

The 6th edition of Chapter 33 reflects the changes in dewatering technology over the last decade or more. Vacuum filters are uncommon now, supplanted by belt filters and centrifuges. Drying beds are less popular but reed beds are gaining popularity as an example of "green" technology. The industry is more dependent on polymers, and this section is greatly expanded. This chapter explains how the various dewatering processes work so readers can understand them and perhaps better operate the process in their own plants.

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Chapter 2

Permit Compliance and Wastewater Treatment Systems

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INTRODUCTION

This chapter reviews the various laws and regulations applicable to the safe treatment and disposal of materials from wastewater treatment facilities, describes the typical processes used to provide safe and acceptable treatment of wastewater, and discusses treatment and disposal alternatives for the solids removed from wastewater. For consistency with federal and state terminology, this manual uses the term *sludge* to refer to the solids separated from wastewater during treatment. For information on permit-required sampling, process control, and compliance sampling, see Chapter 17.

PERMIT COMPLIANCE

Municipal wastewater treatment plants buffer the natural environment from the wastewater generated in urban areas. Because uncontrolled releases of wastewater would degrade the water, land, and air on which life depends, the government has developed a comprehensive set of laws and regulations on safely treating and disposing of wastewater and sludge. They are summarized here. (Government agencies continually modify laws and regulations, so water and wastewater treatment professionals should review the current discharge rules when preparing and submitting the permit application for a specific plant.)

CLEAN WATER ACT. Congress enacted the Water Pollution Control Act Amendments of 1972 in response to growing public concern about water pollution. When amended again in 1977, this law became known as the Clean Water Act (CWA). It established the basic structure for regulating discharges of pollutants into U.S. waters. The Act's four guiding principles are:

- No one has the right to pollute U.S. waters, so a permit is required to discharge any pollutant;
- Permits limit the types and concentrations of pollutants allowed to be discharged, and permit violations can be punished by fines and imprisonment;
- Some industrial permits require companies to use the best treatment technology available regardless of the receiving water's assimilative capacity; and
- Pollutant limits involving more waste treatment than technology-based levels, secondary treatment (for municipalities), or best practicable technology (for industries) are based on waterbody-specific water quality standards.

The Act's primary objective is to restore and maintain the chemical, physical, and biological integrity of U.S. waters. So, the CWA set two national goals: achieve fishable

and swimmable waters (wherever possible) by 1983 and eliminate all pollutant discharges to navigable waters by 1985. The Act's 1977 and 1987 amendments reaffirm the importance of achieving these goals and give states the primary responsibility of implementing CWA through the permitting system established in Section 402.

Anyone discharging pollutants to U.S. waters must have a National Pollutant Discharge Elimination System (NPDES) permit. Dischargers without permits or those who exceed their permit limits are violating the law and are subject to civil, administrative, or criminal penalties. Maximum federal criminal penalties range from $25,000 per day and 1-year imprisonment for negligent violations to $50,000 per day and 3-year imprisonment for knowing violations to $250,000 per day and 15-year imprisonment for knowing endangerment. Federal penalties for violations of permit conditions are pursuant to Title 18, United States Code, Section 1001.

The NPDES permits typically specify the discharge location, the allowable discharge flows, the allowable concentrations (mass loads) of pollutants in the discharge, the limits of the mixing zone (if any), and monitoring and reporting requirements. Before it can be discharged to U.S. waters, municipal wastewater must have received secondary treatment—or more stringent treatment if necessary to meet water quality standards. Effluent from a secondary treatment system typically must contain no more than 30 mg/L of biochemical oxygen demand (BOD_5) and 30 mg/L of total suspended solids (TSS), and be between 6.0 and 9.0 pH (on a 30-day average basis), according to 40 *CFR* 133. This regulation also requires that the secondary treatment plant remove at least 85% of BOD_5 and TSS from municipal wastewater, except combined sewer overflows (CSOs). In addition, treatment plants designed to handle 19 000 m^3/d (5 mgd) or more (and smaller ones with interference and pass-through problems) must establish pretreatment programs to regulate industrial and other nondomestic wastes discharged into sewers.

Permit applications and required reports must be signed by the appropriate authority. According to 40 *CFR* 122.22, all permits and reports submitted by a corporation must be signed by a responsible corporate officer; those submitted by a partnership or sole proprietorship must be signed by one of the general partners; and those submitted by a municipality, state, federal, or other public agency must be signed by a principal executive officer or ranking elected official.

Between 1970 and 1988, the U.S. Environmental Protection Agency (U.S. EPA) provided $61.1 billion in Federal Construction Grants Program funds to help build new or upgrade existing publicly owned treatment works (POTWs). Meanwhile, states, municipalities, and the private sector have invested more than $200 billion on POTWs, and a comparable amount on operations and maintenance (O&M) of these plants.

Subsequent amendments have modified various CWA provisions. In 1981, for example, Congress amended the CWA to streamline the municipal construction grants

program, improving the capabilities of treatment plants built via this funding. In 1987, U.S. EPA began replacing the construction grants program with the State Water Pollution Control Revolving Fund (commonly known as the Clean Water State Revolving Fund):

> With the passage of the Amendments to the [CWA] in 1987, Congress provided for the replacement of the federal Construction Grants program with the Clean Water State Revolving Fund program (CWSRF). The program provides capitalization grants to the states to be used as the basis (along with a required twenty percent state match), to create revolving loan funds which provide low-interest loans to municipalities to finance wastewater infrastructure projects, and to fund water quality projects such as nonpoint source and estuary management.
>
> The states set the loan terms, which may be interest-free to market rates, with repayment periods up to twenty years. Terms may be customized to meet the needs of small and disadvantaged communities. Loan repayments are recycled to perpetuate the funding of additional water protection projects.
>
> Public involvement is an important element of the SRF Programs. Before applying for a capitalization grant, a state is required to provide information about the respective programs and the projects to be funded in an Intended Use Plan which is available for public review and comment. The Intended Use Plan is a requirement in both the Clean Water and Drinking Water State Revolving Fund programs (http://www.epa.gov/region7/water/srf.htm#cwsrf).

Other laws also have changed parts of the CWA. For example, the U.S.–Canadian Great Lakes Critical Programs Act of 1978, which became the Great Lakes Water Quality Agreement of 1980, required U.S. EPA to establish water quality criteria for the Great Lakes. The law specifically requires that the agency determine the maximum levels at which 29 toxic pollutants are safe for humans, wildlife, and aquatic life.

The Act has helped improve water quality tremendously. Many lakes and rivers that were grossly polluted in the 1970s, when the CWA was enacted, now support aquatic life. In the 1960s, worst-case dissolved oxygen levels ranged from 1 to 4 mg/L in heavily polluted waterways; testing in 1985 and 1986 showed that dissolved oxygen levels had risen to between 5 and 8 mg/L.

As improvements have occurred, regulators' focus has changed. For example, regulators initially focused on the chemical aspects of the "integrity" goal. In the last decade, however, they began paying more attention to physical and biological integrity. Regulators originally concentrated on discharges from "point-source" facilities,

such as municipal treatment plants and industrial facilities. In the late 1980s, they also began to manage "nonpoint sources," such as stormwater runoff from streets, farms, and construction sites. Some of the runoff programs are voluntary; others follow the traditional regulatory approach.

In the last 10 years, CWA programs have been evolving from a program-, source-, or pollutant-specific approach to a more holistic, watershed-based approach in which protecting healthy waters is as important as restoring impaired ones. Stakeholder involvement is an integral part of this new approach for achieving and maintaining state water quality and other environmental goals—not just those specified in the CWA.

Solids Management. Between 1972 and 1998, annual sludge production at U.S. wastewater treatment plants increased from 4.6 million to 6.9 million U.S. dry tons. In other words, sludge production has increased 50% since CWA was enacted, while the U.S. population only grew 29%, according to the Council of Economic Advisers (Washington, D.C.). The U.S. Environmental Protection Agency expected annual sludge production to rise to 8.2 million U.S. dry tons by 2010.

Much of this sludge is stabilized to produce biosolids—a primarily organic material—and beneficially used as a soil amendment (land-applied). The U.S. Environmental Protection Agency estimates that by 2010 about 70% of sludge will be beneficially used (Table 2.1). The agency regulates all biosolids that are landapplied, incinerated, or surface-disposed under 40 *CFR* 503 (58 *FR* 9248-9415). Sludge that is landfilled with other waste is regulated under 40 *CFR* 258.

A number of states have more restrictive solids management programs. For example, Oklahoma does not permit surface disposal (disposing of sludge in sludge-only landfills, surface impoundments or lagoons, or waste piles of sludge).

In July 2002, the National Research Council (NRC) published the results of its 18-month study on *Biosolids Applied to Land: Advancing Standards and Practices*.

TABLE 2.1 U.S. Environmental Protection Agency projections for beneficial use and disposal.

	Beneficial use		Disposal			
Year	Land-applied	Advanced treatment	Other use	Landfill	Incineration	Other
1998	41%	12%	7%	17%	22%	1%
2005	45%	13%	8%	13%	20%	1%
2010	48%	13.50%	8.50%	10%	19%	1%

Although there is no documented scientific evidence that the regulations have failed to protect public health, the NRC noted, uncertainty persists about the health effects of land-applied biosolids. So, the NRC made approximately 60 recommendations for addressing the uncertainties. In response, U.S. EPA began developing a strategy to address these issues and published *Standards for the Use or Disposal of Sewage Sludge* (Final Agency Response to the National Research Council Report on Biosolids Applied to Land and the Results of [U.S.] EPA's Review of Existing Sewage Sludge Regulations [*Federal Register* Doc. 03-32217, Filed 12-30-03]). In it, U.S. EPA identified 15 pollutants for possible regulation. These pollutants will undergo a more refined risk assessment and risk characterization, which may lead to a notice of proposed rule making under the CWA (http://www.epa.gov/EPA-WATER/2003/April/Day-09/w8654.htm).

Toxics. The Clean Water Act authorizes U.S. EPA to regulate the discharge of toxic chemicals to the environment. It also declares that U.S. policy is to prohibit toxic amounts of these pollutants from being discharged. Soluble toxics can threaten human health if they are in water used for drinking or swimming. Insoluble toxics can adsorb to sediment, be consumed by aquatic life, and thus enter the human food chain (via bioaccumulation).

The Act currently lists 126 priority pollutants (40 *CFR* 423, Appendix A) that must be controlled. These pollutants are divided into four classes: heavy metals and cyanide, volatile organic compounds, semivolatile organic compounds, and pesticides and polychlorinated biphenyls (PCBs). Also, certain nontoxic organic compounds in wastewater can become toxic chlorinated organic compounds, such as trihalomethanes, when the water is disinfected via chlorine.

Analysts use whole effluent toxicity (WET) testing to determine whether treatment plant effluent is toxic to humans or the aquatic environment. The test is a bioassay in which sensitive aquatic organisms are put in a container of effluent and monitored for several days to see how well they survive. If the effluent is toxic, regulators require that treatment plant staff systematically reduce the toxic components via a toxics reduction evaluation and appropriate treatment-plant or pretreatment-program modifications.

Stormwater. Under 40 *CFR* 122, point sources are prohibited from discharging industrial-related stormwater into a U.S. waterbody without an NPDES stormwater permit. These permits protect receiving waterbodies by requiring the permittee to implement appropriate stormwater controls and best management practices (BMPs). Treatment plants that discharge stormwater into U.S. waters or a municipal separate storm sewer system typically must have a "Sector T—Treatment Works" NPDES multisector general permit, as do 1-mgd or larger treatment plants and those with an approved industrial pretreatment program under 40 *CFR* 403. More information on stormwater

discharges and permits may be found on U.S. EPA Web site at cfpub1.epa.gov/npdes/stormwater/indust.cfm.

OCCUPATIONAL SAFETY AND HEALTH ACT. The Occupational Safety and Health Act (OSHA) addresses the safety and health of industrial workers. It provides guidelines for developing regulations on handling and storing hazardous materials, such as chlorine, acids, caustics, and other chemicals used to treat wastewater. (Although OSHA was not originally written for wastewater treatment plants, several states have applied its provisions to them.)

The Act also protects communities via a material safety data sheet (MSDS) provision that requires wastewater treatment plants to report inventories of hazardous chemicals to state and local emergency response agencies (40 *CFR* 370). Under the Hazard Communication Act, which is part of the Superfund Amendments and Reauthorization Act (SARA) Title III, treatment plants must train employees on proper use and handling of chemicals, provide them with the appropriate MSDSs, and notify state and local officials if they have extremely hazardous materials onsite in quantities exceeding certain thresholds; for example, the threshold quantity for chlorine is 1135 kg (2500 lb). Also, Section 313 of SARA Title III (40 *CFR* 372) requires treatment plants to report significant releases of certain toxic substances not covered by NPDES permits. As an example, the release quantity for chlorine is 4.5 kg (10 lb). (For more information on OSHA, see Chapter 5.)

STATE AND LOCAL PROGRAMS. Under Section 402(b) of the CWA, the U.S. EPA administrator delegated administration of the NPDES program to qualifying states. The state-run programs typically are called SPDES [(State Name) Pollution Discharge Elimination System] programs. These programs address effluent limits and monitoring requirements, sanitary sewer overflow (SSO) reporting, and sludge management requirements.

The effluent limits include conventional and unconventional pollutants, as well as year-round, seasonal, WET, and site-specific requirements. Examples of conventional pollutants include BOD and TSS, whereas unconventional pollutants may include metals, pesticides, and radioactive materials. Typical permit parameters include average and maximum flowrates, BOD_5, TSS, fecal coliform, pH, ammonia, phosphorus, and WET testing. The NPDES/SPDES permit establishes discharge limits (both concentration and mass loading) and monitoring requirements for each parameter.

The permit also requires permittees to develop and comply with approved sludge management plans. The plans establish "acceptable management practices" or numerical limits for pollutants in sludge, as promulgated in CWA Section 405(d)(2).

The permit may also include pollution prevention and pretreatment requirements. Pollution prevention requirements involve assessing treatment plant facilities, equipment, and staff duties to determine whether and how they could be modified to minimize waste and avoid pollution. Pretreatment requirements involve establishing and operating an industrial pretreatment program that complies with CWA Section 402(b)(8), General Pretreatment Regulations (40 *CFR* 403). (More stringent state and local requirements may also apply.) The pretreatment program's goals are to avoid introducing pollutants that will interfere with treatment plant operations or pass through the plant untreated, and to promote opportunities for recycling treated wastewater and sludge.

In addition to NPDES/SPDES permits, local and state ordinances may address environmental protection, pretreatment of waste streams discharged to treatment plants, residuals management, and occupational safety and health. These ordinances are sometimes more stringent than the federal rules for the same activity. For example, some local ordinances only allow Class A biosolids to be land-applied, while the federal regulations permit land application of both Class A and Class B biosolids. Other localities have developed wellhead-protection programs because of concerns about increasing aquifer-contamination rates. And some local agencies regulate the use of treated effluent to irrigate golf courses and other landscapes.

State and local agencies also develop the requirements for certifying POTW staff, including collection system workers, treatment plant operators, and laboratory technicians. The certification requirements typically are based on plant size, complexity, and required reliability. The agencies often establish similar requirements for privately owned or operated systems that discharge to a POTW or to state waters. For more information, check your state's employment requirements.

ENVIRONMENTAL MANAGEMENT SYSTEMS. An environmental management system (EMS) is designed to integrate environmental issues into an organization's management processes. It enables any organization to control the effect of its activities, products, or services on the natural environment, allowing the organization to not only achieve and maintain compliance with current environmental requirements, but also proactively manage future environmental issues that might affect daily activities. Wastewater utilities will find that implementing an EMS improves its environmental, financial, and other results.

Implementing an EMS does not require a utility to create an entirely new system. It simply provides a structure to help organizations incorporate the responsibilities, practices, procedures, processes, and resources needed to implement and maintain an effective environmental management system into their routines. Most of an EMS' required elements are already part of existing management programs.

For more information on EMSs, access U.S. EPA's Web site (www.epa.gov/ems/index.htm) or type "environmental management system" into your favorite Web browser.

LIQUID TREATMENT PROCESSES

Wastewater treatment is a multi-stage process designed to clean water and protect natural waterbodies. Municipal wastewater contains various wastes; it typically consists of about 99.94% liquid and 0.06% solids. A typical U.S. city, including its private dwellings, commercial establishments, and industrial contributors, produces between 379 and 455 L/d/person (100 and 120 gpd/person) of wastewater—not including the water that infiltrates and exfiltrates the collection system. If untreated or improperly collected and treated, this wastewater and its related solids could hurt human health and the environment.

Stormwater runoff and CSOs also produce large volumes of wastewater that can affect public health and the environment. For more information on stormwater and CSO controls, see Water Environment Federation's *Prevention and Control of Sewer System Overflows*.

OBJECTIVES. A treatment plant's primary objectives are to clean the wastewater and meet the plant's permit requirements. Treatment plant personnel do this by reducing the concentrations of solids, organic matter, nutrients, pathogens, and other pollutants in wastewater. The plant must also help protect the receiving waterbody, which can only absorb so many pollutants before it begins to degrade, as well as the human health and environment of its employees and neighbors.

When establishing permit requirements for a treatment plant, regulators may consider the following issues in addition to the minimum statutory requirements:

- Preventing disease,
- Preventing nuisances,
- Protecting drinking water supplies,
- Conserving water,
- Maintaining navigable waters,
- Protecting waters for swimming and recreational use,
- Maintaining healthy habitats for fish and other aquatic life, and
- Preserving pristine waters to protect ecosystems.

One of the challenges of wastewater treatment is that the volume and physical, chemical, and biological characteristics of wastewater continually change. Some changes are the temporary results of seasonal, monthly, weekly, or daily fluctuations in the

wastewater volume and composition. Other changes are long-term, the results of alterations in local populations, social characteristics, economies, and industrial production or technology.

The quality of the receiving water and the public's health and well-being may depend on a treatment plant operator's ability to recognize and respond to potential problems. These responsibilities demand a thorough knowledge of existing treatment facilities and wastewater treatment technology.

COLLECTION SYSTEM. A collection system is a network of pipes, conduits, tunnels, equipment, and appurtenances used to collect, transport, and pump wastewater. Typically, the wastewater flows through the network via conventional gravity sewers, which are designed so each pipe's size and slope will maintain flow toward the discharge point without pumping. Lift stations are used to move wastewater from lower to higher elevations.

There are three principal types of municipal sewers: sanitary sewers, storm sewers, and combined sewers. *Sanitary sewers* convey wastewater from residential, commercial, institutional, or industrial sources, as well as small amounts of groundwater infiltration and stormwater inflow. *Storm sewers* convey stormwater runoff and other drainage. *Combined sewers* convey both sanitary wastes and stormwater.

The type of collection system may profoundly affect treatment plant operations. For example, the high flows and heavy sediment loads discharged by a combined system during and after a storm make effective treatment more challenging. Excessive infiltration and inflow in a poorly maintained sanitary system can have similar results. Extensive collection systems may discharge foul-smelling, septic wastewater to the plant unless the odors are controlled en route.

Today, municipalities rarely construct combined sewers, and most have made efforts to separate stormwater from sanitary wastewater. Their efforts may be inexpensive, such as requiring homeowners to disconnect roof drains from municipal sewer systems, or major construction projects, such as rerouting stormwater from sanitary sewers to nearby creeks and rivers.

PRELIMINARY TREATMENT. Preliminary treatment typically begins with removing materials, such as hydrogen sulfide, wood, cardboard, rags, plastic, grit, grease, and scum, that might damage the plant headworks or impair downstream operations. These materials may be removed via chemical addition, pre-aeration, bar racks, screens, shredding devices, or grit chambers. Preliminary treatment may also include coagulation, flocculation, and flotation to remove particles and biological solids from the wastewater. (For more information on preliminary treatment, see Chapter 18.)

PRIMARY TREATMENT. Primary treatment involves removing suspended and floating material from wastewater. Well-designed and -operated primary treatment facilities may remove as much as 60 to 75% of suspended solids and between 20 and 35% of total BOD_5. They do not, however, remove colloidal solids, dissolved solids, and soluble BOD_5. (For more information on primary treatment, see Chapter 19.)

SECONDARY TREATMENT. Secondary treatment reduces the concentrations of dissolved and colloidal organic substances and suspended matter in wastewater. Generally, secondary treatment reduces 85% of TSS and BOD_5, resulting in concentrations between 10 and 30 mg/L.

Most secondary treatment processes involve biological treatment—typically, attached- or suspended-growth systems. Both rely on a mixed population of microorganisms, oxygen, and trace amounts of nutrients to treat wastewater. The microorganisms consume organic material in the waste to sustain themselves and reproduce. They also convert nonsettleable solids to settleable ones. In *attached-growth systems*, such as trickling filters, packed towers, and rotating biological contactors, the microorganisms are attached to supporting media. In *suspended-growth systems*, such as lagoons and activated sludge processes, the microorganisms are drifting throughout the wastewater.

Secondary treatment process effluent contains high levels of suspended biological solids that must be removed before the effluent is further treated or discharged to a receiving waterbody. Most treatment plants use settling tanks to separate the solids from the liquid, although flotation and other methods may be used.

PHYSICAL–CHEMICAL TREATMENT. Physical and chemical treatment processes typically are used to remove oil, grease, heavy metals, solids, and nutrients from wastewater. For example, screening, sedimentation, and filtration are used to physically separate solids from wastewater. Chemical coagulation and precipitation is used to promote sedimentation. Activated carbon adsorption is used to remove organic pollutants. Breakpoint chlorination and lime addition are used to reduce nitrogen and phosphorus concentrations, respectively. (For more information on physical–chemical treatment, see Chapter 24.)

ADVANCED WASTEWATER TREATMENT. Advanced wastewater treatment (AWT) processes typically are used to further reduce the concentrations of nutrients (nitrogen or phosphorus) and soluble organic chemicals in secondary treatment effluent. These processes may be physical, chemical, biological, or a combination.

For example, membrane filtration—microfiltration, ultrafiltration, nanofiltration, and reverse osmosis—is used to remove organics, nutrients, and pathogens from waste-

water. (It traditionally was used for industrial wastewater treatment but has been gaining popularity at municipal treatment facilities.)

A treatment plant's permit requirements typically influence which, if any, AWT processes are used.

DISINFECTION. Disinfection inactivates or destroys pathogenic bacteria, viruses, and protozoan cysts typically found in wastewater. These pathogens cause such waterborne diseases as bacillary dysentery, cholera, infectious hepatitis, paratyphoid, poliomyelitis, and typhoid.

The growth of water reuse for irrigation and other purposes, and changes in requirements for toxics, including chlorine, to protect aquatic life are altering disinfection policies and, subsequently, disinfection practices. Chemical disinfection processes involving halogens, particularly chlorine, historically dominated the wastewater treatment field. However, concerns about chlorine safety and the requirement to dechlorinate some discharges have made other disinfection methods, such as ozonation and ultraviolet irradiation, more popular. *Ozonation* involves using ozone radicals to destroy pathogen cell walls. *Ultraviolet irradiation* involves using electromagnetic energy to destroy an organism's genetic material (DNA and RNA). Both are more costly than chlorine disinfection, but effective treatment alternatives. (For more information on disinfection, see Chapter 26.)

EFFLUENT DISCHARGE. Effluent matters because where it will be discharged or how it will be reused influences the permit requirements set and the treatment processes needed to meet those requirements. Treatment plant effluent can be discharged to a surface waterbody or wetlands, used to recharge groundwater aquifers via percolation through the ground or deep-well injection, or land-applied. It may be considered an alternative water source (because of its nitrogen and phosphorus content) and used to irrigate golf courses, parks, plant nurseries, and farms. It also could be the source water for a constructed wetland, adding nutrients that support the aquatic environment, thereby enhancing wildlife habitat and public recreation. In addition, effluent can be used by industries as cooling or makeup water for chemical processes.

RESIDUALS MANAGEMENT

Sludge treatment processes are often the most difficult and costly part of wastewater treatment. Untreated sludge is odorous and contains pathogens. Sludge stabilization processes reduce odors, pathogens, and biodegradable toxins, as well as bind heavy

metals to inert solids, such as lime, that will not leach into the groundwater. The resulting biosolids can be used or disposed of safely.

TYPES OF RESIDUALS. Wastewater residuals include primary, secondary, mixed, and chemical sludge, as well as screenings, grit, scum, and ash. Between 40 and 60% of influent TSS is primary sludge. It typically has a concentration of 2 to 6% solids when removed from the primary clarifiers. Secondary (biological) sludge is composed largely of microorganisms. Between 0.5 and 2.0% of TSS is biological sludge. Mixed residuals—commingled primary and secondary sludge—typically makes up 1.0 to 3.5% of influent TSS. The concentration and characteristics of chemical sludge depend on the treatment chemicals (alum, ferric salts, or lime) used. It typically is found at treatment plants that have tertiary treatment, such as phosphorus removal.

The use or disposal method for residuals depends on how much treatment they have received. *Biosolids* are residuals that have been stabilized so they can be beneficially used as a soil amendment. Combustible residuals, such as screenings, may be incinerated or landfilled. Noncombustible residuals, such as grit, may be landfilled.

TREATMENT PROCESSES. Typical solids treatment processes include thickening, stabilization, digestion, chemical, composting, dewatering, incineration, and heat drying. These processes are briefly described below.

Thickening. Thickening processes remove water to reduce the volume of liquid sludge, but the material retains the characteristics of a liquid (e.g., it flows). A thickened sludge typically contains between 1.5 and 8% solids. Thickening is intended to reduce the volume of sludge so sludge treatment, storage, and hauling processes, equipment, and costs can also be reduced.

There are three types of thickening:

- Pre-thickening (thickening before stabilization and dewatering),
- Post-thickening (thickening after stabilization but before beneficial use), and
- Recuperative thickening (thickening biosolids and returning them to the stabilization process).

Pre-thickening processes include gravity thickeners, dissolved air floatation (DAF), centrifuges, gravity belt thickeners, and rotary belt thickeners. Gravity thickeners work best on primary and chemical sludges; they do not work well with combined sludges. DAF is typically used to thicken WAS. Mechanical thickeners, such as centrifuges,

gravity belt thickeners, and rotary belt thickeners, are used on all types of sludges. They remove more water from sludges than a gravity thickener or DAF does.

Stabilization. Stabilization via digestion or chemical stabilization reduces the sludge's pathogen content, making the material a biosolids suitable for beneficial use.

Digestion. Aerobic and anaerobic digestion reduce the volatile solids and pathogen content of sludge, thereby reducing odors and producing an environmentally acceptable soil amendment. Aerobic digestion uses microbes in open or closed vessels or lagoons to oxidize the sludge's organic matter into carbon dioxide, water, and ammonia. It is becoming popular to operate these digesters at temperatures higher than 55 °C (131 °F) because doing so reduces the pathogen level in biosolids.

Anaerobic digestion uses microbes in a closed tank containing little or no oxygen (Figure 2.1). The tank is typically operated at temperatures between 35 and 38 °C (95 and 100 °F), but may be operated at more than 55 °C (131 °F) to further reduce pathogens

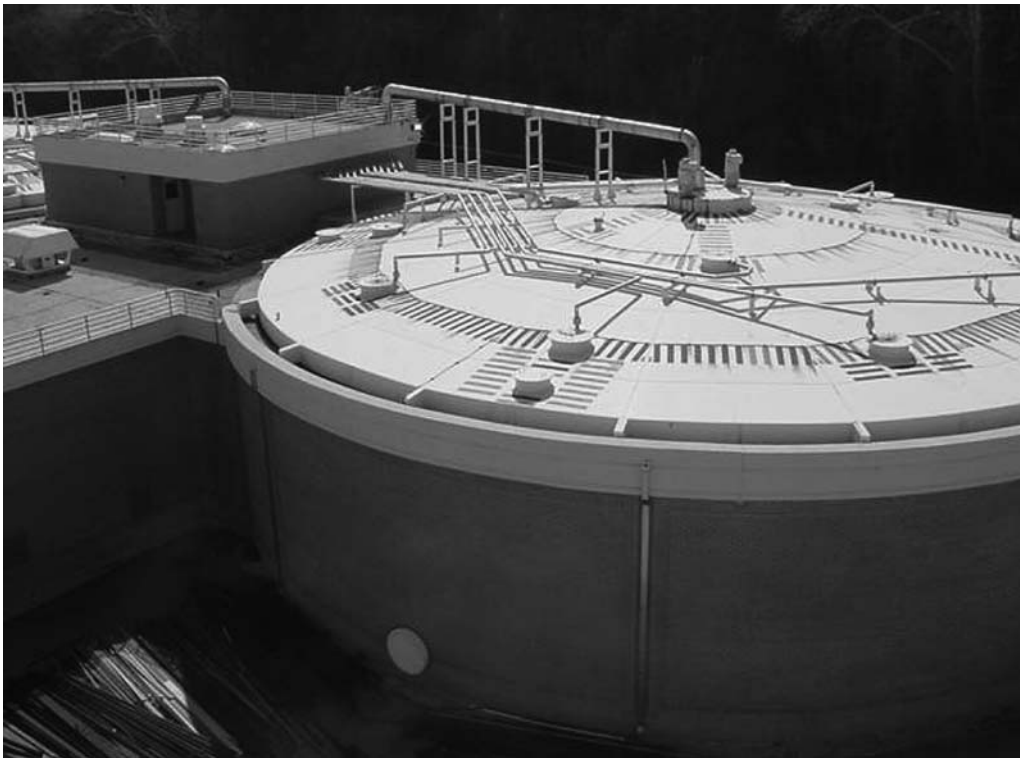


FIGURE 2.1 An example of anaerobic digestion in a closed tank.

and solids. Anaerobic digestion destroys more than 40% of volatile solids and produces an offgas containing about 65% methane, which may be collected and used as a fuel.

Both types of digestion can produce a Class A or Class B biosolids suitable for beneficial use, depending on time, temperature, and flow configurations involved (40 *CFR* 503).

Chemical Stabilization. Chemical stabilization typically involves using lime to raise the sludge's pH to 12.0 for 2 hours. This reduces pathogens and odors. Rules regarding chemical stabilization can be found in 40 *CFR* Part 503 rules. This stabilization method can also produce a Class A or Class B biosolids suitable for beneficial use (40 *CFR* 503).

Composting. Composting—windrow, aerated windrow, static pile, aerated static pile, and in-vessel—involves using microorganisms, a bulking agent (such as wood chips, leaves, or sawdust), and a controlled environment [typically 55 to 60 °C (131 to 140 °F)] to decompose organic matter in sludge, as well as reduce its volume and odors. The moisture and oxygen levels are also controlled to minimize odors during the process. Biosolids are typically used in windrow systems, while sludge can be composted in aerated static piles or an in-vessel system. Composting is gaining popularity because the finished material is an excellent soil conditioner.

Dewatering. Dewatering further reduces the volume and weight of biosolids via air-drying (on sand); vacuum-assisted drying beds; or mechanical dewatering equipment, such as belt filter presses, centrifuges, plate-and-frame filter presses, and vacuum filters. When used with polymers, belt filter presses and centrifuges can produce a biosolids "cake" that contains 15 to 25% solids. Sand drying beds typically produce a cake containing between 10 and 50% solids. Vacuum-assisted beds produce a cake containing 10 to 15% solids (when polymers are used). Plate-and-frame presses can produce a cake containing 30 to 60% solids (when lime, ferric chloride, or fly ash is used). Vacuum filters can produce a cake containing 12 to 30% solids (when the biosolids have first been conditioned with lime, ferric chloride, or polymers).

Heat Drying. Heat drying processes, such as low-temperature heat drying, flash drying, rotary kiln drying, indirect drying, vertical indirect drying, direct–indirect drying, and infrared drying, reduce the volume of secondary sludge and destroy pathogens. They typically produce a commercially marketable biosolids. Digestion is typically not a prerequisite.

Incineration. Incineration typically involves firing biosolids at high temperatures in a multiple-hearth or fluidized-bed combustor, turning them into ash, and destroying volatile solids and pathogens in the process. It degrades many organic chemicals but

can form others (e.g., dioxin), so products of incomplete combustion must be controlled. Air emissions also must be controlled. Metals are not degraded; they concentrate in the ash. Most incinerated municipal sludge will produce nonhazardous ash, which can be landfilled (40 *CFR* 258). It also can be used as an aggregate in concrete or a fluxing agent in ore processing. If inorganic or organic constituents exceed Appendix II to Part 258, disposal in a hazardous waste landfill will be required (http://www.epa.gov/tribalmsw/pdftxt/40cfr258.pdf).

Beneficial Use. Unstabilized sludge that is landfilled with other waste must comply with 40 *CFR* 258. Once stabilized into biosolids, however, 40 *CFR* 503 requires that the material be used or disposed of via one of the following environmentally acceptable alternatives: land application, surface disposal, or incineration. Treatment plant staff should assess local land availability, public acceptance, and transportation constraints before selecting a use or disposal alternative.

Land application involves spreading biosolids on the soil surface or injecting it into soil (Figure 2.2). The material, which adds organic matter and nutrients to soil, must



FIGURE 2.2 An example of land-applying biosolids.

meet Class A or Class B standards to be land-applied (40 *CFR* 503). Class A biosolids require more stabilization to reduce pathogens below detectable limits, but can be commercially marketed or land-applied without any pathogen-related restrictions.

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Chapter 3

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INTRODUCTION

The art of good management is an evolutionary process, and volumes of books have been written on the topic as witnessed by visiting the management section within your local bookstore or, more specifically, publications offered by the Water Environment Federation (WEF), the American Water Works Association, and other relevant trade organizations such as the International City and County Management Association and the American Management Association. This chapter provides an overview of general facility management considerations and does not attempt to convey the full level of detail associated with the topic of management.

Perhaps your organization has just appointed you "facility manager" or perhaps you have selected a career path toward achieving such a critically important position. Maybe you just want to learn what it means to be the person responsible for an expensive and complex treatment plant, or facility, or you might be a member of a large facility's management team. Regardless of your point-of-view, the facility manager is the singular focus for successful facility performance. By "successful performance," we mean the effective orchestration of staff, work processes, and technologies that result in treating wastewater liquid, solids, and airstreams that comply with regulatory limits and meet neighbor and stakeholder expectations.

To manage a facility that continually meets organizational, environmental, and stakeholder expectations is indeed a challenge. As the focal point and voice of the treatment facility, the plant manager must deal effectively with everyone and everything including municipal officials, regulators, media representatives, consultants, design engineers, equipment manufacturers, suppliers, public interest groups, the plant's neighbors and other concerned citizens, and the plant's employees (Figure 3.1). A successful treatment plant manager must also build effective relationships with employees and maintain stakeholder and public interests; possessing technical competency of the plant's unit operations is simply not enough. The definitive task of the manager is to marshal



FIGURE 3.1 Wastewater management challenges.

and effectively apply all available resources and to make the most of them in achieving organization.

AN OVERVIEW OF TREATMENT PLANT MANAGEMENT RESPONSIBILITIES

Facility management is a difficult balancing act; however, when executed properly, it results in a facility and staff performing at their peak potential as well as responding well to changes and challenges that arise. As depicted in Figure 3.2, there are many elements associated with facility management. The following six sections describe general areas of responsibility that the plant manager should consider.

ENVIRONMENTAL AND PUBLIC HEALTH CONSIDERATIONS. The fundamental purpose, or mission, of a treatment facility is *to protect the health of the public and the environment.* The plant manager must never forget about this mission. Although the mission is simple, it is much more difficult to achieve. The major respon-

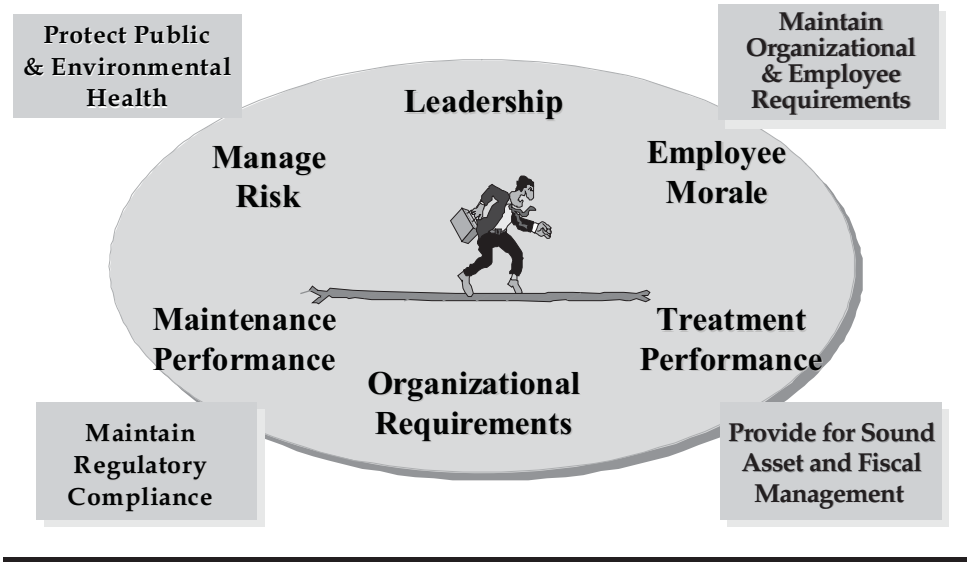


FIGURE 3.2 Facility management is a difficult balancing act.

sibility of ensuring that the facility functions in accordance with specified regulatory and other local requirements lies squarely on the manager's shoulders. The manager's functions include planning, organizing, directing, and controlling to accomplish a plant's mission. A typical mission for the manager includes operating a safe facility in continuous compliance with permit and other applicable legal requirements, yet doing so in an environment with budget limitations as well as organizational policies and procedures. This can be a difficult balancing act as these functions are often carried out in a political atmosphere under the scrutiny of a public keenly aware of environmental and financial concerns.

PHYSICAL ASSET MANAGEMENT RESPONSIBILITIES. The phrase, "physical asset management," refers to the strategy of managing the life-cycle cost (both capital and operations and maintenance expenses), use, and reliability of the systems, equipment, and other physical assets associated with the treatment facility to optimize their value in support of facility operations (Figure 3.3). The bottom line is that the manager must maintain a long-term perspective on the total life-cycle costs of the facility's assets, and must use effective and proactive procedures that support informed system design, equipment selection, proper installation, sound operation strategies, and effective maintenance programs and processes.

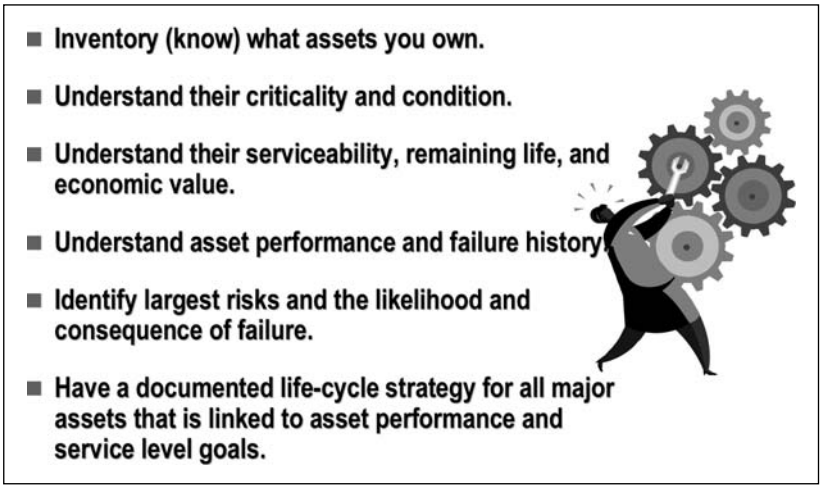


FIGURE 3.3 Asset management strategies.

ORGANIZATIONAL AND LEADERSHIP RESPONSIBILITIES. Organizations have a responsibility to their employees to clearly convey their mission statements. Conversely, the mission statement must communicate the organization's purpose. Managers must take a leadership role and provide the direction necessary for success. Good leadership skills allow managers to get things done through people.

Effective leaders use a number of resources to achieve their goals. They must set the course, energize the group, provide the means, and develop the plan in order to be successful. The role of the wastewater facility manager is to ensure that the organization's mission is met while providing employees with an opportunity for job growth and satisfaction. The organization's goals must be clear, obtainable, and have a general direction for all to follow. Effective managers must communicate the organization's mission to their audience. This includes using language that can be understood; that is, language that is neither too simple nor too complex to bore or threaten those receiving the information.

The manager must also align the goals of the facility with those of the greater organization and governance. As a leader, the manager must balance near-term goals with long-term interests and plans. Good leadership requires the manager to look beyond the daily technical issues of normal plant operation and maintain a perspective of long-term goals and directions. This includes considering organizational and staff requirements necessary to meet these goals.

The work environment is an important element within the manager's control to provide a safe workplace that contributes to employee satisfaction, effective performance (Figure 3.4), and good morale. Employees work harder for managers who are concerned and willing to make changes to put people first. Managers must instill the notion that "we are all in this together" to be successful. Finally, success is the result of every employee working as a team for one common cause.

OPERATIONS AND MAINTENANCE RESPONSIBILITIES. At the foundation of facility operations and maintenance is the concept of efficiency. Although it is often used in association with both positive and negative cost and budgetary effects, the term "efficiency" embodies much more. Efficiency improvement processes are a basic part of the management continuum and, while they often focus on near-term results, they also affect total life-cycle costs. The successful manager leads the organization in recognizing that virtually all processes, activities, or functions can be improved, whether they be treatment process control, energy use, employee performance, or maintenance management. At the heart of this process is the development of, and adherence to, the operations plan described later in this chapter. Achieving improvements requires constant attention to discrete practices, functions, subgroups, personalities, and technologies within the facility. Not being satisfied with the status quo and using effective monitoring strategies associated with recordkeeping and performance measurement are core elements used to manage operations and maintenance activities.



FIGURE 3.4 Maximizing staff performance.

FISCAL MANAGEMENT RESPONSIBILITIES. Wastewater utilities must provide high quality, environmentally responsible services at reasonable costs. Under today's cost control environment, the treatment manager faces a significant economic challenge to fulfill the organization's mission at the lowest practical cost (the term "practical" is used deliberately here). Practical cost management considers the long-term total life-cycle cost component and embodies sound operating strategies coupled with informed maintenance management activities. Cost management (Figure 3.5) is, indeed, a difficult balancing act that pits the constraints of near-term operating budgets against long-term asset management objectives and protection of public and environmental health issues.

All facility managers must advocate for and directly address the challenge of obtaining necessary funds for operating, maintaining, and improving the plant as necessary. The organization's budget process is central to meeting this responsibility, and includes clear definition of operation and maintenance expenses as well as long-term capital improvements necessary to fulfill the facility mission. The core of a sound budget is informed planning, justification and management of cost elements, and the involvement of community stakeholders in setting wastewater fees or rates to support the needs of the organization. In essence, the annual budget may be regarded as the mechanism for administering the operations plan for the facility. Tracking and managing the budget to the organization's goals can be the key to effective facility performance and help balance near and long-term demands. Moreover, tracking progress against this plan as the year progresses is an essential management responsibility.

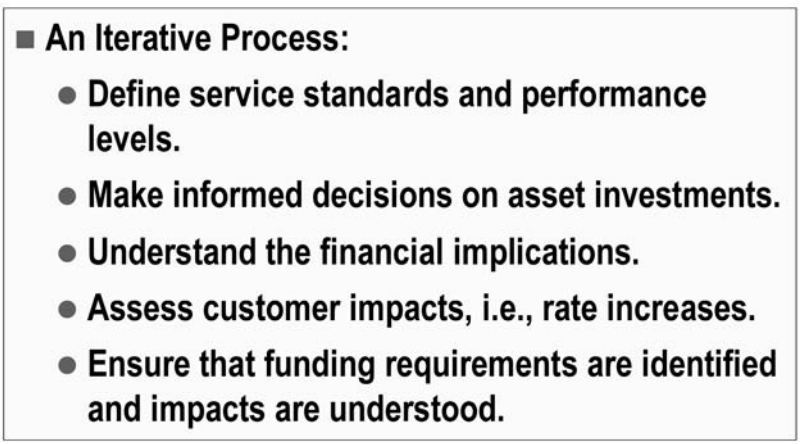


FIGURE 3.5 Fiscal management is a critical responsibility.

REGULATORY, NEIGHBOR, AND OTHER STAKEHOLDER RELATIONSHIP RESPONSIBILITIES. The facility manager has a critical responsibility in developing and maintaining effective relationships with external stakeholders (e.g., those that fall outside of the facility "fence line"). The acceptance of a facility as a good neighbor by the public cannot be understated. The term "effective" implies a relationship management strategy that recognizes and provides constructive means to manage differences in points-of-view and opinion as well as maintain positive relationships as much as possible. External stakeholders include neighbors, regulatory agencies, other groups and departments within the organization (e.g., police, fire, and public works), the media, bargaining units, and special interest groups. Given this diversity, as well as the general nature and perception of wastewater, the facility manager must seek to maintain effective relationships and interactions with external stakeholders. To achieve this requires a sound communications strategy and program that is known and practiced by all staff. In many cases, there is a distinct advantage for the manager to act as the primary "voice" of the plant to facilitate consistent and effective communications with external stakeholders.

MANAGEMENT CONSIDERATIONS

The environment that a facility operates in is constantly changing. Consider the many internal and external pressures and influences that a facility faces (Figure 3.6). These include political interests, regulatory mandates, security, economic development, changing workforce demographics, workforce retention (e.g., succession management), aging infrastructure, labor/management relations, and the organization's regulating policies.

How the facility reacts to these influences is driven by the plant manager's ability to maintain an informed and well-thought-out operations strategy that is supported by sound documentation and performance measurement practices. Responding to any of the aforementioned influences can be made easier and effective by having information available to make sound decisions as well as develop response strategies that are defensible and logical.

Do you find yourself in a reactionary mode dealing with daily issues, with little time to pause and consider things from a long-term perspective? If so, you are not alone. Consider, however, that you may be engaging in a tactical rather than a strategic operating mode and, if that is all you are doing, you may be missing the opportunity to build a strong organization that is better suited to meet the challenges of tomorrow. The phrase, "integrated strategic management approach," describes pathways to strategic thinking and how they can be used to maximize the potential of the organization in the near-term as well as into the future (Figure 3.7). The major pathways to the



FIGURE 3.6 Internal and external influences.

integrated strategic management approach are to develop an outstanding leadership team, engage in thoughtful planning, develop a long-term operating strategy, manage assets from a business-like perspective, and engage mechanisms that develop stakeholder support and alignment.

Of primary importance to the facility is that its strategy be aligned with the objectives of the organization. Linking the facility plan with the overall organizational strategic plan, mission, and goals will ensure alignment and consistency in the organization.



FIGURE 3.7 Pathways to an integrated strategic management approach.

OPERATIONS AND MAINTENANCE PLAN

The operations and maintenance plan is the foundation of an effective operations strategy and serves as the basis for managing the entire operation of the facility. The operations and maintenance plan is considered the core management tool for the plant manager to organize, administer, and respond to daily operational elements at the facility. The operations and maintenance plan not only defines the roles and responsibilities of staff, but also establishes procedures for handling everyday situations and emergencies. By formalizing standard operating procedures, the operations and maintenance plan also provides a framework that facilitates periodic reviews and updates in response to changes.

The operations and maintenance plan should be considered a compilation of individual plans covering specific planning and management elements. As such, it is a living document. Each of the plan's elements should be reviewed and updated annually or when significant events or changes occur that require adjustment. While components of an operations and maintenance plan can vary according to the specific requirements and issues at a given facility, all operations and maintenance plans have the following elements in common: staffing, personnel management, external relations and communication, reporting and recordkeeping, and emergency operations. Each of these elements is described in the following sections.

STAFFING

The staffing section of a facility's operations and maintenance plan should describe the structure of the organization, what reporting relationships exist, and who is responsible for what task. An organization chart should be used to convey this information. The staffing section should include a narrative describing the elements of the organization's structure, with an appendix listing the position descriptions of staff. Position descriptions should be updated as plant equipment, processes, or other conditions change. Each position description typically includes a brief description of the character of the work, a list of the tasks required, the supervisory reporting position (supervision received), the positions to be supervised (supervision exercised), education and experience required for hiring or placement, and typical tasks the incumbent must accomplish if the plant's mission is to be achieved.

Although an organization chart can provide a snapshot of a facility's organizational structure, in reality the organization works in a much more fluid and dynamic way. Consider that the organization that you have laid out is perfect for normal situations as well as ensuring accountability and clarity of roles. However, what happens during periods when normal operations are disrupted? For example, how much independent responsibility should a shift operator have in establishing process directives

during plant upsets? Who defines the hierarchy designated to respond to employee absences or emergencies? Because the way a facility responds to atypical situations is often significantly different from the way it handles normal circumstances (including input from or subordination to external agencies such as firefighters, police, or the mayor), it is important for an organization plan to cover various states of operation including normal, stressed, and emergency operations.

The roles and responsibilities section of the operations and maintenance plan can define the details of the three operating states previously identified. For this section of the plan, think of your facility as a multiple-response team or one that must function under routine circumstances as well as abnormal conditions (e.g., equipment malfunctions, power outages, and service interruptions) and emergencies (e.g., fire, adverse weather conditions, process upsets, and terrorist threats). Staff roles and responsibilities under each of these scenarios should be considered and described. This section of the plan should also designate who assumes responsibility in the event of staff absences, either planned or unplanned. The position descriptions prepared by plant management are not negotiable with employees because they represent the tasks required for each position in the plant's overall organization (Figure 3.8). Position descriptions

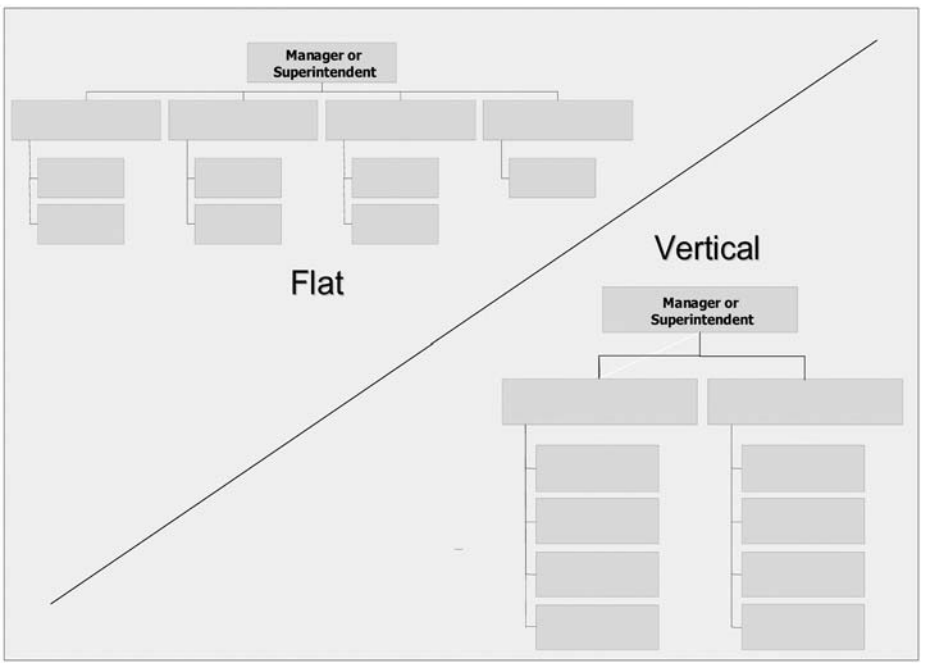


FIGURE 3.8 Types of organizational structures.

need to be updated, however, as plant equipment, processes, technologies, or other conditions change, and an incumbent employee may request such changes in the position description. Each position description includes a brief description of the character of the work, a list of the tasks required, the supervisory reporting position (supervision received), the positions to be supervised (supervision exercised), education and experience required for hiring or placement, and typical tasks the incumbent must accomplish if the plant's mission is to be achieved.

Consider the maintenance function and roles and responsibilities of the maintenance team. Recognize that maintenance and operations are both "part of the team" and must work together and not separately. Thus, strive to foster a workplace atmosphere that supports the accomplishments of both groups and does not put one group subservient to the other. Seek means to maintain an effective communication and cooperative interaction between operations and maintenance personnel.

Consider the following titles that are commonly used in treatment facility position descriptions:

- Superintendent,
- Assistant Superintendent,
- Administrative Assistant,
- Chief Operator,
- Lead Operator or Operator II,
- Shift Operator or Operator I,
- Operations & Maintenance (O&M) Technician II and I,
- O&M Technician or Operator Trainee,
- Process Control Specialist,
- Laboratory Manager,
- Chief Chemist,
- Chemist,
- Laboratory Technician,
- Maintenance Supervisor,
- Heavy Duty Mechanic,
- Lead Mechanic or Mechanic II,
- Mechanic or Mechanic I,
- Mechanic Apprentice,
- Electrician, and
- Instrumentation and Control (I&C) Technician.

While these titles may be common to many organizations, facility managers should recognize that their own organization may use other designations and define varying responsibilities for each role. In addition to these conventional operations and maintenance titles, many facilities may have professional engineers and engineering technicians on staff. Regardless of the titles used by the facility, the facility manager needs to ensure that the organization complies with regulatory-driven roles. One example role is the "operator in responsible charge" or "direct responsible charge." These roles are required by the facility's regulatory rating and discharge monitoring report effluent permit process, and are based on the regulatory mandated minimum levels of certification required for individuals at the facility on a shift as well as an overall basis.

PERSONNEL MANAGEMENT

As the introduction to this chapter points out, effective personnel management is the key to successful operation of a wastewater facility and the manager's primary role centers around people, whether through delegation, motivation, direction, evaluation, or training. For all except small plants, the manager must depend on his or her staff to accomplish the activities necessary to meet the plant's mission. Therefore, to be effective, a manager must master and be comfortable with employee relations and their many facets. These begin with recruiting people who can be trained and motivated, and include development, motivation, evaluation, and discipline (WPCF, 1986). The following are common elements to consider that can support effective personnel management: personnel management system, recruitment, training and development, retention and succession planning, meaningful performance appraisal, and discipline.

PERSONNEL MANAGEMENT SYSTEM. A personnel management system (PMS) includes a records system and other elements required to provide structure, direction, and control for the plant's employees. The PMS encompasses personnel policies and procedures such as compliance with the Occupational Safety and Health Administration's Right-to-Know Act and the Americans with Disabilities Act, as well as control procedures such as disciplinary actions and grievance procedures. A good PMS will help decrease misunderstandings and improve the trust and working relationships between management staff and employees. Although the plant's parent agency may administer the PMS, the plant manager will need to maintain personnel records

in a secure and locked location at the facility. In addition, the plant manager should develop effective working relationships and coordination with the organization's human resources or personnel department.

The PMS specifies written policies and procedures covering personnel administration. Each employee should receive a written copy of the following policies and procedures:

- Listing of employee benefits such as vacation, sick leave, leave of absence, jury duty, and related benefits.
- Policies and procedures on work hours, time accounting, attendance monitoring, overtime, holidays, safety and health, and others.
- Employee "Right-to-Know" information.
- Employment practices of the organization such as equal employment opportunities, outside hiring, termination procedures, retirement, benefit programs, absenteeism and tardiness controls, employee complaints, and problems and appeals procedures.
- Policies and procedures for professional development, training, and continuing education.
- Policies and procedures governing disciplinary actions.
- An employee record file is one of the most important elements of a PMS. This file should contain a complete employment record from the time of entry of an employee until termination of service. The file may contain the following:
  - Employment application;
  - Interview record;
  - Hiring letter;
  - Wage record;
  - Sick leave, vacation, and other attendance-related records;
  - Disciplinary actions (if any);
  - Training and certification records;
  - Honors and awards;
  - Emergency notification information;
  - Promotion and demotion records;
  - Retirement program records;
  - Benefits selection records;
  - Annual performance review records;
  - Termination record; and
  - A copy of the exit interview.

RECRUITMENT. Recruiting and selecting good employees is the beginning of a successful operation. Effective recruitment fosters the interest of qualified applicants and encourages development of the existing staff. The objective of recruitment is to ensure that the number and quality of applicants needed to meet staffing requirements are available. Because recruiting and hiring are controlled by many laws and regulations and often are administered by the human resources or personnel department, obtaining the advice of experienced people on "do's" and "don'ts" should precede recruitment. However, selection criteria must be based on actual job needs without consideration of race, creed, sex, marital status, national origin, religion, or age, unless specific affirmative action programs are in place. If the information sought is related to specific job requirements, determining fitness for a job can include written tests, interviews, police records, former employers, and medical records.

TRAINING AND DEVELOPMENT. The operations and maintenance plan should also include a section on staff training and development. Training is a key component to unlocking the potential of staff. Training exemplifies the philosophy of continuous improvement and is essential to motivating employees. The type and intensity of training vary widely from one facility to the next, ranging from the basics in standard problem-solving tools to the skills required for cross-functional teamwork (Figure 3.9).



FIGURE 3.9 Types of training.

An individual's unique skills are developed over time and are based on a blend of the following two educational elements:

- *Job-specific experience*—This element is "earned" over time and, without the benefit of a program designed to develop job-specific skills, often occurs through "doing". There is generally little formal documentation of this type of knowledge, and documentation of this blend of skills is best captured through a job-skills matrix developed from a profile of individuals who are considered successful within their present position.
- *Formalized instruction*—This element provides an individual with the basis for understanding the "why" and "how" something occurs. Formal instruction can reduce the time an individual requires to become "skilled" in a profession or task. There is generally available documentation for supporting this type of knowledge. Of formalized instruction, there are three basic types: *vocational*, which encompasses secondary education including college, vocational school, or other trades-related formal instruction that provides an individual with his or her core competency; *regulatory*, which encompasses specialized training that focuses on compliance to regulatory requirements including operator certification and health and safety training (this training is provided by trade organizations, the state, and other entities); and *employer-specific*, which covers training required and delivered by the employer to support organization performance and meet the specific requirements of a position (this training includes job-specific and other training to support organizational and individual performance).

The aforementioned elements are required to produce an individual possessing all of the qualities that the plant manager is looking for. Some of the elements for a developmental program that the plant manager should consider implementing include

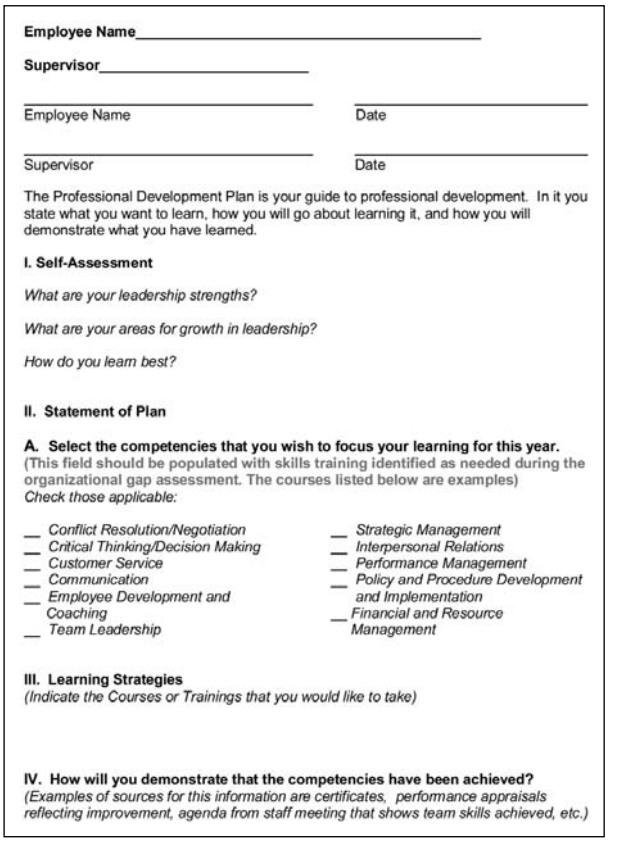
- Hands-on training by experienced staff;
- Cross-training to learn other jobs;
- Formal schooling (night, weekend, or day classes);
- Special project assignments;
- Rotational job assignments;
- Participation in professional associations;
- Regular training sessions such as weekly "tailgate" safety classes or vendor demonstrations;
- Visits to other plants, industries, and city operations;
- Active participation in meetings;

- Increased delegation of authority; and
- State operator certification.

Refer to the sample leadership development plan shown in Figure 3.10.

An experienced operator or supervisor often trains others in a less-formal process called "hands-on instruction." Some hands-on training considerations are discussed here.

- Define and document standard operating procedures (SOPs) for process control, equipment operation and maintenance, laboratory procedures, and data recording. The SOPs become the standard by which consistent practices can be developed and adhered to.



Employee Name_____

Supervisor_____

_____ _____
Employee Name Date

_____ _____
Supervisor Date

The Professional Development Plan is your guide to professional development. In it you state what you want to learn, how you will go about learning it, and how you will demonstrate what you have learned.

I. Self-Assessment

What are your leadership strengths?

What are your areas for growth in leadership?

How do you learn best?

II. Statement of Plan

A. Select the competencies that you wish to focus your learning for this year.
(This field should be populated with skills training identified as needed during the organizational gap assessment. The courses listed below are examples)
Check those applicable:

__ *Conflict Resolution/Negotiation*
__ *Critical Thinking/Decision Making*
__ *Customer Service*
__ *Communication*
__ *Employee Development and Coaching*
__ *Team Leadership*
__ *Strategic Management*
__ *Interpersonal Relations*
__ *Performance Management*
__ *Policy and Procedure Development and Implementation*
__ *Financial and Resource Management*

III. Learning Strategies
(Indicate the Courses or Trainings that you would like to take)

IV. How will you demonstrate that the competencies have been achieved?
(Examples of sources for this information are certificates, performance appraisals reflecting improvement, agenda from staff meeting that shows team skills achieved, etc.)

FIGURE 3.10 Sample leadership development plan.

- Set up a checklist of items to be learned and have the trainer and trainee set a reasonable schedule to learn them. Initial each item after confirmation that the trainee has demonstrated his or her competency.
- Organize an orientation, particularly for new employees, to provide an overview of the whole operation, not just the employee's role.
- Emphasize safety elements.
- Provide technical reading and access to trades magazines. Establishment of a plant "library," where employees can go to access reference documents, is suggested. A library could also include all drawings, reports, equipment manuals, and other documentation.
- Document all training delivered and received into the PMS

RETENTION AND SUCCESSION PLANNING. The manager should recognize an individual's needs for satisfaction and use this knowledge to motivate the employee. In addition, the manager may generally stimulate motivation by creating a work environment that includes the following elements:

- Make responsibilities known and reasonable. Match authority to responsibilities. Eliminate the frustrations of slow approvals, long meetings, and lack of follow-up.
- Find rewards for good performance. Often, prompt recognition by the boss is the easiest, most effective reward.
- The reasons for work must be clear to those who do the work. With shift work, this requires supervisors to visit all shifts and leave instructions that include reasons for the work.
- Working relationships must be comfortable and encouraging for teamwork. Social events, time out for some fun event at work, and fair and equal treatment can help build an environment that encourages good performance.
- Recognition that continued education and training are essential in the modern work environment, which is characterized by exponential growth in technical knowledge required to improve productivity with decreased resources.

Methods used to develop the teamwork that is essential for a successful plant include:

- Arranging for group effort to solve a problem, to develop a budget for the next year, or to undertake another project. As a requirement for such a team effort, everyone must be able to contribute and must have a stake in the outcome.

- Having employees share their knowledge and goals with one another.
- Providing group and individual awards based on group success and individual contributions in the group.
- Rotating jobs or sharing jobs so employees gain a better understanding of other situations.
- Documenting experiences and lessons learned for future reference and knowledge retention.
- Instilling an atmosphere that is rewarding and enjoyable to work in.

Table 3.1 describes how to develop a succession management program.

MEANINGFUL PERFORMANCE APPRAISAL. Organizations use employee performance appraisals as a means to clarify job duties and responsibilities, evaluate employees, provide input into specific development areas, and determine if the employee has achieved the objectives set forth. Generally, the performance appraisal process is directed and administered by the organization's personnel department.

The manager must fully understand and follow the requirements of the performance appraisal process. For example, it is important for the performance appraisal process to clearly define individual duties and responsibilities. The employee must understand what their role is as well as the expectation for their performance. This is done by developing specific, measurable, and reasonable goals that meet the overall objectives of the organization. Managers should encourage employee participation and input when establishing performance criteria. Employees can offer many insights that present opportunities for their success and "buy-in" of the process.

The manager should ensure that a fair and consistent system of employee evaluation is used at all subordinate levels. The system should include prompt recognition and rewards for successful performance, identification of poor performance, and corrective actions needed to improve performance, when necessary. The plant manager uses the performance appraisal to improve day-to-day work procedures and determine long-range needs for further employee development and motivation improvement. The most important part of the performance appraisal is the day-to-day informal communication between the manager and employees. If employees are given timely feedback on their performance throughout the rating period, they should not be surprised with their performance evaluation during the review process.

DISCIPLINE. Tardiness and absenteeism are among the most common and persistent problems; as such, special attention to these issues is essential. Concurrent with the performance appraisal process, the manager should also establish policies or guide-

TABLE 3.1 Developing a succession management program.

1. Institutionalize the process and gain stakeholder support	• Gain commitment from top management and board members • Gather resources • Identify the strategic vision and goals • Incorporate as part of values of the organization • Clearly define objectives for the program

2. Conduct assessments of organizational need	• Conduct "as is" assessment of the organization
	  • Workforce
	  • Processes
	  • Systems and resources
	• Conduct "to be" assessment of the organization
	• Conduct gap analysis

3. Develop the succession planning model	• Determine employee involvement in program • Build a leadership pipeline • Develop successors for critical functions • Identify training and development strategies • Develop retention strategies • Create knowledge management and transfer strategies
4. Implement succession planning strategies	• Determine resource needs for implementation • Identify barriers and develop strategies to overcome • Design needed templates, forms, and systems • Develop or update job descriptions • Prepare organization for change • If needed, implement some strategies on a pilot basis • Link succession strategies with human resource processes • Train staff as necessary
5. Continuously measure, evaluate, and adapt	• Define measures of program success • Design reporting process • Track and communicate progress, celebrate program successes • Capture stakeholder feedback on strategy effectiveness • Adjust program based on evaluative results • Keep top management engaged • Make a 3- to 5-year succession plan part of the organization's strategic planning process

lines that govern employee behavior and attendance. Poor attendance often serves as a warning for a situation that could get worse. Immediate attention by a supervisor may prompt an employee to address the problem without further supervisory action. Managers should avoid diagnosing personal problems for employees that have external issues that affect their work performance. However, they should point out to the em-

ployee that there are sources available to them for assistance, such as an employee assistance program. A program that includes professional counseling is effective in helping employees overcome difficult personal problems and become motivated to work.

Managers must use discipline as a means to correct employee behavior that does not comply with polices and procedures. Discipline should be viewed as a tool to improve performance and/or change behavior. Progressive discipline systems, which are common, may include successive steps of oral and written warning, suspension, and discharge. Returning to work following suspension may be conditional on an employee's written statement of performance commitments. In a union environment, employee rights to representation, appeals, and arbitration may apply.

The plant manager should follow a disciplinary process that includes the following:

- Train all supervisors in disciplinary procedures;
- Ensure that discipline is administered evenly and respectfully;
- Require that investigations, notice, and hearings occur in a timely fashion;
- Ensure that employees understand performance requirements and disciplinary steps; and
- Document performance and discipline and file the records.

EXTERNAL RELATIONS AND COMMUNICATION

The issue of external relations, that is, how your facility interacts with and responds to neighbors and other organizations under normal and emergency conditions, is a key functional role that is often neglected. Many facilities have addressed the issue of responding to emergencies that involve firefighters and police. For example, they have invited both departments to the facility to review scenarios and to ensure that these agencies are familiar with the facility and that there are clear lines of communication open. Likewise, many facilities have established lines of communication required for mutual assistance among themselves and adjoining utilities in locations that support this type of arrangement. The manager should leverage and build relationships with external stakeholders, including the following:

- Plant neighbors;
- Vendors;
- Police department;
- Fire department (especially for emergency response planning and preparation);
- Regulatory agencies;
- Other city or utility departments (e.g., streets and roads, parks, and legal);

- Media (an external media communications policy and strategy should be developed prior to engaging with the media); and
- Professional organizations (e.g., community groups, and local and state WEF affiliates).

Communication is the foundation to developing and maintaining relationships with external entities as well as those within a facility. Consider the need to define protocol for communicating with agencies such as offices of emergency preparedness or disaster coordinators. Furthermore, consider the need to define a methodology for dealing with inquiries from the public and the media. In an era when misinformation can have dire consequences, these issues need to be addressed. Protocol should be designed to ensure that messages to the public are managed with coordination, clear authority, and accountability.

The manager should develop a sound external communications plan for managing general external communications. Indeed, public consciousness and vigilance about environmental issues, tax abatement movements, and reaction to governmental regulation have created an atmosphere in which public support cannot be taken for granted, no matter how beneficial a service may be. Cultivation and retention of support for specific projects, in particular, may benefit from the services of public relations professionals. Communications with the public help the manager understand the public's concerns and viewpoints. Some plant managers have found the following elements to be useful ways to communicate with the public:

- *Elected officials*—Whether directly or through another manager, elected officials need regular reports on the status of major plant financial and performance issues. Newly elected officials should be invited to see the plant. Presentations at meetings of superior policy-making bodies are important, and the presenter should be well prepared.
- *News media*—When a negative event happens, plant personnel should be as honest and open as possible, be sure of their facts, and inform public officials prior to discussions with the media. It is useful to provide a fact sheet to the media if statistics are important.
- *Plant tours*—School and community groups appreciate tours. A tour requires a safe route, a knowledgeable spokesperson, meaningful handouts, and a show of respect for the visitors and their interests.
- *Talks*—Schools and community groups seek informed speakers from the wastewater treatment plant (WWTP) during environmental weeks or when the press covers an issue related to operations. A talk on plant operations requires preparation, practice, and visual aids. A videotape of the plant, photographs, props

(e.g., water samples showing improvement in water quality from raw through final effluent), and handouts are helpful for such talks.

- *Neighborhood communication*—It is worthwhile to pay special attention to plant neighbors and their interests. Once a problem occurs, the plant should promptly provide an honest explanation of the problem (or at least information about the status of any investigation) and make visible efforts to reduce the problem.
- *Special events*—The manager may choose to invite the media and public officials to celebrate installation of new equipment, permit compliance, public works week, or another event. At least one event should be celebrated each year to keep positive aspects visible.
- *Advisory groups*—Both a community environmental problem and a long-term planning effort provide an opportunity to use public opinion to develop recommendations acceptable to the community. The manager must include representatives of concerned groups and provide the technical support and administrative help necessary for their involvement.
- *Community involvement*—Membership in local service clubs can help a manager understand community issues, meet community leaders, and gain public respect.

During emergency situations, nothing is as critical as clear and effective communication. Part of effective management of emergency communications is the establishment of an emergency call list that includes names and responsible parties to call during an emergency. This list should include contact numbers for local police, fire, and other emergency response entities. A schedule for on-call employees should also be defined and posted for immediate access and should be known by all staff. Finally, a media response plan should be established that includes clear procedures for contacting and responding to media inquiries and interviews. Media contact should be cleared by senior management and coordinated with the organization's external relations/public communication staff.

REPORTING AND RECORDKEEPING

Although recordkeeping and reporting responsibilities are well-defined in most utilities, they are often not included in an operations and maintenance plan. A facility's operations and maintenance plan should outline the quality assurance and quality control procedures used in reviewing records and reports before their submittal (i.e., who reviews what and what sign-off procedures are required) and should designate who has primary responsibility for responding to inquiries from the regulatory community.

Reports, operations logs, e-mail, and other documents produced during the course of operations and maintenance are part of the public record and must be filed and kept accessible. Archiving of files and data should be conducted in accordance with the organization's policies and procedures for records retention and storage.

A manager should keep in mind the following phrase: "The job is not done until the paperwork is finished." Accordingly, the manager needs to ensure that records are completed, reviewed for accuracy, and maintained in a library or storage center for the required time as defined by the policies of the organization and by law. The following are some records management strategies and concepts to consider:

- *Knowledge management*—Knowledge management is the strategy used to capture, retain, and make available collective information that an organization and its employees possess. There are many elements to knowledge management including administrative, standard and emergency procedures, records and library management, incident recordkeeping and other types of documentation (e.g., photos, videos, reports, and so on), training, daily logs, mentoring, performance assessment, and informal knowledge transfer (e.g., "on-the-job"). Whatever the means used, knowledge management is about capturing and retaining the experience and skills of individuals that may or may not be documented. Some utilities are investing in information technologies that support "capture and access" to information and various media. These systems generally are Web-based and work with or include electronic document management platforms.
- *Records and file management*—Records need to be filed and maintained using a logical file management system. Records include all reports, files, and printed information produced or used by the facility. Administrative staff are generally responsible for this activity. Some organizations have been including electronic document management tools to maintain records and files.
- *Library management*—The plant library is the knowledge center of the facility and, while it may be closely linked to the file system, is an important element to house and locate all printed (and electronic) information (Figure 3.11). This information includes plans, contract documents, manufacturer information and manuals, books, periodicals, and training materials. One or more individuals should bear the responsibility for maintaining the library. A library should have a location that is secure and environmentally sound for long-term paper storage. One effective way to ensure that a library is current is to allocate a senior staff operator or maintenance person to "own" the library and ensure that all documentation is inventoried, indexed, and available.

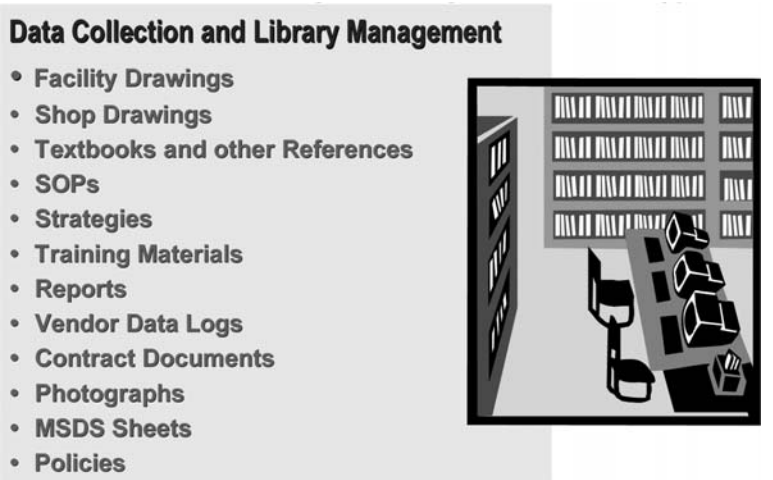


FIGURE 3.11 A centralized facility library is a sound knowledge management strategy (MSDS = material safety data sheet).

EMERGENCY OPERATIONS

Emergency planning for plants is defined as the continued development and documentation of actions and procedures aimed at dealing with all hazards—both natural ones and those caused by humans—that could adversely affect the environment or the efficient operation of the facilities. The emergency operating plan (EOP) component of the facility operations and maintenance plan covers the entire facility and involves all employees. Everyone concerned, however, must realize that emergencies do not follow a standard pattern, and personnel must be prepared to adapt to various emergencies (WPCF, 1989). Providing pre-assigned damage assessment teams, each with the responsibility to react to particular types of emergencies, is recommended.

In some ways, the phrase "emergency planning" is misleading because it implies that planning is a one-time effort done before a disaster (FEMA, 1985). Instead, the plan itself may be less important than the process that produces it. The planning process identifies hazards and needs, sets goals, determines objectives, sets priorities, designs action programs, evaluates results, and repeats the steps.

Emergency activities occur in the following four phases (Hulme, 1986):

- *Preparedness (planning)*
  - Develop EOPs and test them.
  - Inventory local resources.

  - Initiate emergency management contacts (individuals, state and federal programs, and private and public organizations).
- *Mitigation*
  - Train personnel in emergency preparedness procedures.
  - Correct improper operations and maintenance practices such as deferred preventive maintenance.
- *Response*
  - Alert the public when necessary.
  - Mobilize emergency personnel and equipment.
  - Evacuate plant personnel and nearby residents when necessary.
- *Recovery*
  - Reconstruct or rehabilitate structures and equipment.
  - Conduct public information and education programs.
  - Develop hazard-reduction programs.

The first step in the planning process is to identify the hazards and dangers faced by the plant. Typical natural and caused hazards and the resultant dangers are shown in Table 3.2. Goals, objectives, and priorities for a particular plant for each process can be established based on the identified dangers. A vulnerability analysis (Figure 3.12) provides a useful tool for formulating an EOP for each potential situation. An outline for a typical EOP is given here.

- *Emergency flow chart*—This chart should be the first page of the binder so that anyone responding to an emergency can proceed to resolve the emergency problem.

Table 3.2 Hazards and dangers leading to emergencies.

Hazards	Dangers
Natural	
Earthquake	Sewer collapse, building collapse, hazardous material release, possible flooding, power failure.
Food	Electrocution, fire from electrical shorts, hazardous material release, power failure.
Tornado	Building collapse, hazardous material release, power failure.
Winter storm	Power failure, plant inaccessible to employees.
Human	
Chemical release	Damage to the environment, skin and mucous membrane burns; death by inhalation, explosions, fire, or a combination of these.
Supply shortage	Shutdown of operations.
Fire	Death or injury to employees, shutdown of plant processes.
Strike	Shutdown of plant processes.

Vulnerability Analysis Worksheet

Treatment System Capital City Wastewater Treatment Plant

Assumed Emergency Flood (100 years)

Description of Emergency The flood will cause considerable damage to low lying areas. Bridges will be closed, utility poles downed and electrical power interrupted.

System component	Effects of emergency Type and extent	Prevention recommendations
Collection lines		
60" interceptor could be washed out at Back Creek crossing		1. Encase line in concrete 2. Maintain pipe and fitting to repair damaged section. 3. Provide portable pumps to bypass break. 4. Contract for major emergency repair services

FIGURE 3.12 Example of a vulnerability analysis.

- *Contact lists*—All contact lists should contain names, organizational positions, location telephone numbers (including home, cellular phones, and pagers, if appropriate), and radio call numbers/names, if assigned.
- *Chain-of-command*—This item identifies the line of authority in an emergency.
- *Organization chart of duties*—This chart identifies each group and its emergency activities.
- *Damage assessment forms*
- *List of facilities*—This list includes names, addresses, and telephone numbers of all WWTPs, administrative offices, field offices, pumping plants, and other installations.
- *Emergency equipment list*—This list identifies all heavy equipment and vehicles by their locations.
- *Contractors*
- *Mutual aid agreements*—This information should include the name of the organization that will assist, the means of contact by telephone or radio, and the type of mutual aid to be provided.

- *Public information procedures*—These procedures cover public communications about the emergency and response activities.
- *Emergency operations center*—The center should have the following supplies: telephones (including cellular telephones); two-way radios; log books for operations and communications records; maps, drawings, photographs, and video recordings of the plant and surrounding area; operations manuals; first-aid supplies; cameras and video recorders for recording damage and operations; and living facilities including water, food, and bedding.

OPERATING EFFICIENTLY

The concept of operating efficiently is a relative term. As stated earlier, although the term efficiency is often used in association with both positive and negative cost and budgetary effects, the term embodies much more. Seeking improvements in efficiency, whether they be in process, treatment performance, staff effectiveness, or cost control, can be argued to be a fundamental and core focus of management in which acceptance of the status quo is never good enough. Achieving efficiency improvements requires constant attention to discrete practices, functions, subgroups, and technologies within the organization.

Facility operations are mandated by a number of factors including (1) compliance with governing and regulatory requirements; (2) compliance with personnel policies and labor rules; (3) conformance with organizational business practices; and (4) the need to balance all activities with a commitment to minimizing costs. How much the manager departs from the status quo (e.g., to improve efficiency) depends largely on the amount of risk he or she is willing to assume. Most public utilities are inherently risk-averse. However, risk can be mitigated by careful and well-informed thought and planning prior to implementing an improvement. Thus, the key lies in defining perceived versus actual risks. Accordingly, recognizing and managing risk elements are important components of efficiency improvement activities, including decisions about how far the organization wants to go in pursuing optimization.

At the heart of all efficiency management activities is the focus on optimizing resource allocation and consumables consumption. The following general elements govern efficiency at a facility:

- *Individual performance*—An employee's ability or treatment process to perform as efficiently as possible affects overall efficiency at the utility (Figure 3.13). In the case of an individual employee who does not have the appropriate tools or

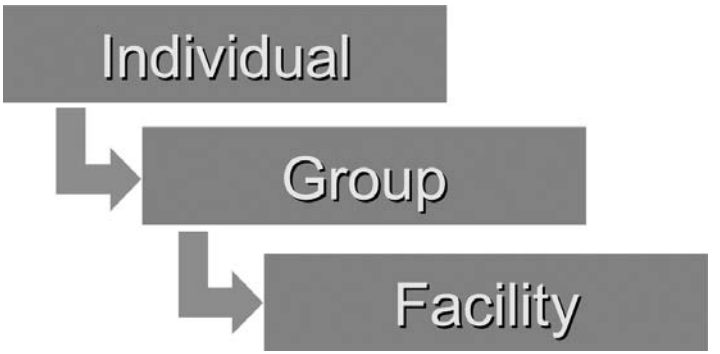


FIGURE 3.13 Efficiency elements.

is not properly trained, the time required to complete a task satisfactorily will most likely be extended. As a result, labor effort to conduct work (e.g., labor costs) will increase. Accordingly, the performance of a single individual can have a direct impact on the cost efficiency of the work unit, the facility, and the organization as a whole. Similarly, a treatment process that is not operating efficiently can substantially affect the performance and efficiency of downstream processes and incur other costs such as increased energy or chemical dosages.

- *Group performance*—Taking the next step from individual employees or treatment processes to groupings, the impacts of inefficient performance can incur even greater cost and risk elements. The performance of teams or work groups affects overall efficiency, and group performance is affected by the efficiency of individual group members. High-performing, efficient work teams excel through their ability to work together while using their individual abilities to the fullest extent practical. Treatment trains (e.g., wet stream or solid streams) can be considered as a group and measured as such.
- *Facility performance*—Facility performance is based on the overall aggregate of staff and/or processes at the facility to operate efficiently in an integrated and coordinated fashion. Although management assumes chief responsibility for organizing and coordinating the interactions and work processes of teams and groups within the facility or unit, a team's composition is usually the most significant factor in determining performance. For example, an energy management team can play a critical role in overall efficiency because team members are focused on a facility-wide initiative, thereby reducing energy costs.

EXTERNAL BENCHMARKING AND PEER REVIEW

In general terms, benchmarking is a systematic approach for comparing an organization's internal processes to those of other external entities. By using external benchmarking to compare and define how other organizations perform similar processes, internal procedures can then be modified to improve efficiencies and performance.

In benchmarking, key target functions within an organization that are candidates for improvement are identified and compared to similar functions within other organizations and competitors. While a relatively simple concept, benchmarking can be a complex process involving many different approaches and methods of comparison. As with other quality improvement endeavors, benchmarking can be costly or not, depending on the type and extent of benchmark comparisons being sought. The many varied approaches and types of benchmarking activities have resulted in a significant difference of opinion among experts and managers alike in what benchmarking really should consist of as well as how it should be applied within the public sector. Despite the many approaches, there are essentially two types of benchmarking categories, metric benchmarking and process benchmarking. These are outlined here.

- *Metric benchmarking*—In metric benchmarking, one organization's costs or other numerical values, such as staff numbers per million gallons and so on, are compared to the same values of others. Metric benchmarks do not, by themselves, identify how to improve a process or increase efficiency. Rather, they are metric parameters that measure the performance of a specific entity. Confusion may arise because of pressure to use performance benchmarks to compare efficiencies between different entities. However, because each entity has its own unique set of controlling variables, direct comparisons may be inaccurate. Considerable effort is required to account for these variables so that equivalent and fair comparisons can be made.
- *Process benchmarking*—Process benchmarking is a more effective way to apply benchmarking efforts in the public arena, as it focuses on improving internal programs and processes by learning how "the best" organizations conduct such activities. In process benchmarking, a utility's practices and other "non-numerical" items such as procedures and systems are compared to others. With this focus, benchmarking does not get bogged down in accounting for control variables that affect performance benchmarking outcomes. Comparing practices and procedures, such as one plant's odor complaint response mechanism to another, helps identify better methods and procedures of conducting business. Process benchmarking is not difficult. However, before looking externally to see how

others achieve best practice, the organization should understand its own process as a baseline for comparison.

FINANCIAL PLANNING AND MANAGEMENT

Using sound financial planning and fiscal management strategies are core responsibilities of the effective plant manager (Figure 3.14). All organizations and management have a fiscal responsibility to manage their budgets within the limits of reasonable rate-setting, grant monies, and other sources of operating and capital funds. The extent of funding sources and the capacity of rate payers will govern the strategies and creativity of the manager to maximize the facility's budget to meet near- and long-term cost objectives. Consider the following elements of sound fiscal management:

- ***Define service standards and performance levels.*** The basis for any budget expenditure decision lies in determining the service standards to which the organization and facility must operate. Producing effluent quality within National Pollutant Discharge Elimination System limits as well as biosolids and air quality that fall within standards are basic expectations and the primary reason the facility exists. However, performance levels come at a cost, that is, should the facility be operated in a manner just to get by (e.g., limited staffing and scrimping on maintenance activities) or should it be operated in a manner without excessive regard to cost of service (e.g., operated, maintained, and staffed conservatively). Although the former may result in a lower annual operating and

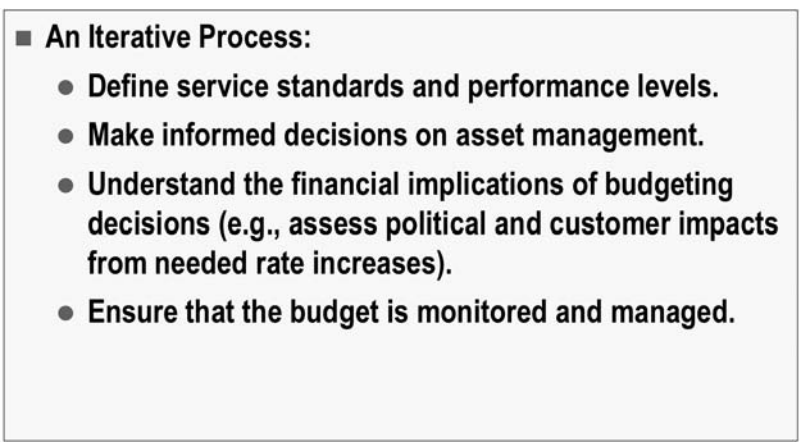


FIGURE 3.14 Fiscal management is a critical responsibility.

maintenance cost, it also may forego long-term maintenance expenditures and other investments that may result in additional or premature future costs to limit present expenditures. The latter has its own cost of operating conservatively and may result in unnecessary expenditures and waste. Thus, clearly defining performance standards that are embraced by the organization (e.g., city management and council) and managing to meet these will provide the best defense against management, political, and ratepayer concern over how much a facility requires in its budget.

- ***Make informed decisions on asset management.*** A solid asset investment and management program includes the development of strategies to maintain assets over time and to ensure that assets perform according to established service levels and design criteria throughout their useful lives. This requires a well-managed life-cycle plan for the plant's assets. Development of this plan includes an upfront risk and criticality assessment, condition assessment, and analysis of historic failures and events. This is perhaps the most involved phase of asset management and includes the integration of many considerations such as spare parts and equipment inventories, preventive and corrective maintenance strategies, renewal and replacement criteria, and rehabilitation requirements. Criticality, capacity, risk, and condition analyses identify focus areas toward which preventive maintenance budgets should be targeted. In an environment where budgets are limited, available dollars must be directed toward assets that have a high probability and/or consequence of failure. Part of this strategy may be accepting that some noncritical components can be run to failure, as it is cost-prohibitive and inefficient to implement a zero-failure preventive maintenance program.
- ***Understand the financial implications of budgeting decisions.*** The budget is a roadmap that ideally is based on informed cost-projecting and sound information as to what capital and operating costs the facility will incur during the fiscal year. The goal of financial forecasting is to provide clear vision regarding the potential financial outcomes of current management decisions. The process of developing a budget, while consuming and difficult, should result in a budget that the manager can accept and use that is based on informed financial forecasting to effectively manage the facility. Both capital and operating budgets impact the bottom line, that is, the rates customers pay to receive the services provided by the organization and the facility.
- ***Ensure that the budget is monitored and managed.*** Most organizations track expenditures against their budget and issue standard reports on a periodic basis

(e.g., monthly and quarterly). If the frequency of reporting is insufficient to effectively track and manage expenditures against the facility budget, it is the manager's responsibility to seek this information. This might require requests for more timely reports or specific information or manual tracking of expenditures. A budget needs to be flexible to accommodate changes or unanticipated costs during the year. Most organizations have provisions to make adjustments to a budget through transfers within a budget or by amending a budget if significant increases (or decreases) are required.

INFORMATION AND AUTOMATION TECHNOLOGIES

Information and automation technologies support efficient and effective operations. They can be powerful tools within the manager's arsenal to manage the facility. Moreover, they are tools to assist both routine and nonroutine activities and can greatly strengthen the performance of the facility and staff. A modern facility cannot be run without plant automation and information management technologies. The following are some of the more common types of automation and information management technologies:

- *Automation technologies*—Process instrumentation and control system technologies provide access to real time data. Supervisory control and data acquisition (SCADA) systems and field instrumentation are tremendous tools to monitor, control, and provide early warning to impending process and equipment problems. When coupled with a data management and reporting system (e.g., data warehouse), SCADA systems can centralize monitoring and control, reduce labor costs for operations, improve the accuracy and timeliness of data used for performance reporting, and furnish critical data to support equipment maintenance.
- *Data management technologies*—At the facility level, data management technologies can include spreadsheets, laboratory information management systems (LIMSs), and computerized maintenance management systems (CMMSs). Of these technologies, organizations seem to struggle most with fully implementing and using the capabilities of a CMMS. Some facilities are investing in more refined commercially available data management technologies such as decision–support systems and sophisticated data reporting technologies. The key idea is that you will need a data warehouse to gather summary-level information together in one place as well as a reporting product to produce the charts and graphs. Consider a general

purpose product that can serve a variety of needs and report data from SCADA, LIMS, CMMS, and any other well-behaved system.

- *Content management systems*—Electronic content management technologies provide the means to store, access, and manage all types of printed information such as manuals, photographs, SOPs, reports, policies, and training materials. They generally are Web-based and can be linked with an electronic document management system, a common technology that many organizations have invested in. Many facilities use their own content management platforms as electronic operations and maintenance manuals.

Technology is constantly evolving and it is beyond the scope of this book to fully review the topic. The facility manager, however, should consider the following in managing and using automation and information technologies:

- A manager needs a structure and process for making the most important decisions about information technologies (or what can be termed "information technology governance"). Do not let every group or the "information technology guru" make isolated decisions. However, the manager should seek input and support from all stakeholders within the organization, including the organization's own information technology group or department. The facility's information technology investments should, as much as possible, "fit" or align with the organization's overall information technology standards and requirements.
- If you are selecting new systems, use a formal process to evaluate software in which the qualities of the vendor are as important as the features of the software. Spend most of your time figuring out how you will do your work and what staff roles/responsibilities are critical. Do not focus on the software until you get this part right.
- Develop an information technology master plan for the facility. Define how the parts are going to fit together, especially how separate systems are going to be integrated so data flows freely. The manager should get help doing this. Do not expect that your (central) information technology group has the expertise or desire to create this sort of plan.
- More and more, control systems are looking like regular computer systems, that is, the same network types, the same computer types, and conventional Windows® and Web-browser software. A manager should stay away from older proprietary systems.
- Key consideration is security. The manager should keep the organization's control network separate from the general purpose network and put a firewall be-

tween them. However, they should not be separated so much that data cannot "flow" because operations data need to flow up in the organization to support regulatory reporting and management decisions.

PUBLIC–PRIVATE PARTNERSHIPS

The water and wastewater industry has witnessed an increased focus on engaging private services as a tool to bolster efficiency and lower costs of service. The term "privatization" has been applied to the broad range of options that involve private sector provision of traditional government-provided goods and services. The privatization movement is based on the premise that there are goods and services that can be effectively and efficiently provided by private entities, either under contract to or independent of the public sector. From a publicly owned utility management perspective, privatization is better defined as *selective outsourcing* and encompasses the host of private-sector services that may be engaged by a public utility.

REGULATORY COMPLIANCE CONSIDERATIONS

Overall, wastewater facilities are subject to regulation by many local and national agencies that are concerned with some aspect of their operation. Regulatory agencies and the public expect compliance with permits that may include wastewater discharges, air emissions, building modifications, underground tanks, and other items. The manager needs to learn which laws and regulations affect the plant and set up systems and controls to ensure that applicable regulatory requirements are met. Violations of some regulations can result in civil and criminal penalties for which the manager can be held liable. A manager must ensure that accurate reports are filed on a timely basis.

A manager should personally meet with representatives of the regulatory agencies. Representatives can help recognize problems and suggest actions to prevent or reduce problems. Important regulatory agencies may be expected to inspect the operation at least once a year. When regulatory problems occur, the manager must inform all regulatory agencies with jurisdiction as well as the appropriate municipal officials. The manager also needs to document the facts, corrective action, and individuals contacted. If the problem becomes severe, records can help protect the community and the manager. Above all, the manager should maintain an attitude of courtesy and cooperation with regulatory agencies.

Facility managers may have opportunities to influence the establishment of regulations under which they must operate. While such opportunities may arise by invitation from the regulatory agency, those who are regulated should not hesitate to make

recommendations, especially through group action of professional organizations. Finally, regulation should be considered to be in a state of evolution.

MAINTENANCE MANAGEMENT

Maintenance processes and activities offer significant opportunities for maximizing the total life-cycle cost and performance of equipment processes and other assets improving efficiency. Historically, utilities have often overlooked the tremendous value of tracking and monitoring maintenance activities, both in terms of controlling costs and efficiently allocating and managing facility resources. Better understanding of maintenance staff perspectives and issues permits facility managers to choreograph maintenance activities in close coordination with operations requirements to better assess how these activities are accomplished and how resources are applied. At the core of this management process is the use of performance measures to drive decision-making. As Figure 3.15 shows, an efficient maintenance process continuously measures management, scheduling, and work output and provides feedback on alternatives for improvement.

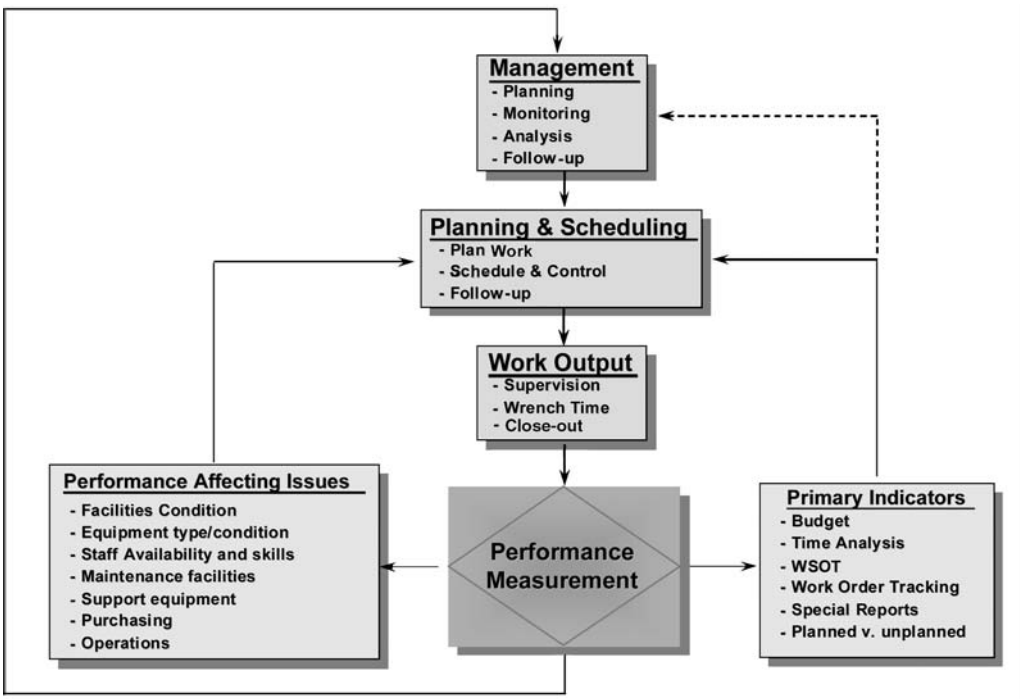


FIGURE 3.15 The maintenance process (WSOT = work spread over time).

Simply put, a wastewater treatment facility depends on good maintenance as much as effective operations. The two functions must be tightly coordinated, which can be difficult when the groups in charge of these functions must sometimes work toward competing goals. Suppose, for example, a sedimentation basin needs to be removed from service for routine maintenance. The maintenance staff, which have planned and allocated tools, supplies, and labor to accomplish the task, can only perform their work once the operations staff have removed the basin from service and made the unit available. The goal of the operations staff is to minimize the time the basin is out-of-service; the goal of the maintenance staff is to complete all the maintenance tasks as planned. If the operations staff fails to make the filter available, or if the time allotted for the maintenance staff to complete its work is too short, the maintenance activity and the effectiveness of the maintenance staff will be compromised. From a long-term perspective, not completing all maintenance activities as planned will likely result in the inefficient use of resources and increase the frequency with which a piece of equipment must be removed from service for maintenance.

SELECTING A MAINTENANCE MANAGEMENT STRATEGY. Managing maintenance activities involves choosing from a number of possible approaches (Figure 3.16). By following equipment manufacturers' recommendations for routine and preventive maintenance, a plant could greatly exceed its annual maintenance budget. Thus,

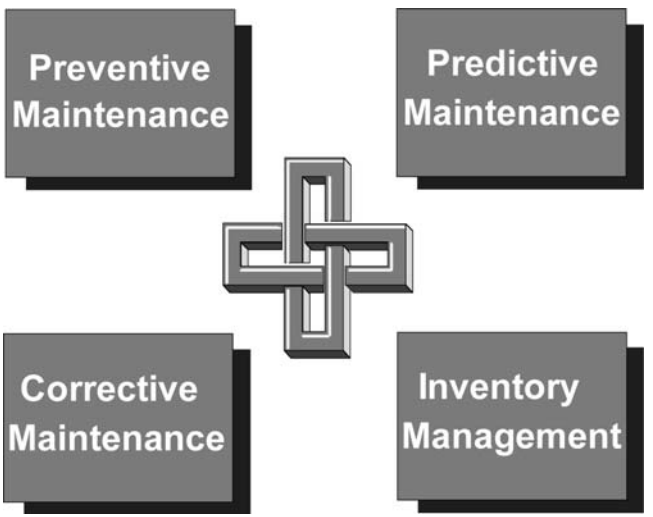


FIGURE 3.16 Components of effective maintenance programs.

the manager must decide what maintenance strategies work best to balance the risks and benefits of deviating from manufacturer recommendations. A classic challenge is balancing preventive maintenance activities, corrective and predictive maintenance practices, and inventory management strategies, which are defined as follows:

- *Preventive maintenance*—Preventive maintenance activities require the allocation of labor and associated costs. Preventive maintenance can be performed efficiently (e.g., by an individual who can do lubrication rounds in record-setting time); however, the challenge lies in deciding which preventive maintenance activities should be performed on what equipment to maximize equipment reliability and life expectancy and to manage risk. Along with risk assessment, cost is an important consideration in selecting preventive maintenance strategies.
- *Corrective maintenance*—Maintenance of equipment that has failed or is nearing failure constitutes corrective maintenance. If corrective maintenance dominates a utility's maintenance activities, this is a hallmark of ineffectiveness and inefficiency. Conversely, letting selected equipment operate to failure can be the least costly strategy if easy service conditions and an evaluation of life-cycle costs suggest that risks and associated corrective maintenance costs are lower than the life-cycle cost of preventive maintenance for that equipment.
- *Predictive maintenance*—Predictive maintenance activities involve monitoring the condition of equipment and selecting the most appropriate time to service it. Although predictive maintenance generally focuses on major equipment that is expensive to service, this strategy represents a highly efficient approach to maintenance in general. Predictive maintenance processes include the application of sensing technologies such as infrared light, vibration, sound, and oil analysis.
- *Inventory management*—Inventory management represents a major cost item in a utility's budget because significant assets can be tied up in inventory. Inventory management can be either a source of or solution to efficiency problems. Consider a maintenance crew that has disassembled a piece of equipment only to find that a key part is not where it is supposed to be in the warehouse. The effect is obvious—a productive allocation of resources (i.e., the crew) is transformed into an inefficient, nonproductive task (i.e., searching for parts within the storage area). Inventory management represents a cost to the utility, and the manager must weigh the costs of creating and maintaining an effective warehousing operation against the costs and risks associated with not formalizing the warehousing process.

An emerging best practice associated with asset management is reliability centered maintenance (RCM). Reliability centered maintenance is a strategy that manages the maintenance function by assessing the replacement cost, criticality, and life expectancy of an asset to determine the desired maintenance strategy. The foundation of RCM is to achieve the lowest life-cycle cost of the asset. For example, the criticality of a small sump pump may not be the same as that for a large aeration blower. The choice to use a rigorous preventive maintenance program on the sump pump (as would logically be used for the blower) may not be the best expenditure of labor and materials for this small piece of equipment with a low criticality. Accordingly, the manager may choose to simply monitor the pump routinely, allow it to operate to failure, and then repair or replace the unit.

MANAGING AND TRACKING THE MAINTENANCE FUNCTION. Performance monitoring and measurement lie within the facility's CMMS. A valuable tool in the manager's arsenal, the CMMS is a powerful means of tracking maintenance activities and costs. Most often, the CMMS is a computerized database with high-level tracking and management capabilities. Table 3.3 highlights some of the primary functions and capabilities of a CMMS. In short, a CMMS can serve as a core information resource for the maintenance function; additionally, it can meet asset management and tracking requirements.

TABLE 3.3 Primary functions and capabilities of a CMMS.

Major Functions
General: allows records of inventory items and utility resources to be entered and maintained, monitors on-hand balances at single or multiple warehouse sites, and processes work orders; can be integrated with other utility management systems as needed.
Time tracking: allows employees to record activities by electronic entry; needs to be validated against project numbers and accounts. System should be able to track time by activity, location, or unit; provides summary (roll-up) information down to employee-specific details.
Fleet maintenance: schedules, prioritizes, records, and tracks all preventive and corrective maintenance activities related to vehicle maintenance; provides cost analysis and support for decisions about vehicle repair and replacement.
Work orders: enters and tracks to closure all work orders, including internal and external resources (time and materials) with a universal work order Web-deployed interface; issues, routes, prioritizes, schedules, and tracks preventive and corrective maintenance activities; reports scheduled and completed activities to managers.
Purchasing: makes and tracks purchases (e.g., receipt of goods, returns) of equipment, tools, and "original equipment manufactured" parts; codes purchases to work orders and job numbers and by employee; allows purchases to be made by credit cards, purchase cards, and purchase orders.

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INTRODUCTION

Many industries discharge their wastes to municipal wastewater treatment works rather than directly to the nation's waterways. These indirect discharges may contain significant quantities of toxic pollutants or other substances that adversely affect the municipality's wastewater treatment system operations or interfere with its performance. Also, some of these pollutants may pass unchanged through the wastewater treatment works and into the receiving waterway, causing the municipality to exceed its National Pollutant Discharge Elimination System (NPDES) permit requirements. The pollutants may also enter the wastewater treatment plant (WWTP) sludge and compli-

cate ultimate disposal of the removed solids. These undesirable consequences can be prevented with effective pretreatment techniques and management practices that reduce or eliminate the offending pollutants from these indirect wastewater discharges. Consequently, an effective program requiring pretreatment of certain nondomestic wastewater discharges can be an important component of operations of a publicly owned treatment works (POTW).

In the United States, the federal government has established the National Pretreatment Program (U.S. EPA, 1999), which provides, among other things, pretreatment standards for nondomestic indirect dischargers and the regulatory basis to require these dischargers to comply with the pretreatment standards. These regulations are designed to preserve and restore the quality of the nation's waterways, to ensure that this valuable resource is available for all generations. While the United States' National Pretreatment Program is not universally mimicked by other countries around the world, it provides a basis for discussion for those nations that do use a similar regulatory approach and enforcement practices. Consequently, the discussion in this chapter is based, in large part, on the United States' National Pretreatment Program.

This chapter offers a brief history of the National Pretreatment Program, an overview of the program requirements, and a brief discussion of the program responsibilities for POTWs and industrial users (IUs). For a more detailed discussion of industrial wastewater pretreatment programs, the reader is referred to the references provided at the end of this chapter and to state and local requirements specific to their locality. Because regulations and requirements are subject to change, the reader should consult the proper authorities before taking any actions that may be affected by laws or regulations.

NATIONAL PRETREATMENT PROGRAM

The National Pretreatment Program is a joint regulatory effort by local, state, and federal authorities that requires the control of pollutants that may pass through or interfere with POTW treatment processes or contaminate wastewater sludge. Control of pollutants before the discharge of wastewater to the sewer minimizes the possibility of adverse effects to POTWs from controlled pollutants.

REGULATORY HISTORY. In 1972, the U.S. Congress passed the Federal Water Pollution Control Act Amendments of 1972, which became known as the Clean Water Act, to restore and maintain the integrity of the nation's waters. This was a national milestone in the management of wastewater and in the United States' efforts to clean up water pollution in the nation's waterways. Although previous legislation had been enacted to address water pollution, those efforts were developed with other goals in

mind. For example, the 1899 Rivers and Harbors Act protected navigational interests, while the 1948 Water Pollution Control Act and the 1956 Federal Water Pollution Control Act merely provided limited funding for state and local governments to address water pollution concerns on their own.

The Clean Water Act established a water quality regulatory approach and empowered the U.S. Environmental Protection Agency (U.S. EPA) (Washington, D.C.) to establish industry-specific, technology-based effluent limitations. The Clean Water Act also required U.S. EPA to develop and implement the NPDES permit program to control the discharge of pollutants from point sources and served as a vehicle to implement the industrial technology-based standards.

U.S. EPA's first attempt to implement pretreatment requirements was promulgated in late 1973 in the *Code of Federal Regulations* (*CFR*) as 40 *CFR* Part 128, which established general prohibitions against treatment plant interference and pass-through and pretreatment standards for the discharge of incompatible pollutants from specific industrial categories. However, as a result of legal complications, in June 1978, U.S. EPA replaced 40 *CFR* Part 128 with the General Pretreatment Regulations for Existing and New Sources of Pollution, 40 *CFR* Part 403 (U.S. EPA, 2007c). These regulations now provide the framework for the National Pretreatment Program, which regulates the introduction of industrial wastes to POTWs. As changes to the NPDES regulations are needed, U.S. EPA issues proposed and final rules related to the NPDES permit program.

REGULATORY STRUCTURE. The General Pretreatment Regulations establish responsibilities of federal, state, and local government; industry; and the public to implement Pretreatment Standards to control pollutants that pass through or interfere with POTW treatment processes or that may contaminate wastewater sludge. U.S. EPA, in coordination with individual states, the regulated community, and the public, develops, implements, and conducts oversight of the NPDES permit program based on statutory requirements contained in the Clean Water Act and regulatory requirements contained in the NPDES regulations. Enforcement of the regulations generally becomes the responsibility of local control authorities. The General Pretreatment Regulations define the term "control authority" as a POTW that administers an approved pretreatment program because it is the entity authorized to control discharges to its system. However, the regulations provide states with the authority to implement POTW pretreatment programs in lieu of POTWs or for U.S. EPA to administer the pretreatment program in states not authorized to do so.

Among other things, the General Pretreatment Regulations require all larger POTWs (i.e., those designed to treat flows of more than 19 000 m^3/d [5 mgd]) receiving discharges subject to the pretreatment standards and smaller POTWs with significant in-

dustrial discharges to establish local pretreatment programs. These local programs must enforce all national pretreatment standards and requirements in addition to any more stringent local requirements necessary to protect site-specific conditions at the POTW.

GENERAL PRETREATMENT REQUIREMENTS (40 *CFR* PART 403). The General Pretreatment Regulations apply to all nondomestic sources that introduce pollutants to a POTW. These sources of "indirect discharge" are more commonly referred to as IUs. However, because not all IUs create problems for POTWs, U.S. EPA developed four criteria to define a significant industrial user (SIU). Many of the General Pretreatment Regulations apply only to SIUs, based on the fact that control of SIUs should provide adequate protection of the POTW.

The four criteria that generally define an SIU are as follows:

- An IU that discharges an average of 95 m^3/d (25 000 gpd) or more of process wastewater to the POTW,
- An IU that contributes a process waste stream making up 5% or more of the average dry-weather hydraulic or organic capacity of the POTW treatment plant,
- An IU designated by the control authority as such because of its reasonable potential to adversely affect the POTW's operation or violate any pretreatment standard or requirement, or
- An IU subject to federal categorical pretreatment standards.

However, the control authority may determine that an IU, which may otherwise be classified as an SIU, is not an SIU because it satisfies the criteria for exemption.

The National Pretreatment Program identifies specific requirements that apply to all IUs, additional requirements that apply to all SIUs, and certain requirements that only apply to categorical industrial users (CIUs). The objectives of the National Pretreatment Program are achieved by applying and enforcing three types of discharge standards:

1. Prohibited discharge standards, which are designed to protect against pass-through and interference generally;
2. Categorical pretreatment standards, which are designed to ensure that IUs implement technology-based controls to limit the discharge of pollutants; and
3. Local limits, which address the specific needs and concerns of a POTW and its receiving waters.

U.S. EPA is constantly developing new guidelines and revising or updating existing guidelines. Section 304(m) of the 1987 Water Quality Act requires U.S. EPA to publish

a biennial plan for developing new effluent guidelines and a schedule for the annual review and revision of existing promulgated guidelines.

Prohibited Discharges (40* CFR *Part 403.5). Prohibited discharge standards are general, national standards applicable to all IUs of a POTW, regardless of whether or not the POTW has an approved pretreatment program or the IU has been issued a permit. These standards are designed to protect against pass-through and interference, protect the POTW collection system, and promote worker safety and beneficial biosolids use. Refer to *Guidance Manual for Preventing Interference at POTWs* (U.S. EPA, 1987) for additional information on managing prohibited discharges.

Specifically, the discharge standards include the following prohibitions:

- Pollutants that will create a fire or explosion hazard in the POTW;
- Pollutants that will cause corrosive structural damage to the POTW, but never discharges with pH lower than 5.0, unless the plant is specifically designed for such discharges;
- Solid or viscous pollutants in amounts that will cause obstruction of the flow in the POTW;
- Any pollutant, including oxygen-demanding pollutants (biochemical oxygen demand [BOD]) and suspended solids, discharged at a flowrate or pollutant concentration that will cause interference in the POTW;
- Heat in amounts that will inhibit biological activity in the plant, resulting in interference, but never heat in such quantities that the temperature at the POTW is higher than 40 °C (104 °F), unless specifically authorized;
- Petroleum oil, nonbiodegradable cutting oil, or products of mineral oil origin in amounts that will cause interference or pass-through;
- Pollutants that result in the presence of toxic gases, vapors, or fumes within the POTW, in a quantity that may cause acute worker health and safety problems; and
- Any trucked or hauled pollutants, except at discharge points designated by the POTW.

These prohibited discharge standards are intended to provide general protection for POTWs. However, their lack of specific pollutant limitations creates the need for additional controls, namely categorical pretreatment standards and local limits.

Categorical Pretreatment Standards (40* CFR *Parts 405 to 471). Categorical Pretreatment Standards are limitations on pollutant discharges to POTWs, promulgated by U.S. EPA, that apply to specific process wastewaters of particular industrial categories.

These are national, technology-based standards that apply regardless of whether the POTW has an approved pretreatment program or the IU has been issued a permit. Industries with such discharges are called CIUs.

Categorical standards apply to regulated wastewaters, which are wastewaters from an industrial process that is regulated for a particular pollutant by a categorical pretreatment standard. Compliance with categorical pretreatment standards is intended to be based on measurements of waste streams containing only the regulated process wastewater. Therefore, compliance is measured at the process discharge point and not at the end of the pipe discharge point for the industrial facility. To monitor the regulated process in situations where the discharge from the regulated process cannot readily be isolated from the nonregulated waste streams, U.S. EPA developed the combined waste stream formula (CWF) and the flow-weighted average (FWA) approach for determining compliance with combined waste streams. The CWF is applicable where a regulated waste stream combines with one or more unregulated or dilute waste streams before treatment. Where nonregulated waste streams combine with regulated process streams after pretreatment, the more stringent approach (whether CWF or FWA) is used to adjust the allowable discharge limits.

As of January 2007, there are 56 regulated industrial categories listed in 40 *CFR* Subchapter N, Effluent Guidelines and Standards. U.S. EPA has published a separate regulation for each industrial category that specifies the effluent guidelines (for direct dischargers) and/or categorical pretreatment standards (for indirect dischargers) for that category (refer to 40 *CFR* Parts 405 to 471). Direct dischargers are regulated by NPDES permits, and indirect dischargers are regulated by the National Pretreatment Program. Table 4.1 lists the 30 currently identified industrial categories, with specific contaminant pretreatment standards, the general regulatory citation, and primary contaminants of concern. Note that each industrial category may have several subcategories with differing pretreatment requirements. Also, individual standards may be expressed in concentration units (milligrams per liter or micrograms per liter), production-based units (i.e., milligrams per kilogram of metal produced), or mass units (i.e., kilograms per day).

Table 4.2 lists toxic pollutants, known as priority pollutants, which are subject to regulation.

Local Limits [40* CFR *Part 403.5(c)]. Local limits are specific requirements developed and enforced by the control authority (often a POTW) to protect the wastewater treatment system infrastructure and the POTW's receiving waters. The National Pretreatment Program requires the use of local limits, where necessary, to manage pollutants that would otherwise pass through or interfere with the performance of the POTW.

TABLE 4.1 Selected categorical industrial users and potential effects on POTWs.

Industry category	40 *CFR* Part	Pollutants of concern
Aluminum forming	467	Chromium, cyanide, zinc, oil and grease, total toxic organics (TTO)
Battery manufacturing	461	Cadmium, chromium, cobalt, copper, cyanide, lead, manganese, mercury, nickel, silver, zinc
Carbon black manufacturing	458	Oil and grease
Centralized waste treatment	437	Antimony; arsenic; cadmium; chromium; cobalt; copper; lead; mercury; nickel; silver; tin; titanium; vanadium; zinc; bis(2-ethylhexyl)phthalate; carbazole; o-cresol; p-cresol; n-decane; fluoranthene; n-octadecane; 2,4,6-trichlorophenol; oil and grease; pH; total suspended solids (TSS)
Coil coating	465	Chromium, copper, cyanide, fluoride, phosphorus, zinc, oil and grease, TTO
Copper forming	468	Chromium, copper, lead, nickel, zinc, oil and grease, TTO
Electrical and electronic components	469	Antimony, arsenic, cadmium, chromium, fluoride, lead, zinc, TTO
Electroplating	413	Cadmium, chromium, copper, cyanide, lead, nickel, silver, zinc, total metals, TSS, pH, TTO
Fertilizer manufacturing	418	Ammonia, organic nitrogen, nitrate, phosphorus
Glass manufacturing	426	Fluoride, mineral oil, oil, pH, TSS
Inorganic chemicals manufacturing	415	Chromium, copper, cyanide, fluoride, iron, lead, mercury, nickel, silver, zinc, pH, chemical oxygen demand (COD)
Iron and steel manufacturing	420	Ammonia, chromium, cyanide, lead, nickel, zinc, benzo(a)pyrene, dioxins, naphthalene, phenols, tetrachloroethylene
Leather tanning and finishing	425	Chromium, sulfides, pH
Metal finishing	433	Cadmium, chromium, copper, cyanide, lead, nickel, silver, zinc, TTO
Metal molding and casting	464	Copper, lead, zinc, oil and grease, phenols, TTO

TABLE 4.1 Selected categorical industrial users and potential effects on POTWs (*continued*).

Industry category	40 *CFR* Part	Pollutants of concern
Nonferrous metals forming and metal powders	471	Antimony, cadmium, chromium, copper, cyanide, fluoride, molybdenum, lead, nickel, silver, zinc, ammonia
Nonferrous metals manufacturing	421	Antimony, arsenic, beryllium, cadmium, chromium, cobalt, copper, cyanide, fluoride, gold, indium, lead, mercury, nickel, selenium, silver, tin, titanium, zinc, TSS, pH, benzo(a)pyrene, phenol
Organic chemicals, plastics, and synthetic fibers	414	Cyanide, lead, zinc, numerous organics
Paving and roofing materials (tars and asphalt)	443	Oil and grease
Pesticide chemicals	455	Priority pollutants
Petroleum refining	419	Ammonia, oil and grease
Pharmaceutical manufacturing	439	Acetone, ammonia, n-amyl acetate, benzene, cyanide, ethyl acetate, isopropyl acetate, methylene chloride, toluene, xylenes, and many other organics
Porcelain enameling	466	Chromium, lead, nickel, zinc
Pulp, paper, and paperboard	430	Zinc, adsorbable organic halides, chloroform, dioxins, pentachlorophenol, trichlorophenol
Rubber manufacturing	428	Chromium, lead, zinc, COD, oil and grease
Soap and detergent manufacturing	417	COD, 7-day BOD
Steam electric power generating	423	Copper, polychlorinated biphenyls, priority pollutants except chromium and zinc in cooling tower blowdown
Timber products processing	429	Arsenic, chromium, copper, oil and grease
Transportation equipment cleaning	442	Cadmium, chromium, copper, lead, mercury, nickel, zinc, fluoranthene, phenanthrene, silica gel treated n-hexane extractable material (SGT-HEM; nonpolar)
Waste combustors	444	Arsenic, cadmium, chromium, copper, lead, mercury, silver, titanium, zinc

TABLE 4.2 Priority pollutants (U.S. EPA, 2007a).

1,1,1-Trichloroethane	Anthracene	Endrin
1,1,2,2-Tetrachloroethane	Antimony	Endrin Aldehyde
1,1,2-Trichloroethane	Arsenic	Ethylbenzene
1,1-Dichloroethane	Asbestos	Fluoranthene
1,1-Dichloroethylene	Benzene	Fluorene
1,2,4-Trichlorobenzene	Benzidine	gamma-BHC (Lindane)
1,2-Dichlorobenzene	Benzo(a)Anthracene	Heptachlor
1,2-Dichloroethane	Benzo(a)Pyrene	Heptachlor Epoxide
1,2-Dichloropropane	Benzo(b)Fluoranthene	Hexachlorobenzene
1,2-Diphenylhydrazine	Benzo(ghi)Perylene	Hexachlorobutadiene
1,2-Trans-Dichloroethylene	Benzo(k)Fluoranthene	Hexachlorocyclopentadiene
1,3-Dichlorobenzene	Beryllium	Hexachloroethane
1,3-Dichloropropene	beta-BHC	Indeno(1,2,3-cd)Pyrene
1,4-Dichlorobenzene	beta-Endosulfan	Isophorone
2,3,7,8-TCDD Dioxin	Bis2-ChloroethoxyMethane	Lead
2,4,6-Trichlorophenol	Bis2-ChloroethylEther	Mercury
2,4-Dichlorophenol	Bis2-ChloroisopropylEther	Methyl Bromide
2,4-Dimethylphenol	Bis2-EthylhexylPhthalate	Methyl Chloride
2,4-Dinitrophenol	Bromoform	Methylene Chloride
2,4-Dinitrotoluene	Butylbenzyl Phthalate	Naphthalene
2,6-Dinitrotoluene	Cadmium	Nickel
2-Chloroethylvinyl Ether	Carbon Tetrachloride	Nitrobenzene
2-Chloronaphthalene	Chlordane	N-Nitrosodimethylamine
2-Chlorophenol	Chlorobenzene	N-Nitrosodi-n-Propylamine
2-Methyl-4,6-Dinitrophenol	Chlorodibromomethane	N-Nitrosodiphenylamine
2-Nitrophenol	Chloroethane	Pentachlorophenol
3,3′-Dichlorobenzidine	Chloroform	Phenanthrene
3-Methyl-4-Chlorophenol	Chromium III	Phenol
4,4′-DDD	Chromium VI	Polychlorinated Biphenyls (PCBs)
4,4′-DDE	Chrysene	
4,4′-DDT	Copper	Pyrene
4-Bromophenyl Phenyl Ether	Cyanide	Selenium
4-Chlorophenyl Phenyl Ether	delta-BHC	Silver
4-Nitrophenol	Dibenzo(a,h)Anthracene	Tetrachloroethylene
Acenaphthene	Dichlorobromomethane	Thallium
Acenaphthylene	Dieldrin	Toluene
Acrolein	Diethyl Phthalate	Toxaphene
Acrylonitrile	Dimethyl Phthalate	Trichloroethylene
Aldrin	Di-n-Butyl Phthalate	Vinyl Chloride
alpha-BHC	Di-n-Octyl Phthalate	Zinc
alpha-Endosulfan	Endosulfan Sulfate	

Among the factors a POTW should consider in developing local limits are the POTW's efficiency in treating wastes; its compliance with its NPDES permit limits; the condition of the water body that receives its treated effluent; any water quality standards that are applicable to the water body receiving its effluent; the POTW's retention, use, and disposal of wastewater sludge; and worker health and safety concerns.

Local limits may be used to translate general prohibitions in the General Pretreatment Regulations into site-specific needs and to control industrial discharges of pollutants not regulated by the categorical standards. A local limit supersedes the categorical pretreatment standard if it is more stringent than the categorical standard for a given pollutant. However, a local limit typically applies at the point of discharge to the sewer system, while a categorical pretreatment standard generally applies at the end of the regulated process.

In evaluating the need for local limit development, it is recommended that control authorities

- Conduct an industrial waste survey to identify all IUs that might be subject to the pretreatment program;
- Determine the character and volume of pollutants contributed to the POTW by these industries;
- Determine which pollutants have a reasonable potential for pass-through, interference, or sludge contamination;
- Conduct a quantitative evaluation to determine the maximum allowable POTW treatment plant headworks (influent) loading for at least arsenic, cadmium, chromium, copper, cyanide, lead, mercury, molybdenum, nickel, silver, and zinc;
- Identify additional pollutants of concern;
- Determine contributions from unpermitted sources to determine the maximum allowable treatment plant headworks loading from "controllable" industrial sources; and
- Implement a system to ensure that these loadings will not be exceeded.

The POTWs should routinely reevaluate their local limits to ensure that they continue to provide adequate protection for POTW operation. An ongoing monitoring program is recommended to support review and revision of local limits and verification/identification of pollutants of concern. An effective ongoing monitoring program should include periodic sampling of influent, effluent, sludge, domestic/commercial wastewaters, and industrial wastewater discharges. U.S. EPA recommends annual reviews of local limits. U.S. EPA has developed a number of guidance documents to assist control authorities in the development of local limits. A guidance manual entitled

Local Limits Development Guidance and a separate document entitled *Local Limits Development Guidance Appendices* are available on the U.S. EPA Web site (http://www.epa.gov) (U.S. EPA, 2004a; U.S. EPA, 2004b). In addition, many U.S. EPA regions and states have developed local limits guidance to address regional and state issues.

One of the methods commonly used to derive local limits is the maximum allowable headworks loading (MAHL) method. A summary of the method is presented below.

Maximum Allowable Headworks Loading Method Summary. First, pollutant by pollutant, treatment plant data are used to calculate actual removal efficiencies through the POTW. This allows the back-calculation of the MAHL for each pollutant based on applying the most stringent criterion (i.e., water quality, sludge quality, NPDES permit, or pollutant inhibition levels) for the POTW allowable effluent concentration for each pollutant. After subtracting contributions from domestic sources (which are uncontrollable), the allowable industrial loading for each pollutant is then calculated. This is then either evenly distributed among the industrial users or allocated on an as-needed basis to those industrial users discharging the particular pollutant. Industrial users exceeding their allocation must pretreat their wastewater before discharge to comply with their local limit allowance. However, the regulations also provide a means for POTWs to potentially reduce the pretreatment requirements of their IUs based on the POTW's effectiveness in removing certain pollutants from its waste stream. The "removal credits" potentially available to IUs from the POTW, at its discretion, are summarized below.

Removal Credits (40* CFR *Part 403.7). If a POTW can treat certain pollutants to high levels of removal, it can obtain permission from U.S. EPA (or a state that has been granted authority by U.S. EPA) to issue credit to IUs, providing the IU with adjusted pretreatment requirements for those pollutants (40 *CFR* Part 403.7) that factor in the removal achieved by the POTW. A POTW can only issue removal credits if it has an approved local pretreatment program, consistently removes the pollutant for which the removal credit will be issued, and the granting of removal credits will not result in the violation of any local, state, or federal sludge requirements [as defined in 40 *CFR* Part 403.7(a)(1)(ii)]. Removal credits for several pollutants are available through 40 *CFR* Part 403 (Appendix G, Section I) when disposal practices used by a POTW meet the requirements of 40 *CFR* Part 503 for the intended practice (land application, surface disposal, or incineration). Additionally, a removal credit can be obtained for pollutants listed in 40 *CFR* Part 403 (Appendix G, Section II) if their respective concentration in the POTW's wastewater sludge is less than the threshold concentration listed in Appendix G. If a POTW sends all of its wastewater residuals to a municipal solid waste

landfill that meets the requirements of 40 *CFR* Part 258, the POTW can issue removal credits for any pollutant in wastewater sludge.

PRETREATMENT PROGRAM RESPONSIBILITIES FOR PUBLICLY OWNED TREATMENT WORKS

Any POTW or municipal authority that has a total design wastewater flow greater than 19 000 m^3/d (5 mgd) and receives pollutants from industrial users that pass through or interfere with the operation of the POTW or are otherwise subject to pretreatment standards will be required to establish a POTW Pretreatment Program, unless the NPDES state exercises its option to assume local responsibilities as provided for in the General Pretreatment Regulations. Those POTWs with a design flow of 19 000 m^3/d (5 mgd) or less may also be required to develop a POTW Pretreatment Program, if the circumstances warrant. Such circumstances include the nature or volume of the industrial influent, history of treatment process upsets, violations of POTW effluent limitations, and contamination of municipal sludge. Furthermore, the POTW's NPDES permit will be reissued or modified by the NPDES state or U.S. EPA to incorporate the approved pretreatment program as enforceable conditions of the NPDES permit.

ESTABLISHING LEGAL AUTHORITY. The POTW Pretreatment Program must be administered to ensure that industrial users comply with applicable pretreatment standards and requirements. Generally, the POTWs act as the pretreatment control authorities, with respect to the IUs that discharge to their systems, while either the state or U.S. EPA generally acts as the pretreatment approval authority. Approval authorities review and approve the pretreatment program and oversee the implementation of the program by the control authorities. In the absence of an approved POTW pretreatment program, the state or U.S. EPA approval authority serves as the control authority.

Control Authority (Local). Before a control authority can implement a pretreatment program, it must develop policies and procedures to administer the program and be given the legal authority to implement and enforce the program requirements. A control authority's legal authority is based on state law; therefore, state laws that confer the minimum federally mandated legal authority requirements on a control authority must be in effect. The policies and procedures for administering the program and the reference to the legal authority to implement and enforce the program are generally embodied in local regulations established by the control authority. Where the control authority is a municipality, legal authority is generally detailed in a Sewer Use Ordinance, which is typically part of city or county code. Regional control authorities fre-

quently adopt similar provisions in the form of "rules and regulations." Likewise, state agencies implementing a statewide program set out pretreatment requirements as state regulations, rather than as Sewer Use Ordinances.

Specific control authority responsibilities include the following:

- Develop, implement, and maintain the approved pretreatment program;
- Evaluate the compliance of regulated IUs;
- Initiate enforcement action against industries, as appropriate;
- Submit reports to approval authorities;
- Develop local limits (or demonstrate why they are not needed); and
- Develop and implement an Enforcement Response Plan (ERP).

U.S. EPA's 2007 guidance document, *EPA Model Pretreatment Ordinance* (U.S. EPA, 2007b), provides a model for POTWs that are required to develop pretreatment programs.

Approval Authority (State). Local pretreatment programs must be approved by the approval authority—either U.S. EPA or the authorized state—that is also responsible for overseeing implementation and enforcement of these programs. The approval authority is responsible for ensuring that local program implementation is consistent with all applicable federal requirements and is effective in achieving the National Pretreatment Program's goals. Specific responsibilities include the following:

- Notify POTWs of their responsibilities,
- Review and approve requests for POTW pretreatment program approval or modification,
- Review requests for site-specific modifications to categorical pretreatment standards,
- Oversee POTW program implementation,
- Provide technical guidance to POTWs, and
- Initiate enforcement actions against noncompliant POTWs or industries.

To carry out these responsibilities, the approval authority monitors local program compliance and effectiveness and dictates or takes corrective actions, where needed, to meet these goals. The approval authority generally uses the following three oversight mechanisms to make these determinations: (1) the program audit, (2) the Pretreatment Compliance Inspection, and (3) the control authority's annual pretreatment program performance report.

As noted in Table 4.3, a total of 46 states/territories are authorized to implement state NPDES permit programs as of January 2007, but only 35 are authorized to be the

TABLE 4.3 State program status (U.S. EPA, 2007e).

State	Approved state NPDES permit program	Approved to regulate federal facilities	Approved state pretreatment program	Approved general permits program
Alabama	10/19/1979	10/19/1979	10/19/1979	06/26/1991
Alaska				
American Samoa				
Arizona	12/05/2002	12/05/2002	12/05/2002	12/05/2002
Arkansas	11/01/1986	11/01/1986	11/01/1986	11/01/1986
California	05/14/1973	05/05/1978	09/22/1989	09/22/1989
Colorado	03/27/1975			03/04/1982
Connecticut	09/26/1973	01/09/1989	06/03/1981	03/10/1992
Delaware	04/01/1974			10/23/1992
District of Columbia				
Florida	05/01/1995	05/01/2000	05/01/1995	05/01/1995
Georgia	06/28/1974	12/08/1980	03/12/1981	01/28/1991
Guam				
Hawaii	11/28/1974	06/01/1979	08/12/1983	09/30/1991
Idaho				
Illinois	10/23/1977	09/20/1979		01/04/1984
Indiana	01/01/1975	12/09/1978		04/02/1991
Iowa	08/10/1978	08/10/1978	06/03/1981	08/12/1992
Kentucky	09/30/1983	09/30/1983	09/30/1983	09/30/1983
Louisiana	08/27/1996	08/27/1996	08/27/1996	08/27/1996
Maine	01/12/2001	01/12/2001	01/12/2001	01/12/2001
Maryland	09/05/1974	11/10/1987	09/30/1985	09/30/1991
Massachusetts				
Michigan	10/17/1973	12/09/1978	04/16/1985	11/29/1993
Midway Island				
Minnesota	06/30/1974	12/09/1978	07/16/1979	12/15/1987
Mississippi	05/01/1974	01/28/1983	05/13/1982	09/27/1991
Missouri	10/30/1974	06/26/1979	06/03/1981	12/12/1985
Montana	06/10/1974	06/23/1981		04/29/1983
Nebraska	06/12/1974	11/02/1979	09/07/1984	07/20/1989
Nevada	09/19/1975	08/31/1978		07/27/1992
New Hampshire				
New Jersey	04/13/1982	04/13/1982	04/13/1982	04/13/1982
New Mexico				
New York	10/28/1975	06/13/1980		10/15/1992
North Carolina	10/19/1975	09/28/1984	06/14/1982	09/06/1991
North Dakota	06/13/1975	01/22/1990	09/16/2005	01/22/1990
Northern Mariana Islands				
Ohio	03/11/1974	01/28/1983	07/27/1983	08/17/1992
Oklahoma	11/19/1996	11/19/1996	11/19/1996	09/11/1997
Oregon	09/26/1973	03/02/1979	03/12/1981	02/23/1982

TABLE 4.3 State program status (U.S. EPA, 2007e) (*continued*).

State	Approved state NPDES permit program	Approved to regulate federal facilities	Approved state pretreatment program	Approved general permits program
Pennsylvania	06/30/1978	06/30/1978		08/02/1991
Puerto Rico				
Rhode Island	09/17/1984	09/17/1984	09/17/1984	09/17/1984
South Carolina	06/10/1975	09/26/1980	04/09/1982	09/03/1992
South Dakota	12/30/1993	12/30/1993	12/30/1993	12/30/1993
Tennessee	12/28/1977	09/30/1986	08/10/1983	04/18/1991
Texas	09/14/1998	09/14/1998	09/14/1998	09/14/1998
Trust Territories				
Utah	07/07/1987	07/07/1987	07/07/1987	07/07/1987
Vermont	03/11/1974		03/16/1982	08/26/1993
Virgin Islands	06/30/1976			
Virginia	03/31/1975	02/09/1982	04/14/1989	04/20/1991
Washington	11/14/1973		09/30/1986	09/26/1989
West Virginia	05/10/1982	05/10/1982	05/10/1982	05/10/1982
Wisconsin	02/04/1974	11/26/1979	12/24/1980	12/19/1986
Wyoming	01/30/1975	05/18/1981		09/24/1991

pretreatment program approval authority. In all other states and territories, U.S. EPA is the approval authority.

Federal Authority (U.S. Environmental Protection Agency). U.S. EPA, both at the national and the regional level, has responsibilities for the National Pretreatment Program. At the regional level, U.S. EPA must

- Fulfill approval authority responsibilities for states without a state pretreatment program;
- Oversee state program implementation; and
- Initiate enforcement actions, as appropriate.

At the national level, U.S. EPA

- Oversees program implementation, at all levels;
- Develops and modifies regulations for the program;
- Develops policies to clarify and further define the program;
- Develops technical guidance for program implementation; and
- Initiates enforcement actions, as appropriate.

IDENTIFYING AND MONITORING INDUSTRIAL USERS. The cornerstone for achieving the objectives of an industrial waste pretreatment program is the identification and classification of the IUs in a community. From the output of this process, the municipality assigns monitoring and enforcement priorities based on each industry's potential for affecting the POTW. The quality of the pretreatment program depends on the personnel involved and the information on which enforcement decisions are based. Therefore, the municipality must frequently update its industrial information base to achieve local and national pollution abatement goals.

Industrial Survey. An industrial survey begins with compiling an inventory of industries and their waste streams. Ideally, the municipal wastewater treatment authority should survey all industries and waste streams in its service area. The survey starts with a preliminary inventory that may be obtained from a review of sources, such as the following:

- Industrial directories;
- Property tax records;
- Municipal agency files (i.e., sewer and water billings);
- Local telephone directories;
- Toxic Release Inventory reports;
- State and federal wastewater discharge monitoring reports; and
- Permit application forms.

To complete the survey, the preliminary inventory is verified and updated through a questionnaire, followed, where appropriate, by a physical inspection of the facility. The questionnaire usually seeks specific information on the following:

- Raw materials used;
- Basic steps involved in plant operations;
- Industrial processes in the plant;
- North American Industry Classification System codes;
- Water usage information;
- Number of connections to the sanitary sewer system;
- Types and quantities of wastes discharged;
- Type of pretreatment technologies used;
- Sludges or process residues disposed of (type and volume);
- Types and quantities of hazardous materials used or stored; and
- Description of chemical storage areas, including information regarding connection to sanitary or storm sewers.

U.S. EPA's 1983 document *Guidance Manual for POTW Pretreatment Program Development* is still a good resource and presents an example of a survey questionnaire that may be suitable for use by control authorities.

The database developed from the survey can be used to identify those industries subject to categorical pretreatment standards and to assign industrial monitoring priorities for efficient use of available sampling equipment and personnel. This information is also necessary for compliance with the POTW's reporting requirements for NPDES permits and approved pretreatment programs.

Whether the POTW has only a few industries or thousands, it needs the database and a system to collect and process the information for future reference or routine access. Selection of the system type, ranging from manual filing to complex data processing equipment, may depend on the amount of data to be stored and available funding.

Inspection of Industrial Facilities. Sampling and analyses of industrial discharges are important elements of an effective enforcement program. In addition to providing a database, sampling serves as the basis for determining compliance with local, state, and national discharge requirements. Before doing a sampling study, inspections of industries are needed to select the type and duration of sampling. Inspections can be conducted as scheduled, unscheduled, or random, depending on the situation.

Scheduled inspections are generally used to obtain information relating to production schedules and cleanup operations and to sketch the facilities' process layout. The sketch should show the location of buildings, process areas, water meters, wastewater treatment facilities, and sampling points. It can also provide other information about the sampling program. Pre-inspection arrangements may be advisable to obtain water-usage data and production records, if the industry is subject to production- or mass-based discharge standards. Once the background data have been obtained, unscheduled inspections or monitoring may follow.

Unscheduled monitoring of an industry may range from a complete industrial plant and recordkeeping inspection to inspection and sampling of only the industrial wastewater treatment facilities. Observations during an unscheduled inspection will likely show the normal operating conditions at the industrial facility and may lead to the municipality's reassessment of its enforcement priorities. Thus, spot checks are useful for determining the reliability of data collected through scheduled monitoring or self-reporting, detecting unreported discharges to the sewer system, or assessing routine operation of wastewater treatment equipment.

U.S. EPA has published a guidance manual entitled *Control Authority Pretreatment Audit Checklist and Instructions* (U.S. EPA, 1992), which presents U.S. EPA-recommended

procedures to be used by POTW personnel when conducting an inspection or sampling visit at an IU.

SAMPLING. The type of sampling selected for a facility should be based on the type of discharge and the nature of the operations. This section presents a brief discussion of sampling of industrial wastewater discharges. Chapter 17 of this manual provides a more detailed discussion of characterization and sampling of wastewater at POTWs.

Some basic sampling decisions to characterize wastewater include the following:

- Grab or composite sampling,
- Time-based or flow-proportioned sampling, and
- Automated or manual sampling.

A grab sample is a single sample taken at any time that is representative of the flow only at the time it was taken. A composite sample, which is composed of two or more samples taken from the same source and combined into one container to form a single sample, is more representative of the average quality of a discharge over a period of time. The composite sample may be made up of equal portions taken at fixed intervals (time-based composite), or the size and numbers of the portions or subsamples in the composite sample may be based on the discharge rate at the time each subsample is taken (flow-proportioned composite). This type of composite sample best represents the total mass of various pollutants in the waste discharge, particularly when the pollutant concentrations or flowrates change with respect to time.

In general, flow-proportional sampling is recommended wherever possible, except for those parameters that cannot be held and must be collected as grab samples. However, physical constraints at facilities may preclude the collection of flow-proportional sampling, in which case, time-proportional sampling, if executed properly, could be an acceptable substitute. Please refer to Chapter 17 of this manual for additional discussion of sampling methodology and sample-handling protocol.

U.S. EPA has published a guidance manual entitled *Industrial User Inspection and Sampling Manual for POTWs* (U.S. EPA, 1994), which presents U.S. EPA-recommended procedures to be used by POTW personnel when conducting an inspection or sampling visit at an IU.

Also, *CFR* Title 40, Part 136 (U.S. EPA, 2007d), presents guidelines establishing test procedures for the analysis of pollutants, including those pertinent to wastewater sampling.

ENFORCEMENT IMPLEMENTATION. A successful industrial pretreatment program stems from a consistent, effective enforcement response policy. The policy must be based on reasonable discharge standards contained in a control mechanism, such as an ordinance, permit, or contract. These standards should protect the municipality's sewer system, employees, wastewater treatment facilities, and the receiving waterway. Where the municipality has an approved pretreatment program, it must enforce the federal categorical pretreatment standards, the general discharge prohibitions, and its own local limits. The policies and terms used by the municipality to deal with noncompliance are contained in the municipality's ERP. To assist control authorities in their enforcement obligations, U.S. EPA has published the guidance document entitled *Pretreatment Compliance Monitoring and Enforcement Guidance* (U.S. EPA, 1986).

Enforcement Response Plan. The General Pretreatment Regulations require control authorities to adopt and implement an ERP. The ERP regulations establish a framework for POTWs to formalize procedures for investigating and responding to instances of IU noncompliance. With an approved ERP in place, POTWs can enforce against IUs on a more objective basis.

To ensure that enforcement response is appropriate and that the control authority actions are not arbitrary or capricious, U.S. EPA strongly recommends that an Enforcement Response Guide (ERG) be included as part of the approved ERP. The ERG identifies responsible control authority officials, general time frame for actions, expected industrial user responses, and potential escalated actions based on the following:

- Nature of the violation (pretreatment standards, reporting [late or deficient], and compliance schedules);
- Magnitude of the violation;
- Duration of the violation;
- Frequency of the violation (isolated or recurring);
- Potential effect of the violation (i.e., interference, pass-through, or POTW worker safety);
- Economic benefit gained by the violator; and
- Attitude of the violator.

U.S. EPA has published a guidance manual entitled *Guidance for Developing Control Authority Enforcement Response Plans* (U.S. EPA, 1989a), which presents U.S. EPA-recommended procedures to be used by POTW personnel when conducting an inspection or sampling visit at an IU.

Compliance Review of Industrial User Data/Reports. Review of monitoring data and supporting documentation provides information regarding the compliance status of an IU's discharge, the quality and quantity of its contribution to the municipal WWTP, and the costs of treating the waste contribution. Compliance with pretreatment program regulations requires IUs to submit reports of self-monitoring activities, including the Baseline Monitoring Report (BMR), semiannual reports, and compliance schedule progress reports. The municipality must acknowledge and act on the industry's self-reported departures from applicable standards. Failure of individual industries to submit required reports should result in prompt enforcement action. In addition, any industry contending that it has no discharge from a regulated process should be required to affirm this claim semiannually and to notify the municipality immediately of any change in its discharge status. Follow-up inspections are needed for those companies subject to regulations and those that claim to be exempted.

Enforcement Mechanisms. The control authority will have at its disposal a number of mechanisms, embodied in the Sewer Use Ordinance, to enforce the requirements of the pretreatment program. These mechanisms, which generally represent an escalating sequence of actions that may be applied, if necessary, to ensure compliance, may range from a telephone call to a criminal lawsuit. Common enforcement mechanisms include the following:

- Notice of violation—may be issued for noncompliance and requires the user to identify the cause of the violation and provide a plan and schedule for remediating the violation.
- Consent agreement—a voluntary agreement between the user and the control authority that identifies a specific action required of the user and a specified date to achieve the action.
- Show cause order.
- Compliance order.
- Cease and desist order.
- Emergency suspension.
- Termination of discharge.

In addition, most control authorities can levy administrative fines for violations.

Enforcement Tracking. It is essential for control authorities to effectively manage information to demonstrate proper implementation of the pretreatment program. The Clean Water Act allows citizens to file suit against a control authority that has failed to

implement its approved pretreatment program as required by its NPDES permit. The control authority may be fined and required to enforce against noncompliance with pretreatment standards and requirements in a court order. Furthermore, unresolved noncompliance issues may result in the approval authority enforcing directly against the IU and/or the control authority, and U.S. EPA may also take enforcement action where it deems action by the state or the control authority is inappropriate.

An approval authority will routinely review the overall performance of a control authority in monitoring IUs, identifying noncompliance, and enforcing regulations. Performance will be evaluated based on POTW self-monitoring data, written ERPs, audits, inspections, and pretreatment program reports. Therefore, it is incumbent on the control authority, regardless of the response action taken, to document and track all contact, notices, and meetings with IUs and the responses received.

Publication of a List of Noncompliant Industries. An approved federal pretreatment program requires the municipality to publish, at least annually, a list of industries that were in significant noncompliance with the applicable pretreatment standards during the previous 12 months. The list is to be published in the daily newspaper of largest circulation within the municipal authority's jurisdiction. The definition of *significant noncompliance* can be found in U.S. EPA's General Pretreatment Regulations [40 *CFR* Part 403.8(f)(2)(viii)].

RECORDKEEPING AND REPORTING. ***Data Management System.*** The type and complexity of the system required to manage the information generated in operating an industrial pretreatment program is governed by the size of the industrial community to be monitored and the amount of information and data to be stored for future retrieval. For a municipality with a small industrial community, manual files may suffice for the necessary records, including those for inspections, sampling, and storage of industrial self-monitoring reports. Also, the manual approach may be appropriate for fulfilling NPDES and federal pretreatment reporting requirements. A municipal wastewater treatment authority monitoring a large industrial community would certainly need a computerized data management system. In either case, the information to be stored should include the following:

- Industry survey data;
- Self-monitoring report data;
- Company enforcement history;
- Reports of POTW inspections;

- Analytical data from POTW sampling studies; and
- POTW influent, effluent, and residuals.

A computerized data management system offers a calendar as a valuable tool for monitoring the required periodic performance of all necessary functions, such as self-reporting by industrial dischargers, inspection and sampling by the municipality, automated detection of delinquent reports, review and comparison of municipal and industry analytical data, and generation of municipal reports for NPDES permit and federal pretreatment program reporting requirements. A computerized data system can also flag violations of permit limits, an important capability for municipalities with many industries.

Publicly Owned Treatment Works Reporting. A POTW with an approved pretreatment program is required to submit an annual report to U.S. EPA briefly describing the pretreatment program activities for the preceding year. Information to be submitted includes a summary of program changes; a listing of IUs and their compliance status; and the compliance activities initiated, including enforcement actions.

INDUSTRIAL USER PRETREATMENT PROGRAM RESPONSIBILITIES

The responsibilities of IUs under the National Pretreatment Program are briefly highlighted in this section. Additional details regarding IU responsibilities can be found in *Industrial Wastewater Management, Treatment, and Disposal* (WEF, in press) and in 40 *CFR* Parts 403.12, 403.16, and 403.17. The IUs need to constantly monitor the regulations, as they are subject to periodic revisions. Control authorities need to know which responsibilities IUs have so they can properly monitor their IU performance.

The IUs are required to comply with all applicable pretreatment standards and requirements. Demonstration of compliance requires certain IUs to submit reports, self-monitor, and maintain records. Because control authorities are responsible for communicating applicable standards and requirements to IUs and for receiving and analyzing reports, it is essential for control authority personnel to understand IU reporting and notification requirements contained in the General Pretreatment Regulations. These requirements are summarized below.

CATEGORICAL INDUSTRIAL USER REPORTING REQUIREMENTS.

An IU that is subject to a categorical pretreatment standard is identified as a CIU. Principal reporting requirements for CIUs are highlighted below.

Baseline Monitoring Report [40* CFR *Part 403.12(b)]. The CIUs are required to submit a BMR within 180 days after the effective date of the categorical standard or at least 90 days before commencement of discharge for new sources. The BMR is a one-time report, based on sampling of the CIU's discharge or estimating the discharge characteristics for new sources.

Compliance Schedule Progress Report [40* CFR *Part 403.12(c)(3)]. A CIU that is not in compliance with the applicable categorical standards by the time the standards are effective often will have to modify process operations and/or install end-of-pipe treatment to comply. Federal regulations require that the control authority develop and impose a compliance schedule for the CIU to install technology to meet applicable standards. In no case can the final or completion date in the schedule be later than the final compliance date specified in the categorical standards. The CIU must submit progress reports to the control authority no later than 14 days following each date in the compliance schedule.

90-Day Compliance Reports [40* CFR *Part 403.12(d)]. Section 403.12(d) of the General Pretreatment Regulations requires a CIU to submit a final compliance report to the control authority. An existing source must file a final compliance report within 90 days following the final compliance date specified in a categorical regulation or within 90 days of the compliance date specified by the control authority, whichever is earlier. A new source must file a compliance report within 90 days from commencement of discharge to the POTW.

Upset Reports [40* CFR *Part 403.16]. The CIUs are allowed an affirmative defense for noncompliance with categorical standards if they can demonstrate that the noncompliance was the result of an upset. Conditions necessary to demonstrate that an upset has occurred are detailed in 40 *CFR* Part 403.16 and require the CIU to submit at least an oral report to the control authority within 24 hours of becoming aware of the upset.

Signatory and Certification Requirements [40* CFR *Part 403.12(l)]. Pursuant to 40 *CFR* Part 403.12(l), BMRs, 90-day compliance reports, and periodic compliance reports from CIUs must be signed by an authorized representative of the facility and contain a certification statement attesting to the integrity of the information reported.

CATEGORICAL AND SIGNIFICANT INDUSTRIAL USER REPORTING REQUIREMENTS—PERIODIC COMPLIANCE REPORTS [40 *CFR* PARTS 403.12(E) AND (H)]. After the final compliance date, CIUs (except nonsignificant CIUs) are required to report, during the months of June and December, the self-monitoring results of their wastewater discharge(s), although control authorities may require

more frequent monitoring. Also, the control authority must also require semiannual reporting from SIUs not subject to categorical standards. All the results for self-monitoring performed must be reported to the control authority, even if the IU is monitoring more frequently than required.

A control authority may choose to monitor IUs in lieu of the IU performing the self-monitoring.

REPORTING REQUIREMENTS FOR ALL INDUSTRIAL USERS. ***Notification of Potential Problems [40* CFR *Part 403.12(f)].*** All IUs are required to notify the control authority immediately of any discharges that may cause potential problems. These discharges include spills, slug loads, or any other discharge that may cause a potential problem to the POTW.

Bypass [40* CFR *Part 403.17]. The General Pretreatment Regulations define *bypass* as the intentional diversion of waste streams from any portion of an IU's pretreatment facility. If a bypass results in noncompliance—even if it was the result of essential maintenance—the IU must provide a report to the control authority detailing a description of the bypass; cause and duration of the bypass; and steps being taken and/or planned to reduce, eliminate, and prevent reoccurrence of the bypass. Oral notice must be provided to the control authority within 24 hours of the detection of an unanticipated bypass, with a written follow-up due within 5 days. For an anticipated bypass, the IU must submit notice to the control authority, preferably 10 days before the intent to bypass.

Noncompliance Notification [40* CFR *Part 403.12(g)(2)]. If monitoring performed by an IU indicates noncompliance, the IU is required to notify the control authority within 24 hours of becoming aware of the violation. In addition, the IU must repeat sampling and analysis and report results of the resampling within 30 days. The repeat sampling is not required if the control authority samples the IU at least once per month or if the control authority samples the IU between the time of the original sample and the time the results of the sampling are received.

Notification of Changed Discharge [40* CFR *Part 403.12(j)]. All IUs are required to promptly notify the control authority in advance of any substantial changes in the volume or character of pollutants in their discharge.

Notification of Discharge of Hazardous Wastes [40* CFR *Part 403.12(p)]. All IUs discharging more than 15 kg per month of a waste that, if otherwise disposed of, would be a hazardous waste pursuant to the Resource Conservation and Recovery Act (RCRA) requirements under 40 *CFR* Part 261, are required to provide a one-time written notification of such discharge to the control authority, state, and U.S. EPA. All IUs

discharging any amount of waste, that, if disposed of otherwise, would be an acutely hazardous waste pursuant to the RCRA, must also provide this notification.

SELF-MONITORING REQUIREMENTS. All SIUs, including CIUs, must conduct self-monitoring as part of several different reporting requirements. For CIUs, this includes the BMR, 90-day compliance report, and periodic compliance reports. Noncategorical SIUs are required to self-monitor as part of the periodic reporting requirements. Sample collection and analysis for all required pretreatment program reports must be conducted using 40 *CFR* Part 136 procedures and amendments thereto.

Self-monitoring for periodic compliance reports must be conducted in accordance with the IU's discharge permit requirements. The control authority must ensure that these permits specify sampling location(s), required sampling frequencies, sample types to be collected, sampling and analytical procedures, and associated reporting requirements. U.S. EPA's *Industrial User Permitting Guidance Manual* (U.S. EPA 1989b) provides guidance on managing the permitting process.

At a minimum, CIUs must monitor for all categorically regulated pollutants at least once every 6 months, although permits issued by the local control authority may require more frequent monitoring.

INDUSTRIAL USER RECORDKEEPING REQUIREMENTS. All IUs are required to maintain records of their monitoring activities. Information, at a minimum, should include the following:

- Sampling methods, dates, and times;
- Identity of the person(s) collecting the samples and of the sampling location(s);
- Dates the analyses were performed and the methods used; and
- Identity of the person(s) performing the analyses and the results of the analyses.

These records should be retained for at least 3 years or longer in cases where there is pending litigation involving the control authority or IU or when requested by the approval authority. These records must be available to the control authority and approval authority for review and copying. Historically, most control authorities do not dispose of any records; rather, older records are archived at an off-site location.

OVERVIEW OF INDUSTRIAL WASTEWATER PRETREATMENT

This section briefly reviews basic considerations in the pretreatment of industrial wastewater before its discharge to the municipal wastewater treatment system. Additional

details regarding industrial wastewater pretreatment can be found in *Industrial Wastewater Management, Treatment, and Disposal* (WEF, in press) and the other references cited in this section.

INDUSTRIAL WASTEWATER CHARACTERISTICS. Industrial wastewaters may contain organic and/or inorganic constituents that may be detrimental to the operation of a POTW. The composition of industrial wastewater may change as raw materials and processes are changed. Fluctuations may occur in the flow and composition of wastewater. Wastewater characteristics vary widely from one type of industry to another and even among plants within the same industrial category. Because the list of regulated pollutants is broad, almost any industry may be a source of one or more of these pollutants. Refer to Table 4.1 for a partial list of industries with categorical discharges and potential contaminants of concern for these industries.

INDUSTRIAL WASTEWATER PRETREATMENT PROCESSES. The pretreatment requirements for industrial wastewater depend on the wastewater characteristics, particular pollutants requiring removal, flowrates, and degree of pretreatment needed. The various wastewater treatment processes are generally classified as physical, chemical, and biological, and each is described briefly below. Detailed discussions of industrial wastewater characteristics, specific pretreatment applications, and design of industrial wastewater treatment systems can be found in the literature (Eckenfelder, 1999; Nemerow, 1978; WEF, in press). Such information is beyond the scope of this chapter.

Reductions in the volume or strength of raw wastewater may often be achieved through industrial recycling or reuse systems, improved housekeeping practices, and production process modifications to reduce constituents of concern. Application of these industrial plant controls should be considered and can make a significant difference in the pretreatment requirements for an industry.

Physical processes are designed to remove targeted constituents from waste streams by removing the constituents without producing any change in the constituent. Commonly used physical processes include filtration, adsorption, stripping, and solids separation using screening, sedimentation, or flotation. The result of physical pretreatment is a waste stream with lower concentrations of the targeted constituents, while the physically removed constituents must be managed separately for disposal.

Chemical processes produce a change in the targeted constituents in the waste stream by chemically altering the constituents or chemically binding the constituents to other chemical compounds. Neutralization, oxidation, reduction, and coagulation are

examples of chemical processes. The result of physical pretreatment is a waste stream with lower concentrations of the targeted constituents, while the chemically removed constituents must be managed separately for disposal. Examples of commonly used coagulants include aluminum and iron salts. Oxidants typically used include chlorine, peroxide, ozone, or oxygen.

Biological processes are primarily designed to reduce dissolved organic materials. Aerobic biological processes include trickling filters and other fixed-film systems and activated sludge systems, including sequencing batch reactors. Anaerobic processes, such as anaerobic filters and anaerobic reactors, have been used for high-strength industrial wastewater. Many industrial wastewaters may require a pretreatment step to reduce toxic pollutants that would otherwise interfere with the operation of biological units.

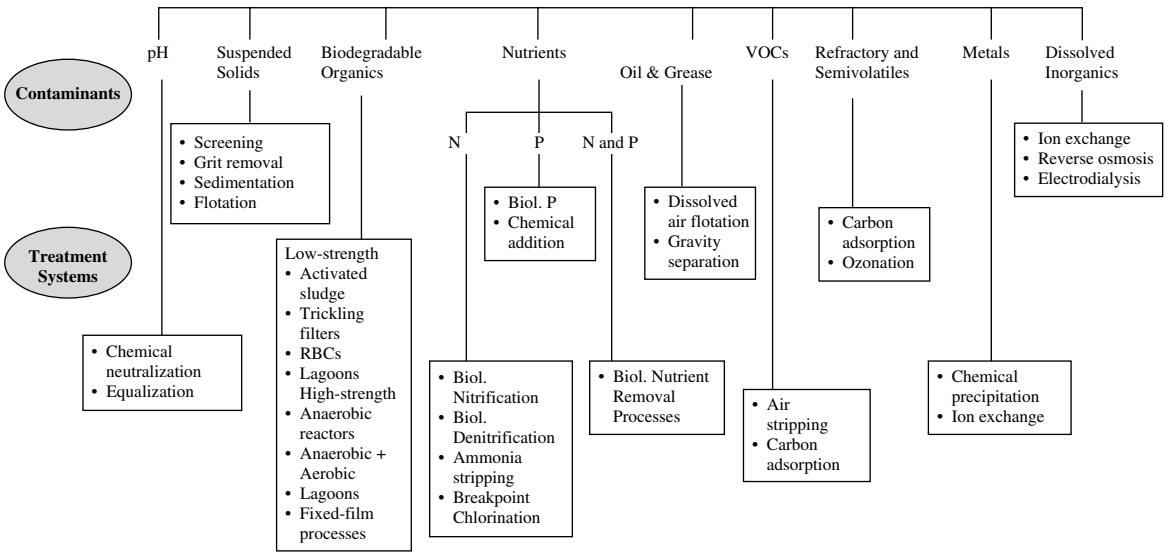
Treatment technologies for heavy metals removal generally include a precipitation process. Sometimes, effective treatment may require a chemical oxidation step before precipitation. The pH of the wastewater and the oxidative state of the metal influence treatment effectiveness. Sulfide addition precipitates arsenic, and lime or caustic addition can precipitate many metals as hydroxides. Caustic converts hexavalent chromium to the trivalent state and then precipitates the trivalent chromium. Other incompatible pollutants, such as cyanide, are oxidized under alkaline conditions using chlorine.

One of the following four types of treatment processes can remove organic compounds:

- Stripping by air or steam;
- Advanced oxidation processes using various combinations of ozone, hydrogen peroxide, and UV light;
- Adsorption on activated carbon or a synthetic resin; and
- Biological degradation.

The performance of any of those processes for a specific application varies greatly and depends on the nature of the organic compound and the presence of other pollutants. Therefore, a small-scale model study on the specific waste to be treated is recommended before developing any of these processes.

For reference, Figure 4.1 presents a general list of common contaminants and the general treatment systems that may be used to pretreat wastewaters containing these contaminants before discharge to the POTW.



*VOCs = volatile organic compounds, RBCs = rotating biological contactors, N = nitrogen, and P = phosphorus.

FIGURE 4.1 General treatment systems commonly used to remove major contaminants.*

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INTRODUCTION

Safety, by definition, is (1) freedom from danger, risk, or injury; or (2) a device designed to prevent accidents (*American Heritage Dictionary*, 1997). This is a book definition; however, in the field, safety can mean many different things. It can mean working in a manner that will not endanger the lives and limbs of workers and passersby. It can also mean working to avoid losing work days. Unfortunately, safety can also be spoken about, but not practiced.

How does this happen? Everyone knows that there should be work practices used where no one gets hurt or sick. However, often, there are pressures to produce more work on time and more cheaply, and this can result in careless mistakes by workers and even uncorrected bad work habits. Pressures to produce more work on time and

more cheaply actually create an atmosphere or culture in which administrators may say the right things but really do not mean them. The term *buy-in* has become popular in management training, and it is used to signify an emotional investment in a topic. Management tries to get workers to "buy-in" to a program. The programs can range from profit sharing, to disciplinary actions, to esprit de corps, to safety. It is the responsibility of management to ensure that personnel understand the idea of working safely. Management can accomplish this in many ways, including through training, disciplinary action for unsafe work, on-site inspections, bonuses for employees, and fostering willing participation in safety programs by paying for them. It is easy for management to talk about safety without paying for it, especially in current times, when there seems to be no extra income to establish or maintain such programs. Some examples of this would be failing to provide the following: compensation for safety shoes for people who require steel-toed shoes, on-site training before workers use new equipment, or annual hearing tests for workers who regularly work where there is noise greater than 85 dB. Management must make sure that any initiative that is started is well-funded and continued. One of management's many responsibilities is to establish a work culture that embraces and supports safe work practices.

Workers bear much responsibility in this attitude also. After all, when the worker is out in the field, he or she is the one doing the work, and he or she bears the results of his or her own actions. If he or she does not, those working closely with him or her will. The wastewater treatment profession is fraught with danger. Wastewater treatment professionals work around many different kinds of hazards, including electrical, bacteriological, viral, confined space, engulfment, mechanical hazards, and simple hazards, such as oncoming traffic and traffic control. The job requires the worker to maintain awareness at all times.

It would be nice to believe that everyone in the world wished protection, advancement, fulfillment, and the best for their fellow humans. It is sad that this is not always the case. Workers are sometimes careless because "it is not their problem", or a worker may think "nobody will know if I do . . . ", or workers may be thinking about personal problems while working. Management sometimes will have financial constraints or be apathetic toward their laborers. Other times, poor judgment is involved that leads to injuries. A biosolids hauler once washed out his trailer with a power washer and entered the tank without thinking. He died within minutes from lack of oxygen. He may have been insufficiently trained or simply made a mistake; either way, he paid for this mistake with his life. It is essential that workers make sure that their place of work actually has a safety culture and does not just discuss one.

To protect workers who sometimes can be taken advantage of by administrative policies that may not have the worker's health as the primary concern, the federal govern-

ment created the Occupational Safety and Health Administration (OSHA) by passing the Occupational Safety and Health Act of 1970 (*CFR* 1910; Occupational Safety and Health Hazards, 2005) (there is a construction section of law, *CFR* 1926, that is pertinent to the wastewater treatment industry because it deals with trenching, ladders, and other things that collection system maintenance and infrastructure repair crews deal with). It is OSHA's responsibility to ensure the safety of the worker by setting up rules and regulations that protect the worker.

Oddly enough, there are many workers who are not be covered by the OSHA safety rules. Some federal and state workers do not fall under the jurisdiction of the regulation. Also, the employer (town, special district, or municipality) must have a minimum of nine employees to be held to these regulations. As an administrator or supervisor, it is important to realize that *all subcontractors who enter your facility to perform work must meet your safety and training standards.* They are your responsibility. Still, the OSHA regulations are the industry safety standards for much litigation. They will be considered as the baseline for safety guidelines in this text. Most often, employers must realize that they fall under the general duty clause of the OSHA regulations.

The drafters of the Occupational Safety and Health Act also realized that they could not cover every set of circumstances that might arise in a safety and health hazard situation. So, they included a General Duty Clause, which states, in Section 5(a)1, "Duties", the following:

(a) Each employer
    (1) Shall furnish to each of his employees employment and a place of employment which are free from recognized hazards that are causing, or likely to cause, death or serious physical harm to his employees.
    (2) Shall comply with occupational safety and health standards promulgated under this Act.
(b) Each employee shall comply with occupational safety and health standards and all rules, regulations, and orders issued pursuant to this Act which are applicable to his own actions and conduct.

The OSHA General Duty Clause is the catch-all for employer compliance. If OSHA cannot issue a citation based on a specific regulation, it will cite under the General Duty Clause. Remember, as an employer, you must provide a safe workplace for your employees. Mere compliance with all OSHA regulations may not be enough. You must endeavor to ensure that your employees are safety conscious in all activities at your facility.

COMMUNITY RIGHT-TO-KNOW

There is another set of rules enacted by the federal government for the protection, not of workers, but for other stakeholders that may be affected by chemicals used at wastewater treatment plants. These stakeholders are the surrounding communities that may be affected by any chemical releases. This set of rules is called the Superfund Amendments and Reauthorization Act of 1986, also known as SARA or the Emergency Planning and Community Right-to-Know Act (EPCRA). The latter is actually a free-standing law included in SARA, commonly known as SARA Title III. The purposes of the regulations are to encourage and support emergency planning efforts at the state and more localized levels, so that information concerning potential chemical hazards is known and emergency response plans can be formulated.

Why is this necessary? One would think that somewhere in state records are the design criteria and process records for all wastewater plants and the chemicals they use; however, this is not the case. In one instance, a wastewater treatment professional attempted to obtain authorization that would have changed the treatment process of a small mountain wastewater treatment plant. The county had lost all records that such a facility existed. Later, when going to the state, the professional found that the original site and process applications had been lost and discharge permit renewal applications contained none of this information because they were incomplete as filed. Before computers were used, many databases were manually kept on hand-designed graphs, charts, and checklists, and many regulatory agencies do not have the budget to transfer hand-kept files into state-of-the-art relational databases; these conditions can create problems when attempting to access information. In addition, problems can arise in plants where the operations staff may have changed the processes internally and failed to mention changes on permit update paperwork.

The EPCRA rules are an amendment of the Comprehensive Environmental Response, Compensation, and Liability Act (commonly known as Superfund) regulations of 1980 (CERCLA, 1980). The U.S. Environmental Protection Agency (U.S. EPA) (Washington, D.C.) administers the EPCRA. States create emergency response commissions who, in turn, set up emergency planning committees and districts. These committees typically consist of a representative of the emergency response personnel, state and county officials, environmental personnel, fire departments, and law enforcement. It is their responsibility to ensure that all potentially hazardous materials used in the district are accounted for and that there is a solution in the event of a hazardous release. For example, very large municipal plants may have the trained personnel to deal with chlorine gas leaks safely, but many small communities cannot afford the training of personnel, let alone the materials, tools, and staff to handle emergencies, so they

coordinate with districts to make sure that trained personnel exist nearby and that they know who to contact. Title III exists so that communities know what hazardous materials are produced, transported, or used by industries and services so that emergency planning and response activities can be coordinated. The law covers industries and businesses that produce, store, buy, ship, or use hazardous materials.

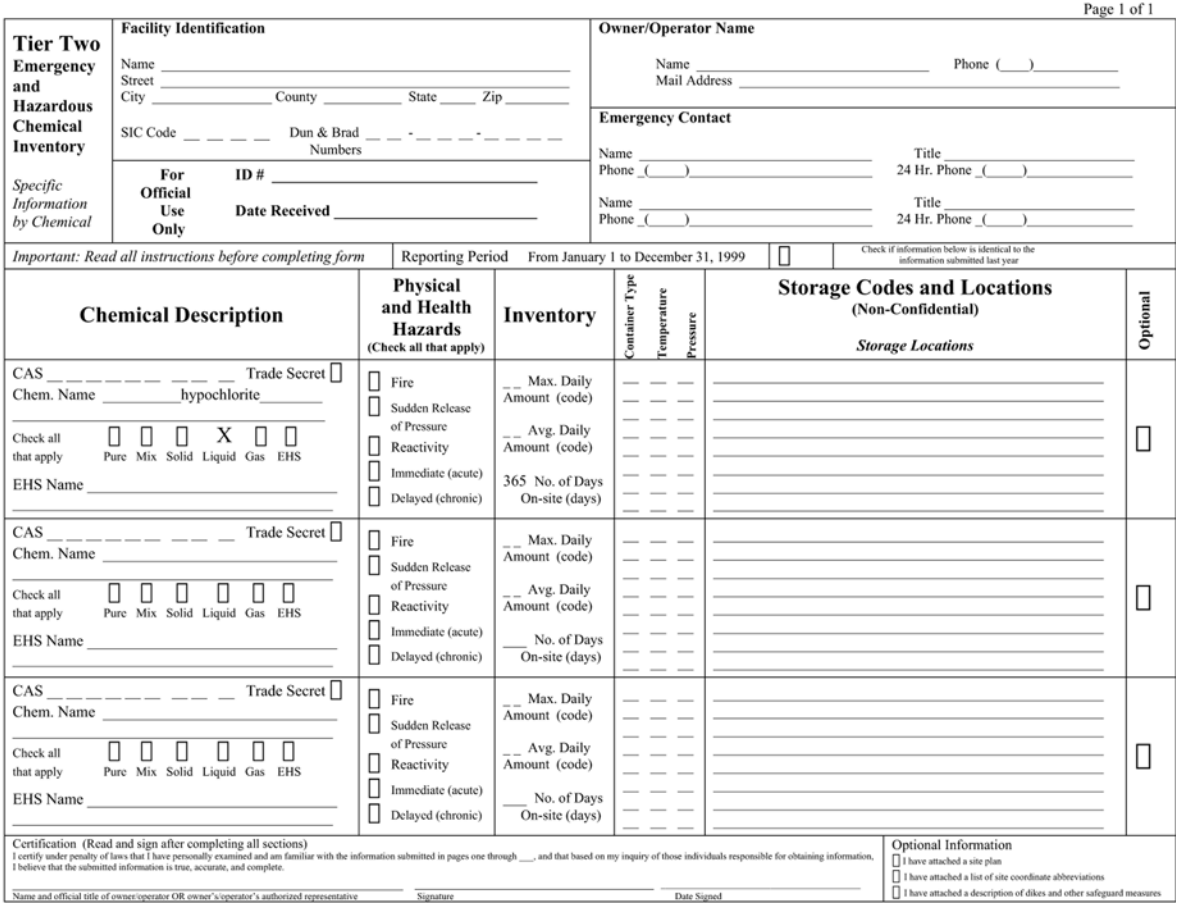
The first installment of these regulations, or Tier 1, was enacted in the 1980s and required that producers and users of over 4500 kg (10 000 lb) of chemicals report the location to local regulatory agencies. Later, the second, more inclusive series of regulations, Tier 2, were enacted. The level of chemicals that a plant used were much lower, requiring reporting to appropriate local special emergency response districts and the state.

Wastewater treatment facilities are typically involved in the use, storing, and shipping of hazardous substances. U.S. EPA publishes a list of Extremely Hazardous Substances (EHS) (U.S. EPA, 2001), including the quantitative limits, which are typically 230 kg (500 lb) or the threshold planning quantity, whichever is lower. For example, chlorine gas has a limit of 45 kg (100 lb), which is far less than the typical 230-kg (500-lb) limit. Quantitative limits for other hazardous chemicals (non-EHS) are typically 4500 kg (10 000 lb).

Some examples of hazardous chemicals used at wastewater treatment plants are chlorine gas, alum, ammonia, sulfuric acid, sulfur dioxide, methanol, lime, and sodium hydroxide. Complete lists can be found on the Web or by contacting the local authority.

It is important to become familiar with your local district regulatory interface personnel. They will help you set up emergency plans that are economical and reflect a concern for public safety. They will also typically be the first contact in case of emergency. Under SARA and EPCRA, local officials have the decision-making power to lower quantitative limits for hazardous chemicals if they feel that, for some reason, they pose a specific risk because of geographic or localized conditions. In many areas, this district, fire district, and law enforcement departments all have specific laws and jurisdictions that may overlap and may not be the same. For example, a fire district may have more stringent regulations for chlorine than does the county emergency response district or state regulations. In one case, a water treatment facility had a much lower chlorine storage limit than another because a grade school was built next to the plant and the amount of chlorine gas that could be stored there was drastically reduced when the school was ready to open. It is important to know your local regulatory agencies, find the most restrictive regulation, and be sure that you are in compliance with it.

Notification of hazardous chemicals was mandated in 1986. Before that, specific sheets were designed; a Material Safety Data Sheet (MSDS) was allowed to be submitted. Currently, there are forms that have been specifically designed for SARA Title III Tier 2 regulations (Figure 5.1). These forms are typically submitted annually to the ap-



Page 1 of 1

Tier Two Emergency and Hazardous Chemical Inventory

Specific Information by Chemical

Facility Identification

Name _____
Street _____
City _____ County _____ State ____ Zip _____

SIC Code __ __ __ __ Dun & Brad Numbers __ __ - __ __ __ - __ __ __ __

For Official Use Only

ID # _____

Date Received _____

Owner/Operator Name

Name _____ Phone (___)_____
Mail Address _____

Emergency Contact

Name _____ Title _____
Phone _(____)_____ 24 Hr. Phone _(____)_____

Name _____ Title _____
Phone _(____)_____ 24 Hr. Phone _(____)_____

Important: Read all instructions before completing form

Reporting Period From January 1 to December 31, 1999 ☐ Check if information below is identical to the information submitted last year

Chemical Description	Physical and Health Hazards (Check all that apply)	Inventory	Container Type / Temperature / Pressure	Storage Codes and Locations (Non-Confidential) — *Storage Locations*	Optional
CAS __ __ __ __ __ __ __ __ __ __ Trade Secret ☐ Chem. Name _____hypochlorite_____ Check all that apply: ☐ Pure ☐ Mix ☐ Solid X Liquid ☐ Gas ☐ EHS EHS Name _____	☐ Fire ☐ Sudden Release of Pressure ☐ Reactivity ☐ Immediate (acute) ☐ Delayed (chronic)	__ Max. Daily Amount (code) __ Avg. Daily Amount (code) 365 No. of Days On-site (days)	— — —	_____	☐
CAS __ __ __ __ __ __ __ __ __ __ Trade Secret ☐ Chem. Name _____ Check all that apply: ☐ Pure ☐ Mix ☐ Solid ☐ Liquid ☐ Gas ☐ EHS EHS Name _____	☐ Fire ☐ Sudden Release of Pressure ☐ Reactivity ☐ Immediate (acute) ☐ Delayed (chronic)	__ Max. Daily Amount (code) __ Avg. Daily Amount (code) ___ No. of Days On-site (days)	— — —	_____	☐
CAS __ __ __ __ __ __ __ __ __ __ Trade Secret ☐ Chem. Name _____ Check all that apply: ☐ Pure ☐ Mix ☐ Solid ☐ Liquid ☐ Gas ☐ EHS EHS Name _____	☐ Fire ☐ Sudden Release of Pressure ☐ Reactivity ☐ Immediate (acute) ☐ Delayed (chronic)	__ Max. Daily Amount (code) __ Avg. Daily Amount (code) ___ No. of Days On-site (days)	— — —	_____	☐

Certification (Read and sign after completing all sections)
I certify under penalty of laws that I have personally examined and am familiar with the information submitted in pages one through ___, and that based on my inquiry of those individuals responsible for obtaining information, I believe that the submitted information is true, accurate, and complete.

Name and official title of owner/operator OR owner's/operator's authorized representative _____ Signature _____ Date Signed _____

Optional Information
☐ I have attached a site plan
☐ I have attached a list of site coordinate abbreviations
☐ I have attached a description of dikes and other safeguard measures

FIGURE 5.1 Tier 2 document (http://www.co.ha.md.us/lepc/tier2form.html).

propriate agencies. If the regulatory agency does not provide a copy of the form, it can be found on the Web at sites such as local county Web sites (i.e., http://www.co.ha.md.us/lepc/tier2form.html).

There are responsibilities that go beyond basic reporting that typically must be fulfilled. An emergency communication protocol needs to be established. This includes who should be called, in which order, in case of emergency. This contact information and an emergency action plan should be laminated and displayed in a prominent place that will be easy to get to, near a telephone. Emergency response must be practiced so that, in case of emergency, there will be few loose ends that could lead to problematic situations. It is up to management to coordinate these practices with the

agencies designated in the emergency response plan. Reviews and practices will lead to the elimination of potential problems before they can happen. It is important to note that, while the topic of emergency response plans is being discussed here under chemical emergencies, there are many other emergencies, such as flood, power outages, avalanche, and effects of vandalism, that need to have established action plans. The plan should include specific actions to alleviate the emergency, identification of who should perform the actions, a communication tree for handling the emergency and notifying the public, and a method for resolving the situation. A basic list of contents for an emergency response plan follows:

- Identification of the facilities and the transportation routes for extremely hazardous chemicals. This would also include transport routes for biosolids and sludge, when being transported near bodies of water.
- Emergency response procedures.
- Designation of community and facility coordinators to carry out the emergency response plan.
- Emergency notification procedures.
- Methods for determining if a chemical release has occurred and the probable affected area and population.
- Description of the community's emergency response equipment and identity of responsible programs.
- Evacuation plans.
- Description and schedules of a training program for emergency response personnel.
- Methods and schedules for carrying out emergency response plans.

It is important to remember that any paperwork of this nature becomes public record. Often, diagrams and maps of where hazardous chemicals are kept are submitted with emergency response plans and can be quite detailed. As reported on National Public Radio KCFR 90.1 FM in Denver in April 2003, many of these maps were found on confiscated terrorist computers. Some of the sites detailed railcars of chlorine gas at wastewater plants near sensitive population centers. Whenever details of hazardous chemical storage become part of the public record, plans for security of these chemicals need to be made. In 2004, the U.S. Congress passed a law that requires drinking water facilities to perform vulnerability assessments of key chemical holding areas, water reservoirs, treatment facilities, and pumping stations and submit them to regulatory agencies. Because of primacy issues in many states, these laws have become state code in many areas. Please be aware that the states may have primacy in vulnerability assess-

ment issues and that, nationally, the Homeland Security Department has taken the lead, instead of U.S. EPA. These are fairly detailed and are designed to thwart terrorists. With this in mind, there will be a good amount of security around these vulnerability assessments. The draft before Congress in 2005 of the Wastewater Treatment Works Security Act (Jim Jeffords, I-VT) included the same type of legislation for wastewater facilities.

In designing emergency response plans, most of the material mentioned is related to the EPCRA. However, when making your emergency response plan, it is important to remember that there are other types of emergencies. These can vary, from sanitary sewer overflows and potential watershed contamination, to floods, tropical storms, earthquakes, and extended power outages. All of these are very real possibilities and, while some are unlikely in some geographic areas, there is a need to be creative when considering all the things that could go wrong so that you will not be unprepared as a public health professional in an emergency situation.

OCCUPATIONAL SAFETY AND HEALTH ADMINISTRATION HAZARDOUS COMMUNICATION STANDARD

Having the "right-to-know" has another meaning that is important to wastewater workers. This is the OSHA Hazardous Communication Standard, or HAZCOM. Basically, workers need to know the chemicals with which they will be dealing. They need to know the proper ways to handle chemicals and proper personal protective equipment (PPE) to use when handling them, any hazards the chemical may pose, limits of exposure, and other significant topics. These can be found in a number of places. Primarily, these are included in the MSDS. The MSDSs of all chemicals used in a facility are to be kept in a labeled notebook or binder in a specific location near the entrance to the facility. In fact, in some large facilities, by code, all of the outbuildings need their own MSDS volumes. Many emergency protection or response districts specify a color for this notebook (sometimes yellow or, often, safety orange).

An MSDS will include a list of the specific information pertaining to the chemical. This information will include the following:

- Identification of composition, Chemical Abstract Services number, formula, chemical weight, and synonyms.
- 24-hour emergency number.
- Physical data on boiling, freezing, and melting points; specific gravity; solubility; and vapor pressure.

- Reactivity, such as incompatibility, decomposition products, and polymerization potential.
- Health-hazard data on effects of exposure (acute and chronic), permissible exposure limits (PELs), and warning signals.
- Environmental effects, such as toxicity effects on the environment.
- Instructions for shipping and compliance with other pertinent federal regulations.
- Exposure control methods, such as PPE and engineering and administrative controls.
- Work practices, such as handling and storage procedures, cleanup, and waste disposal methods.
- Emergency procedures for handling spills, fires, and explosions.
- First-aid procedures.

The MSDS forms the basis of an employee training program on chemical handling. It should *never* be considered a substitute for training, particularly because there is no readability standard for the MSDS. Some are written in easily understood language, and others are written in technical language, as used by chemists and industrial hygienists. As a reference source, the MSDS must be acceptable to supervisors and all employees. Training to read and understand the information presented in the MSDS must be provided by the administration. The MSDS book must have routine checks and updates as newer MSDSs are received or changes in process require new chemicals. *No chemical should ever be received, labeled, stored, or used on-site without the safety and health information being recorded and filed.* There are other reference books that are not required but that list important information, such as threshold limit values and PELs, which are developed by the National Institute for Occupational Safety and Health (NIOSH) (Washington, D.C.) and the American Society of Safety Engineers (Des Plaines, Illinois). These are found in *The NIOSH Pocket Guide to Chemical Hazards* (NIOSH, 2005).

HAZARDOUS CHEMICALS

We have mentioned HAZCOM, but why is this so important? One of the most serious and problematic hazards that wastewater workers have to deal with is working with hazardous chemicals. There are many that are used regularly in the wastewater treatment industry, including chlorine gas, hydrogen peroxide, sulfuric acid, hydrochloric acid, acetic acid, and caustic soda. There are many others with varying degrees of immediate hazard. Without discussing all of the hazards, the following sections discuss ways of controlling hazards for workers who use these chemicals daily.

CONTROL MEASURES. When dealing with chemicals, the economic feasibility of eliminating the use of that chemical must be a primary consideration. Too often, the use of hazardous chemicals continues because "it was always done that way". Other methods of controls are engineering controls that lower the liability in using chemicals or ensuring safe work practices.

Elimination. The use of specific chemicals may be eliminated by changing the process (i.e., the use of anoxic zones to release some of the alkalinity during denitrification to lower the amount of chemical needed); changing equipment; or substituting chemicals that may be less hazardous to use. There are many resources that offer help, and often these are free. Chemical suppliers can suggest alternatives that may be safer to use that may not be familiar to managers. Often, state inspectors may be a helpful resource; they may suggest alternative controls that would lower liability. For example, the City of Anchorage, Alaska, reviewed its chlorine use and found that, because of chemical delivery schedules, it had a high risk factor. Chlorine was delivered infrequently because of the city's location, and large amounts of chlorine were stored on-site. Rather than maintain such a huge possible environmental liability, the city decided to switch to an alternative method of disinfection that uses salt for on-site chlorine generation. While the new method was more expensive, the amount of training and continuous monitoring that was reduced offset any economic advantages of delivering cheaper chlorine gas.

Engineering Controls. Primary measures include ventilation (both general and local exhaust), isolation, enclosure, and workplace redesign. Ventilation controls primarily airborne hazards to separate the hazard from the worker. Again, it is important for managers to work with local stakeholders. The local fire department or hazardous materials division may be able to suggest inexpensive solutions to safety issues. If you work easily with them, they are willing to share their experience with you.

Work Practices. The following are common work practices used to help safeguard employees:

- Initial training for proper safe handling and work practices.
- Using proper PPE.
- Proper housekeeping and storage procedures.
- Developing and using standard operational procedures for routine jobs that have some hazard associated with them.
- Using vacuums or sweeping compounds to keep chemical storage areas clean.
- Prohibiting smoking in areas of possible exposure.
- Using separate eating and washing facilities where ingestion hazard is identified.

- Labeling containers properly, including appropriate National Fire Protection Agency (NFPA) (Quincy, Massachusetts) signs or other detailed information. This is particularly important when the original chemical is transported in another container for use. It is possible to obtain NFPA signs and stickers to put on the container. At the very least, the container should be labeled with the correct contents.
- Posting warning signs to alert employees to hazardous conditions and special precautions.
- Posting emergency instructions at critical operations.
- Having emergency procedures in place for fires, chemical emergencies, spills, and first-aid requirements and practicing them.
- Training and maintaining training records for safe use and handling of all hazardous chemicals.
- Using job safety analyses to help perform operation and maintenance tasks.

The training of personnel to safely handle these chemicals and the provisions of PPE cannot be stressed enough once it is determined that it is not possible to lower exposure to these chemicals by elimination or engineering controls.

COMMON CHEMICALS. Table 5.1 is a list of common chemicals found in wastewater treatment, their characteristics, and the most common immediate dangers they can pose to a wastewater employee.

As indicated in the table, many of the gases are colorless, odorless, and tasteless, necessitating the use of gas sensors. Gas sensor use is covered in the section on confined spaces.

STORAGE GUIDELINES. ***Standard for Fire Protection Practice for Wastewater Treatment Plants and Collection Facilities.*** *Standard for Fire Protection Practice for Wastewater Treatment Plants and Collection Facilities* (NFPA, 1995) lists information regarding the storage and handling of chemicals found in wastewater treatment facilities. Sections of the Uniform Fire Code (NFPA, 2006; managers should use the current code that has been adopted and has regulatory jurisdiction in their areas) also discuss the storage, dispensing, and use of most hazardous chemicals used in a wastewater treatment plant. Once the manager becomes familiar with these standards, it is important to contact the local fire and building inspectors and other appropriate officials to determine who has jurisdiction and who has the most stringent standard to meet. Sometimes, officials may not agree; however, by initiating dialogue, the manager may facilitate a process whereby all inspectors and regulatory agencies can agree on practices for a particular facility.

TABLE 5.1 List of common chemicals found in wastewater treatment, their characteristics, and the most common immediate dangers they can pose to a wastewater employee.*

Common name	Physical characteristics	Danger	Safety precaution
Chlorine gas	Greenish-yellow gas, amber liquid under pressure, highly irritating odor, corrosive in moist atmosphere	Respiratory irritant: 30 mg/L coughing; 40 to 60 mg/L dangerous in 30 minutes; 1000 mg/L lethal in a few breaths	SCBA
Caustic soda	Viscous liquid, high pH	Chemical burn	Gloves, face shield or goggles, chemical wash station
Sulfuric acid	Liquid, low pH, distinctive odor	Chemical burn	Gloves, face shield or goggles, chemical wash station
Hydrochloric acid	Liquid, low pH, distinctive odor	Chemical burn	Gloves, face shield or goggles, chemical wash station
Carbon dioxide	Odorless gas	Asphyxiation	Ventilation, SCBA
Carbon monoxide	Colorless, odorless, tasteless gas	Asphyxiation, flammable, explosive	Ventilation, SCBA
Methane	Colorless, tasteless, odorless, nonpoisonous	Flammable, explosive	Ventilation
Hydrogen sulfide	Rotten egg smell, deadens sense of smell	Death in few minutes at 0.2%	Ventilation, SCBA
Hydrogen	Colorless, odorless, tasteless gas	Asphyxiation, flammable, explosive	Ventilation

*Note that this list is not comprehensive of the chemicals found in wastewater plants or all of the dangers that they may pose but is only an example of the immediate dangers. For all of the dangers presented by chemicals on-site, please consult the MSDS sheets and the current issue of the *NIOSH Guide to Chemical Hazard* (NIOSH, 2005).

Chlorine Storage and Chlorine Room Design. Chlorine rooms are worthy of special mention because chlorine is probably the single most dangerous chemical commonly used in wastewater treatment plants, and the storage rooms for chlorine have specific design standards. Many of these design standards can be found in design or standard practice manuals. It is a good idea to be familiar with the following basic principles, but always remember to check local building and fire codes, as they may be different and more stringent:

- Chlorine rooms should be adequately heated (typically higher than 10 °C [50 °F] to keep the chlorine from forming chlorine ice crystals).

- There should be adequate light so that the operator can easily see what he or she is doing.
- There should be an adequate controlling and measuring method so that the chlorine can be dispensed safely. Taking too much chlorine from the cylinder in one day can also form ice crystals. Maximum flow from a 45- or 68-kg (100- or 150-lb) cylinder is 18 kg/d (40 lb/d) and from a 900-kg (1-ton) cylinder is 180 kg (400 lb).
- The chlorine cylinders should be safely fastened in place. This is typically done by using chains or clamps. It should be easy to handle and store cylinders; 45- and 68-kg (100- and 150-lb) cylinders are always stored in a vertical position.
- There should be appropriate carts, clamps, chain falls, or hoists available so that the cylinders can be moved without undue stress on the worker's body.
- Chlorine room doors should have safety glass placed in them so that an outside observer can watch any work being performed or simple periodic visual checks can be made. When chlorine room doors are opened, they should trigger a ventilation fan so that the room is ventilated with fresh air whenever anyone is in the room.
- Because chlorine gas is heavier than air, the ventilation inlet is near the floor to dilute any chlorine gas that may have leaked. The outlet of the ventilation system should be away from the inlet at the top of the room and also away from any traffic patterns that may occur outside the room. This would reduce the threat of accidentally gassing pedestrian traffic. Chlorine rooms in larger plants should have chlorine detection alarms that will typically have battery backup in case of power failure.
- Outside the chlorine room, there should be a self-contained breathing apparatus (SCBA) to be worn in case of emergency entrance to the chlorine room while there is a leak. These need to be tested regularly and fit-tested on the employees that wear them.

During an emergency is not the time to find out that routine maintenance and worker practice have been forgotten. This could easily create a life-threatening situation.

CHEMICAL DELIVERY AND DISTRIBUTION. While many wastewater treatment professionals work in larger plants, where chemicals are delivered, there is a small percentage of operators who work in small systems, where chemicals must be brought in or moved from place to place by workers, because delivery is not immediately possible. For example, there are small mountain communities where chlorine gas delivery trucks could not even make it up the road to get there. This means chemicals

must be moved in the plant's service truck. All chemical delivery of this type falls under the jurisdiction of the Department of Transportation (DOT) (Washington, D.C.).

When hauling chlorine gas or sulfur dioxide cylinders, the plant's service truck must have the appropriate DOT placards (Figure 5.2). Placarding examples can be found in DOT manuals and purchased from many safety and industrial suppliers.

There will be a need for a chain-of-custody form that shows the quantity, chemical name, emergency response telephone number, class of chemical, UN number, and quantity and class of container. It also requires the signature of the driver for the load. This paperwork needs to be kept on a clipboard on the dash, in the front seat, or in the door panel for immediate accessibility. The MSDS sheet for the chemical also should be attached to the clipboard. Drivers need to have hazardous chemical transportation safety classes.

When transporting liquid chemicals, such as 10% sodium hypochlorite or caustic soda, there cannot be more than 450 kg (1000 lb) on the truck. That basically means one barrel, or possibly two, if the weight is known. The same protocol as above must be followed, with the exception of placarding. In either case, NFPA signage must be on the containers. When carrying containers containing less than 18 L (5 gal), no chain-of-custody paperwork or extensive protocols need to be followed. By using common sense and good common safety procedures, no chemicals that will react with each other should be carried together. All small containers that are carried still need the appropriate marking, class of container, and NFPA decals on the container.

NATIONAL FIRE PROTECTION ASSOCIATION. Below is a brief description of the symbols system used by NFPA for marking chemicals (Figure 5.3; NFPA, 2005). These diamond symbols should be on all chemical storage drums and smaller containers and can be purchased from many safety suppliers. For fire protection, these symbols should be displayed outside of buildings that house chemicals.

Other symbols, abbreviations, and words that some organizations use in the Special Hazards section of Figure 5.3 are shown in Figure 5.4 (NFPA, 2005). These uses are **not** compliant with NFPA 704; they are presented to help clarify their meaning when they appear on an MSDS or container label.

MICROBIOLOGICAL HAZARDS

One thing that unites wastewater workers, schoolteachers, and nursery workers are the microbial milieu found in the workplace. While medical personnel in an emergency room will see severe cases of infectious diseases, they work in a sterile environment with many ready safety precautions. Much of their hazard is based on



FIGURE 5.2 Typical examples of DOT placards. (Courtesy of Environmental Chemistry.com).

bloodborne pathogens. In a wastewater plant, there are commonly either stagnant anaerobic conditions or an aerated mass of heated microbial material. Wastewater workers are often exposed to low-level aerosolized versions of microbes, some of which may be infectious. The immune systems of many wastewater treatment professionals build up antibodies to a variety of bacterial and viral infectious agents. They become what are nicknamed "universal carriers" because they are often in contact with low levels of infectious agents that will not make them ill, but that they can build immunity to, much like vaccination theory. However, if wastewater workers' bodies do get run down or they come into contact with a significant infectious agent, they can easily become ill.

In an early 1970s text, it was noted that, in testing, approximately 14% of wastewater employees had some type of parasitic infection (Geldreich, 1972). In almost all cases, these were noninvasive, asymptomatic, or dormant, and the body had built defenses against them. As many current wastewater treatment professionals have become more aware of the microbial hazards of the work environment, this number has probably decreased. In any case, it is important to become familiar with some of the more common infectious agents.

AMOEBIC PARASITES. ***Entamoeba hystolitica.*** *Entamoeba hystolitica* is an amoebic intestinal parasite that enters the body through oral–fecal contamination as a cyst. The cyst splits into eight amoebic cells in the small intestine that often pass into the large intestine to live without damage to cell walls. At other times, the amoebas may attack the walls of the large intestine and cause severe cramps. In severe cases, the amoebas may pass into the liver or other organs. There are prescription drugs available to treat this parasite. The cyst can be long-lived and is somewhat chlorine-resistant. The symptoms are severe cramping and can escalate to dysentery.



Health Hazard	
4	Very short exposure could cause death or serious residual injury, even though prompt medical attention was given.
3	Short exposure could cause serious temporary or residual injury, even though prompt medical attention was given.
2	Intense or continued exposure could cause temporary incapacitation or possible residual injury, unless prompt medical attention is given.
1	Exposure could cause irritation, but only minor residual injury, even if no treatment is given.
0	Exposure under fire conditions would offer no hazard beyond that of ordinary combustible materials.



Flammability	
4	Will rapidly or completely vaporize at normal pressure and temperature or is readily dispersed in air and will burn readily.
3	Liquids and solids that can be ignited under almost all ambient conditions.
2	Must be moderately heated or exposed to relatively high temperatures before ignition can occur.
1	Must be preheated before ignition can occur.
0	Materials that will not burn.



Instability*	
4	Readily capable of detonation or of explosive decomposition or reaction at normal temperatures and pressures.
3	Capable of detonation or explosive reaction, but requires a strong initiating source or must be heated under confinement before initiation, or reacts explosively with water.
2	Normally unstable and will readily undergo violent decomposition but does not detonate. Also may react violently with water or form potentially explosive mixtures with water.
1	Normally stable, but can become unstable at elevated temperatures and pressures or may react with water with some release of energy, but not violently.
0	Normally stable, even under fire exposure conditions, and are not reactive with water.



Special Hazards

This section is used to denote special hazards. There are only two NFPA 704 **approved** symbols:

OX	This denotes an oxidizer—a chemical which can greatly increase the rate of combustion or fire.
W	Unusual reactivity with water. This indicates a potential hazard using water to fight a fire involving this material.

*Before 1996, the "Instability" section was entitled "Reactivity". The name was changed because many people did not understand the distinction between a "reactive hazard" and the "chemical reactivity" of the material. The numeric ratings and their meanings remain unchanged.

FIGURE 5.3 Brief description of NFPA symbol system (NFPA, 2005).

ACID	This indicates that the material is an acid—a corrosive material that has a pH lower than 7.0
ALK	This denotes an alkaline material, also called a base. These caustic materials have a pH greater than 7.0
COR	This denotes a material that is corrosive (it could be either an acid or a base).
	This is another symbol used to indicate that a material is corrosive.
	The skull and crossbones symbol is used to denote a poison or highly toxic material.
	The international symbol for radioactivity is used to denote radioactive hazards; radioactive materials are extremely hazardous when inhaled.
	Indicates an explosive material. This symbol is somewhat redundant because explosives are easily recognized by their instability rating.

FIGURE 5.4 Other symbols, abbreviations, and words that some organizations use in the Special Hazards section of Figure 5.3 (note that only those appearing in Figure 5.3 are NFPA 704 approved symbols). The exact guidelines by which you can place a *chemical* in one of these categories are available in the NFPA standard (NFPA, 2005).

Giardia lamblia. Often seen in natural water sources, this parasite is also cystic in nature and enters the body via oral–fecal transmission. The effects of this amoebic infection are severe cramps and diarrhea. The effects have been nicknamed beaveritis or beaver fever from its suspected historical host (many mammals can be a source of this disease, including humans). This can be treated with a course of antibiotics. Recent research has shown that cysts that have passed through UV disinfection in wastewater effluent have become noninfectious (Thompson et al., 2003). Prescription drugs have been used to eliminate infections.

Cryptosporidium. *Cryptosporidium* is a protozoan—a single-celled parasite that lives in the intestines of animals and people. This microscopic pathogen causes a disease

called *cryptosporidiosis*. The dormant (inactive) form of *Cryptosporidium*, called an oocyst, is excreted in the feces (stool) of infected humans and animals. The tough-walled oocysts survive under a wide range of environmental conditions. Infection occurs through oral–fecal contamination. The most common symptom of cryptosporidiosis is watery diarrhea. There may also be abdominal cramps, nausea, low-grade fever, dehydration, and weight loss. Symptoms typically develop 4 to 6 days after infection, but may appear anytime from 2 to 10 days after infection. People with healthy immune systems are typically ill with cryptosporidiosis for several days, but rarely more than 2 weeks. Some infected individuals may not even get sick. Some people with cryptosporidiosis seem to recover, then get worse again. Those who are infected may shed oocysts in their stool for months, even after they no longer appear ill. This infection can be life-threatening to people with compromised immune systems. Cryptosporidia became prominent in the vernacular of water and wastewater workers in the late 20th century, when more than 400 000 people became infected in Milwaukee, Wisconsin, when the rivers flooded out the filters of the water plant and entered the distribution system. There is no drug to cure the disease. The body's immune system alone must fight the infection.

Other Parasites. Tapeworm and roundworm have been found in wastewater, but their prevalence is low compared to other parasites. The former grows generally in the large intestine and is transmitted by eggs. The route of contamination is oral–fecal. Remember that people infected with all of the above-mentioned parasites can pass over 1000 000 eggs or cysts daily in their stool. Roundworm, in various forms, lives in the large intestine and can cause severe cramps and diarrhea. These worms can be controlled and eliminated though prescription drugs.

HEPATITIS. ***Hepatitis A and E.*** These two types of hepatitis are being grouped together in this discussion because of the common methods of infection. Both of these are spread fecal to oral, by touching contaminated material and then touching oral pathways of entry or by drinking contaminated water or eating contaminated food. Hepatitis A is more prevalent in the United States and Canada than Hepatitis E. The latter is more prevalent in Mexico, India, and Africa. Both cause infectious hepatitis (an acute inflammation of the liver). Symptoms can include fatigue, nausea, vomiting, fever and chills, loss of appetite, yellowing of the eyes and skin, and tender liver. Many times, the carrier can be asymptomatic. Infectious hepatitis is an extremely environmentally resistant disease, where the carrier releases 1000 000 000 virions/g feces. It can survive months or years outside of a host. There is a vaccine for prevention of Hepatitis A, and ozone and chlorine can inactivate it. Like Hepatitis A, Hepatitis E never develops into

a chronic or long-term illness, but shares the same symptoms as Hepatitis A. Currently, there is no preventative vaccine developed for Hepatitis E. The Center for Disease Control (Atlanta, Georgia) states that wastewater workers are no more at risk than any other occupation.

Hepatitis B, C, D, and G. The symptoms of these viral infections are much the same as other forms of hepatitis. However, the means of transmission of these infections is bloodborne. This means that the virus must come into contact with blood to cause infection. This can happen through puncture wounds, open sores on the inside of the mouth, and open cuts on hands and other parts of the body. This means that the probability of contacting these diseases as a wastewater worker is less than the previously discussed forms of hepatitis. Some of the infections are long-term or chronic, however, with cirrhosis of the liver and liver cancer being the results of infection. There is a vaccination for Hepatitis B that, many times, is part of a preventive health care program provided by employers and is often provided for free or at low cost in rural counties.

HUMAN IMMUNODEFICIENCY VIRUS. Human Immunodeficiency Virus (HIV) was a shocking discovery in human health over the past 30 to 40 years. People were not recovering from what seemed to be less-than-fatal infections. In fact, their bodies were getting numerous infections simultaneously. It took time to isolate the cause of the disease, commonly called Acquired Immunodeficiency Syndrome. For wastewater workers, it is good to keep in mind that, at times, there could be infectious HIV particles in wastewater. The levels of HIV in wastewater are generally less than levels of polio. It is a bloodborne infectious agent and must enter an open sore and contact blood in sufficient quantity to establish itself (Casson and Hoffman, 1999). Standard safety and hygiene practices should prevent any chance of infection. At this time, there is no cure or vaccine. There are drugs that seem to stabilize the condition in case of infection.

SEVERE ACUTE RESPIRATORY SYNDROME. Severe Acute Respiratory Syndrome (SARS) is a very new infectious agent. It is a viral infection that can survive up to four days in excrement, according to the World Health Organization (2003). There is no known vector of transmission. It is thought to be transmitted by **direct** person-to-person contact through droplets spread when an infected person coughs or sneezes and the droplets are spread to a nearby contact. It probably is not transmitted through a fecal–oral route. In one case, leaking wastewater pipes within a building helped spread the disease. In Taipei (Taiwan), sections of the collection system were

chlorinated as a preventative measure for collection system workers (SARS Prevention, 2003).

LEPTOSPIROSIS. Leptospirosis is a bacterial disease that affects humans and animals. It is caused by bacteria of the genus *Leptospira*. In humans, it causes a wide range of symptoms, although some infected persons may have no symptoms at all. Symptoms of leptospirosis include high fever, severe headache, chills, muscle aches, and vomiting and may include jaundice (yellow skin and eyes), red eyes, abdominal pain, diarrhea or a rash. If the disease is not treated, the patient could develop kidney damage, meningitis (inflammation of the membrane around the brain and spinal cord), liver failure, and respiratory distress. In rare cases, death occurs. The risk of transmission of this disease through wastewater now seems minimal, but it has been considered a risk for collection system workers.

AEROSOLS. With the use of activated sludge as a standard treatment process, the wastewater worker walks above and around a cauldron of airborne aerosols. These aerosols may contain bacterial and viral infectious agents, and infections may result from contact with these aerosol mists. It is impossible to eliminate all sources of aerosol contamination in a wastewater treatment plant. Particle masks may help where there is heavy misting and could be part of PPE for those conditions. Aerosols settling on clothes are another infection vector. A good safety practice is to change clothes before leaving the facility so that possible infectious agents are not transported away from the site. Good personal hygiene practices and a health protection immunization program lower the risk of infection. Another practice that typically only larger plants can afford is to examine the processes used and analyze air samples to see if certain areas are higher risk areas, and then devise a PPE program and engineering practices to lower the risk. Otherwise, in areas where this is not affordable, the manager can consider possible risks and see which ones can be eliminated. Airborne infectious agents typically are not inhaled in a large enough number to be sufficient to cause infection (Kuchenrither et al., 2002).

PERSONAL HYGIENE AND HEALTH PROTECTION. This is an easily overlooked and highly effective method of protecting your health. Children are taught to wash their hands before putting anything into their mouths. The same applies to wastewater professionals. This very simple practice can eliminate some infectious agents before they come into contact with routes of infection. Washing hands thoroughly before eating, putting a cigarette in the mouth or eyedrops in the eyes, or blowing the nose lowers the chance of infectious agents reaching the mucous

membrane. The following are personal hygiene and PPE guides that would lower workers' possible exposure:

- Keep hands and fingers away from eyes, nose, mouth, and ears.
- Wear rubber gloves when cleaning screenings, pumps, process sludges, grit, and wastewater or when doing any task that involves direct contact with wastewater or solids. Use gloves that are appropriate for the task (e.g., light nitrile or latex gloves—be careful of allergic reactions to latex—for sampling and heavier gloves for pump repairs).
- Always wear impervious gloves when the skin is chapped and burned or when the skin is broken or has open cuts and sores.
- Wash hands with warm water and soap thoroughly before eating, smoking, and after work. If there are no facilities available for this (small rural systems), use no-rinse antiseptic soaps. Remember, the steering wheel of an automobile can be a great place for the growth of microbes.
- Keep fingernails short and remove foreign material from underneath them with a stiff soapy brush.
- Store clean clothes in a locker and change before leaving the worksite. The locker should be separate from the one where work clothes are stored.
- Report all cuts and scratches and receive first aid for them. Clean them thoroughly.
- Shower before leaving work, if possible.
- When working in an area that will have a splashing hazard where microbial hazards may come into contact with the eyes, wear safety goggles or face shields.
- Always wear PPE where applicable. There should be some determination of what PPE is necessary by a safety committee or officer, and it is important to adhere to this. Again, there should be training for employees regarding microbial hazards in the workplace.
- Consider immunizations for common diseases. Table 5.2 shows a standard immunization program. Some employers pay for all of these, and others may pay for some of these.

As mentioned previously, there are many simple things that can be done to keep workers safe. While these hazards are present in the work environment, some prevention is common sense. If a person is constantly stressing the body by staying up late, then the immune response of the body decreases. Poor nutrition, cigarette smoking, and obesity will also decrease the immune response of the body. Lowering personal

TABLE 5.2 A standard immunization program.

Infection	Immunization
Hepatitis A	Immunoglobulin treatment
Hepatitis B	Three immunoglobulin vaccinations in a complete cycle
Influenza	Annual flu vaccines
Measles	Combined measles, mumps, and rubella (MMR) vaccines
Mumps	MMR vaccines
Rubella	MMR vaccines
Tetanus and diptheria	TD vaccine
Pnuemoccal disease	Pnuemococcal polysaccharide disease

risk factors outside the workplace will help the body's immune response. "Workers with a weak immunity system continually get sick and leave the job. According to WRRC (2001), those who stay have a good immune system and continue working. Normal precautions may be sufficient for those workers who can adjust to the work environment." There does seem to be evidence that a person who works in wastewater treatment for fewer than 2 years is more likely to suffer gastrointestinal illness more often than seasoned veterans. Also, the sanitary conditions found at the plant and among workers do have an effect on health (Kuchenrither et al., 2002). Generally, however, cancer, airborne risks, and pathogen risks do not seem to be increased by the work environment after the initial work period.

CONFINED SPACES

A confined space is a hazard that wastewater workers encounter with great regularity. Wastewater professionals are very familiar with confined spaces, such as manholes or storage tanks, but often overlook simple regular tasks in confined spaces, such as cleaning aerators in aeration basins, hosing down clarifiers, or even working in the subfloors of a building. A confined space is an accessible area with at least one of the following three conditions:

(1) Limited entrance and egress. There is typically one way in or out of the space.
(2) Unfavorable neutral ventilation (stale air). This is the most overlooked condition for a confined space.
(3) A design that allows for limited occupancy. The design for the area is one that really is not made for continual occupancy.

Many deaths, injuries, and job-related illnesses in the wastewater treatment industry result from occupancy in confined spaces or from hazards found in these spaces, such as toxic gases, oxygen deficiency, or engulfment. The following sections discuss some of the characteristics of confined spaces and the necessary precautions in more detail.

LIMITED ENTRY AND EGRESS. Confined spaces are limited by the entry and exit, by either size or location. Openings are typically small. Some openings are smaller than the standard 610-mm (24-in.) manhole openings. They are difficult to move through and pose a particular hazard if there is the need for an emergency retrieval. If a person must contort the body to get into the opening, getting an unmoving and uncooperative body out is even more difficult. It would not be unusual to have PPE, such as a respirator, hard hat, face shields, or SCBA, dislodged by the small opening. Keep in mind, not all confined spaces are defined by small openings, but could be aeration basins, digesters, or clarifiers that are difficult to enter or exit. Open top spaces could be excavations or the previously mentioned ones and would require a ladder or hoists to enter or exit. Being rescued from areas like this may be easier than from small openings, but require specialized equipment and at least one spotter or helper.

VENTILATION HAZARDS. A ventilation hazard may as simple as stale air or oxygen deficiency but can also be dangerously high levels of gases, such as hydrogen sulfide, carbon monoxide, or even carbon dioxide. There also can be explosive gases in the confined space. These can be particularly dangerous in areas such as manholes or lift stations, when a worker has no control or advance notice of the problem. The atmosphere may be so oxygen-rich that it also becomes a hazard. Later in this section, some of the more common gases will be defined and their hazards will be listed.

LIMITED OCCUPANCY. Most confined spaces not only have limited access, but are not designed to have continuous occupancy. They are designed, at best, to have short-term occupancy for maintenance or repair, cleanup, or similar tasks. These tasks are often dangerous because of the chemical or physical hazards they can pose, often in a limited-visibility situation.

Hazards. The following are hazards that may be found in a confined space:

- Oxygen-deficient atmosphere. If the oxygen content is or drops below 19.5%, a worker should avoid entering a confined space or should leave that space

immediately. Use of an oxygen sensor is necessary when entering a confined space and should be worn while in that space. Entry to an oxygen-deficient atmosphere should not be attempted without SCBA.

- Flammable atmosphere. There may be methane present from the decomposition of organic materials, or someone may pour flammables, such as gasoline, down the sewer. Any ignition source could cause an explosion or start a fire in such an atmosphere. There may be times when the upper explosive limit (UEL) of a flammable gas is exceeded before ventilation is applied. This means that the gas will not combust. When ventilation is applied, it could then be explosive. Monitoring while in the combined space by a gas monitor is a good practice for these reasons.
- Toxic atmosphere. Some gases and vapors, if present in a confined space, may be toxic, even if not flammable. The atmosphere inside a confined space may change while a person is working in it. There have been times when the atmosphere inside a confined space was above the UEL and the space was ventilated, which, in actuality, brought the working conditions in the space to a greater hazard limit as the concentration of the gas decreased to below the UEL. Fumes from equipment that is used may accumulate in the space (i.e., carbon monoxide from a combustion engine on a pump), or cleaning chemicals being used may give off vapors.
- Temperature extremes. Extremely hot or cold temperatures in a confined space can affect or injure workers. Again, temperatures may rise or fall while working in a confined because of equipment being used. Because of the chance of smaller air exchange through smaller entrances, temperatures can stay warmer or colder for long periods of time.
- Engulfment hazards. Materials stored in a bin or hopper can engulf or suffocate a worker. Chemicals, grain, and sand are typically stored in hoppers. If a worker is in an area such as the bottom of a clarifier or digester or pumping station, he or she should be sure that some sort of lockout/tagout (discussed later in this chapter) is used to ensure that fluid cannot engulf him or her.
- Noise. A confined space is a great echo chamber. When a person is in a confined space and the sound can do nothing other than assault a person's hearing, damage could occur. The sound can come from either inside or outside of the chamber and impair speech or drown out shouting.
- Slick or wet surface. Confined spaces often have a wet surface, which can be slippery and dangerous for maneuvering within it.
- Falling objects. It is important to be aware of the possibility of objects entering a confined space and falling on someone. This could be as simple as a person

walking by and unknowingly kicking a rock into the hole or unsafely throwing tools into and out of the hole. Use common sense and a rope and a bucket for such operations.

Precautions. The following are safe work practices that are recommended before entering a confined space:

- Air monitoring. More precisely, this should be called *atmosphere monitoring*. First, the air is sampled with an oxygen sensor. There must be a minimum of 19.5% oxygen present before a person can go into the space. The worker should be sure the oxygen is measured at the levels he or she must pass through and the level where he or she will be working. There can be a stratification of gases caused by poor ventilation that could be oxygen-deficient. A gas monitor should always be used to check for the presence of explosive or deadly gases. Most four-gas detectors monitor for oxygen, combustibles, carbon monoxide, and hydrogen sulfide; however, with plug-in modules now available, some of these can be reconfigured to sample other gases. Air monitors must routinely be calibrated and tested with "bump gas" per manufacturer specifications. When working within a confined space, a worker should wear a portable detector to monitor atmospheric conditions and possible deadly changes. The oxygen sensor/broad-range sensor is best-suited for initial use in situations where the actual or potential contaminants have not been identified because broad-range sensors, unlike substance-specific sensors, enable employers to obtain an overall reading of the hydrocarbons (flammables) present in the space. However, such sensors only indicate that a hazardous threshold of a class of chemicals has been exceeded. They do not measure the levels of contamination of specific substances. Therefore, substance-specific devices, which measure the actual levels of specific substances, are best-suited for use where actual and potential contaminants have been identified.
- Ventilation. The confined space should have general ventilation or localized exhaust ventilation in place before entry and during occupancy. It is important to be sure that the air being used to ventilate the space is not pulling in toxic fumes from the outside (diesel fuel, gasoline vapors, etc.).
- Personal protective equipment. Respiratory equipment is essential for safe confined space entry. If a worker can be sure that the atmosphere is safe and that there is little chance it will change, PPE may not be necessary. If an oxygen-deficient atmosphere exists, workers will need to wear a SCBA. If the space cannot be entered while the worker is wearing the SCBA, equipment supplying forced

outside air or escape respirators may be used (such as a self-rescuer for mining). Workers need to be fit-tested for a respirator or an SCBA before using one, and workers with beards cannot wear one. It is important to remember that air-purifying respirators may only filter out or neutralize certain contaminants at specific concentrations. Atmospheres with oxygen concentrations that are either too high or too low cannot be made safe by using air-purifying respirators. Workers' questions should be directed to their supervisor or industrial hygienist.

- Labeling and posting. In a work environment, all confined-space entrances should be posted. The labels should clearly be marked so that all employees can understand them.
- Training. As with chemical hazards, all workers who must work around confined spaces need routine training, including knowing how to identify confined spaces, use air analyzers, and define permit-required spaces. They should be familiar with rescue procedures and communication in confined work spaces and complete lockout/tagout training and attendant training. Periodic follow-up training is recommended to reinforce safe work practices. This training should be evaluated to make sure that it is effective and current (a video that has been shown to workers multiple times will lose its effectiveness).
- Medical surveillance. Employees who must use a SCBA respirator to work in a confined space to perform their duties need to have their lung capacities checked annually and obtain medical clearances in addition to completing annual fitness tests.
- Isolation. The supervisor for any confined-space entry must be aware of any hazards that may exist. It is the supervisor's responsibility to lock up any lines and valves that may cause engulfment hazards. Also, electrical lockout/tagout procedures need to be followed. If an entrant notices any possible hazards that were not covered, he or she should communicate them to the supervisor.
- Attendant. Any time there is a confined-space entry, there should be an attendant whose sole duty is to communicate with entrants and make sure that they are not in danger. This may mean using a common sign language or radios (if the entrant gets out of the line of sight). It is also the attendant's responsibility to bring the entrant out using a harness and tripod if there are problems. This means the attendant cannot be performing traffic control, wandering off, or talking on the cell phone. The person below trusts the attendant with his or her life. No one should ever follow a collapsed fellow worker into a confined space. Often, there has been a rapid change of atmosphere that has caused the worker to collapse; when another worker enters the same atmosphere, he or she has just removed the victim's chance of rescue.

- Tripod and harness. The person entering a confined space should wear a harness. There are too many variations of harnesses to list; the best source for viewing them would be safety catalogs. An effective harness should allow the person being removed to be lifted straight up out of the confined space without forcing their head and neck to awkward angles. Harnesses should be comfortable to work in. One size does not fit all. Often, safety supply companies will allow customers to try on their stock before purchase to see if it works for the individuals. Tripods or lifting cranes are again varied and depend on the application. The tripod that fits over a manhole will not work to pull someone safely out of a deep clarifier or digester. There are even lifts designed to fit into mounts on bumpers of wastewater service vehicles for sewer lines. Maintenance of equipment and practice are essential to getting someone out of a dangerous situation safely.
- Procedures. There should be written procedures (typically in the form of a checklist) to be completed before entry to a confined space. When these procedures are followed and completed, the chances of injury decrease. A sample checklist will follow in this chapter. These procedures must be practiced. A life-or-death situation is no time to find out that something is not understood or that some procedures have been bypassed.

PERMIT-REQUIRED VERSUS NON-PERMIT-REQUIRED CONFINED SPACES. There is a distinct difference between these types of confined spaces. A permit-required confined space is one that meets the definition of a confined space and has one or more of the following characteristics:

- Contains or has the potential to contain a hazardous atmosphere,
- Contains a material that has the potential for engulfing an entrant,
- Has an internal configuration that might cause an entrant to be trapped or asphyxiated by inwardly converging walls or by a floor that slopes downward and tapers to a smaller cross section, and/or
- Contains any other recognized serious safety or health hazards.

It is the on-site supervisor's responsibility to determine whether the space is a permit-required confined space. To comply with OSHA Title 29 *CFR* Part 1910.146 (Permit Required Confined Spaces, 2005) (the rules that govern confined spaces), entry to a permit-required confined space requires that certain actions be performed by the employer**:**

- Follow the general requirements of paragraph (c) of the standard;
- Have a permit-required confined-pace program that complies with paragraph (d) of the standard;

- Follow the permit system requirements of paragraph (e) of the standard;
- Complete the entry permit as required in paragraph (f);
- Comply with employee training requirements of paragraph (g);
- Ensure that authorized entrants, attendants, and entry supervisors know their responsibilities as required in paragraphs (h), (i), and (j);
- Provide for rescue and emergency services as stated in paragraph (k); and
- Ensure that employees are allowed participation in these processes as required in paragraph (l) of the standard.

In general, employers must evaluate the workplace to determine if spaces are permit-required confined spaces (see Figure 5.5). If there are permit-required confined spaces in the workplace, the employer must inform exposed employees of the existence, location, and danger posed by the spaces. This can be accomplished by posting danger signs or by another equally effective means. If employees are not to enter and work in permit-required confined spaces, employers must take effective measures to prevent their employees from entering them. If employees are expected to enter these spaces, employers must comply with all requirements of the OSHA standard.

Requirements of a Written Program. If the employer allows employee entry to a permit-required confined space, a written program must be developed and implemented. Among other things, the OSHA standard requires the employer's program to do the following:

- Identify and evaluate permit space hazards before allowing employee entry.
- Test conditions in the permit space before entry operations and monitor the space during entry.
- Perform, in the following sequence, appropriate testing for atmospheric hazards: oxygen, combustible gases or vapors, and toxic gases or vapors.
- Implement necessary measures to prevent unauthorized entry.
- Establish and implement the means, procedures, and practices (such as specifying acceptable entry conditions, isolating the permit space, providing barriers, verifying acceptable entry conditions, purging, making inert flushing, or ventilating the permit space) to eliminate or control hazards necessary for safe permit-space entry operations.
- Identify employee job duties.
- Provide, maintain, and require the use of PPE and any other equipment necessary for safe entry (e.g., testing monitoring, ventilation, communications, lighting equipment, barriers, shields, and ladders).

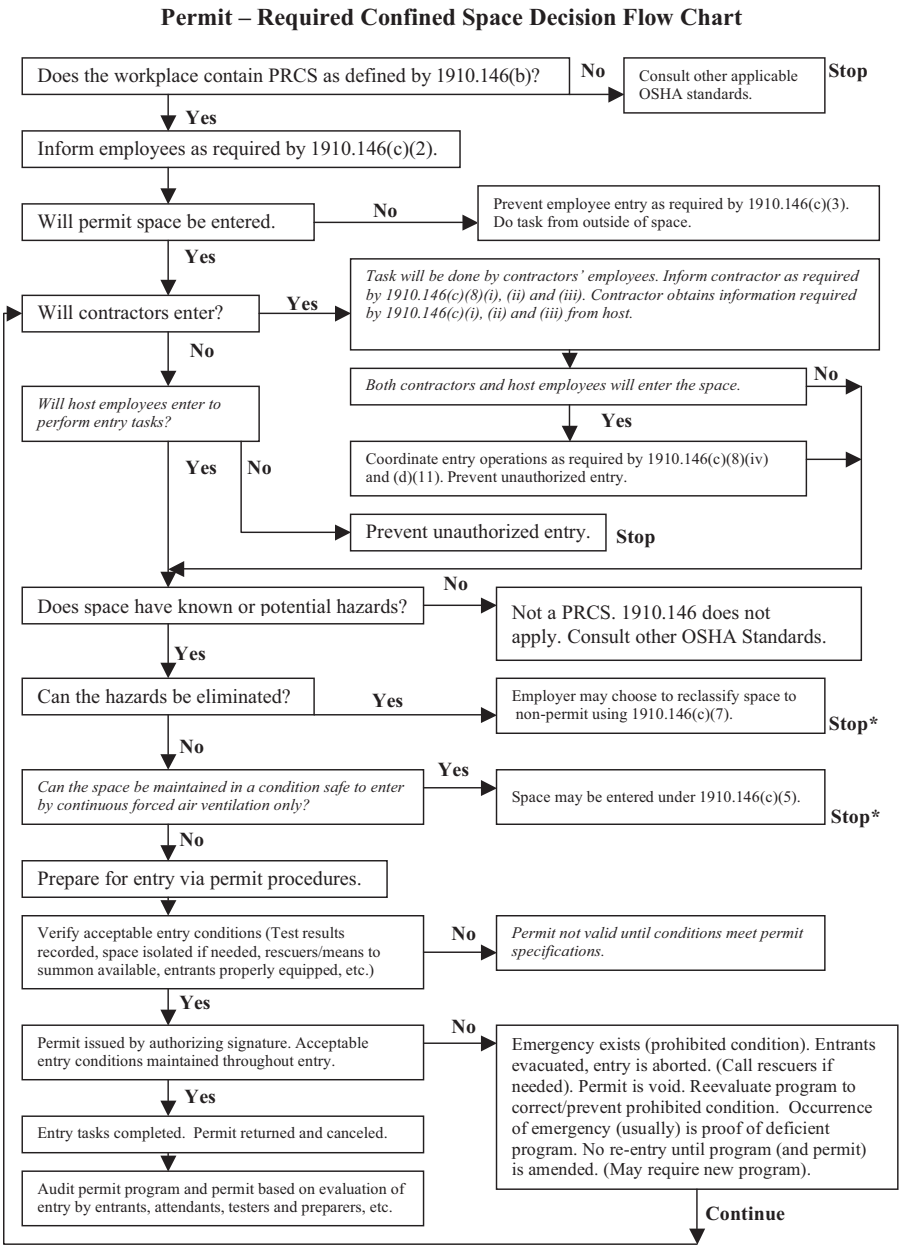


FIGURE 5.5 Permit-required confined space (PRCS) decision flowchart (http://www.cehs.siu.edu/occupational/confined_space/flowchart.htm; accessed March 2006).

- Ensure that at least one attendant is stationed outside the permit space for the duration of entry operations.
- Coordinate entry operations when employees of more than one employer are to be working in the permit space.
- Implement appropriate procedures for summoning rescue and emergency services.
- Establish, in writing, and implement a system for the preparation, issuance, use, and cancellation of entry permits.
- Review established entry operations and annually revise the permit space entry program.
- When an attendant is required to monitor multiple spaces, implement the procedures to be followed during an emergency in one or more of the permit spaces being monitored.

If hazardous conditions are detected during entry, employees must immediately leave the space, and the employer must evaluate the space to determine the cause of the hazardous conditions.

When entry to permit spaces is prohibited, the employer must take effective measures to prevent unauthorized entry. Non-permit-required confined spaces must be reevaluated when there are changes in their use or configuration and, where appropriate, must be reclassified.

Contractors also must be informed of permit spaces and permit space entry requirements, any identified hazards, the employer's experience with the space (i.e., the knowledge of hazardous conditions), and precautions or procedures to be followed when in or near permit spaces.

When employees of more than one employer are conducting entry operations, the affected employers must coordinate entry operations to ensure that affected employees are appropriately protected from permit space hazards. Contractors also must be given any other pertinent information regarding hazards and operations in permit spaces and be debriefed at the conclusion of entry operations.

Permit System. A permit, signed by the entry supervisor and verifying that preentry preparations have been completed and that the space is safe to enter, must be posted at entrances or otherwise made available to entrants before they enter a permit space.

The duration of entry permits must not exceed the time required to complete an assignment. Also, the entry supervisor must terminate entry and cancel permits when an assignment has been completed or when new conditions exist. New conditions must be noted on the canceled permit and used in revising the permit space program.

The standard also requires the employer to keep all canceled entry permits for at least one year.

Entry Permits. Entry permits must include the following information (Figure 5.6):

- Test results.
- Tester's initials or signature.
- Name and signature of supervisor who authorizes entry.
- Name of permit space to be entered, authorized entrants, eligible attendants, and individuals authorized to be entry supervisors.
- Purpose of entry and known space hazards.
- Measures to be taken to isolate permit spaces and eliminate or control space hazards (i.e., locking out and tagging of equipment and procedures for purging, making inert, ventilation, and flushing permit spaces).
- Name and telephone numbers of rescue and emergency services.
- Date and authorized duration of entry.
- Acceptable entry conditions.
- Communication procedures and equipment to maintain contact during entry.
- Additional permits, such as for hot work, that have been issued to authorize work in the permit space.
- Special equipment and procedures, including PPE and alarm systems.
- Any other information needed to ensure employee safety.

Training and Education. Before the initial work assignment begins, the employer must provide proper training for all workers who are required to work in permit spaces. Upon completing this training, employers must ensure that employees have acquired the understanding, knowledge, and skills necessary for the safe performance of their duties. Additional training is required when the following occur:

- Job duties change,
- There is a change in the permit space program or the permit space operation presents a new hazard, and
- An employee's job performance shows deficiencies.

Upon completion of training, employees must receive a certificate of training that includes the employee's name, signature or initials of trainer, and dates of training. The certification must be made available for inspection by employees and their authorized representatives. In addition, the employer also must ensure that employees are trained in their assigned duties.

Confined Space Entry Permit

Date and Time Issued _____ Date and Time Expires _____
Job Supervisor _____ Job Location _____
Equipment to be entered _____
Work to be performed _____

Isolation and Lockout /Tagout
•Pumps /Lines Blinded, Disconnected or Blocked _____Yes _____ No _____ N/A
•All Energy Sources Locked out/ Tagged out _____ Yes _____ No _____N/A

Ventilation_____ Mechanical _____ Natural _____ N/A _____
Monitoring/Atmosphere Testing

•Oxygen _____ 19.5% to 23.5%
•Flammable/Combustible _____ % LEL
•Toxics - Hydrogen Sulfide _____ PPM
- Sulfur Dioxide_____ PPM
- Chlorine _____ PPM
- Other(s) _____
Meter Calibrated _____Yes _____No _____ Date _____ SN

_____ _____
Tester Signature **Time**
Continuous Monitoring _____ Yes _____ No_____N/A
Communication Procedure _____
Rescue Procedure _____
Emergency Phone Number _____
Entry Watch/Standby Person _____
Equipment /PPE

•Safety Harness and Lifeline	Yes	No	N/A
•Hoisting/Retrieval Equipment	Yes	No	N/A
•Lighting (12 volt or GFI)	Yes	No	N/A

•Protective Clothing _____
•Respiratory Protection
Period Monitoring/Atmosphere Testing

Oxygen	Flammable	Toxic(s)		Initials
Time				
Time				
Time				
Time				
Time				

Permit Approved/Issued By: _____

(a)

FIGURE 5.6 (a) Sample permit and (b) entrants' log.

Entrants Log

Name	In	Out	In	Out	In	Out

(a)

FIGURE 5.6 (a) Sample permit and (b) entrants' log.

Authorized Entrant's Duties. The following are duties of the authorized entrant:

- Know space hazards, including information on the mode of exposure (e.g., inhalation or dermal absorption), signs or symptoms, and consequences of the exposure;
- Use appropriate PPE properly;
- As necessary, maintain communication with attendants to enable the attendant to monitor the entrant's status and to alert the entrant to evacuate;
- Exit from permit space as soon as possible when ordered by an authorized person, when the entrant recognizes that the warning signs or symptoms of exposure exists, when a prohibited condition exist, or when an automatic alarm is activated; and
- Alert the attendant when a prohibited condition exists or when warning signs or symptoms of exposure exist.

Attendant's Duties. The following are duties of the attendant:

- Remain outside permit space during entry operations unless relieved by another authorized attendant.

- Perform non-entry rescues when specified by employer's rescue procedures.
- Know existing and potential hazards, including information on the mode of exposure, signs, or symptoms; consequences of the exposure; and their physiological effects.
- Maintain communication with and keep an accurate account of those workers entering the permit-required space.
- Order evacuation of the permit space when a prohibited condition exists, when a worker shows signs of physiological effects of hazard exposure, when an emergency outside the confined space exists, and when the attendant cannot effectively and safety perform required duties.
- Summon rescue and other services during an emergency.
- Ensure that unauthorized persons stay away from permit spaces or exit immediately if they have entered the permit space.
- Inform authorized entrants and entry supervisor of entry by unauthorized persons.
- Perform no other duties that interfere with the attendant's primary duties.

Entry Supervisor's Duties. The following are duties of the entry supervisor:

- Know space hazards, including information on the mode of exposure, signs, or symptoms and consequences of exposure;
- Verify emergency plans and specified entry conditions, such as permits, tests, procedures, and equipment before allowing entry;
- Terminate entry and cancel permits when entry operations are completed or if a new condition exists;
- Take appropriate measures to remove unauthorized entrants; and
- Ensure that entry operations remain consistent with the entry permit and that acceptable entry conditions are maintained.

Emergencies. The standard (OSHA Title 29 *CFR* Part 1910.146) requires the employer to ensure that rescue service personnel are provided with and trained in the proper use of personal protective and rescue equipment. All rescuers must be trained in first aid and cardiopulmonary resuscitation (CPR) and, at a minimum, one rescue team member must be currently certified in first aid and CPR. The employer also must ensure that practice rescue exercises are performed yearly and that rescue service personnel are provided access to permit spaces so that they can practice rescue operations. Rescuers also must be informed of the hazards of the permit space.

Also, where appropriate, authorized entrants who enter a permit space must wear a chest or full-body harness with a retrieval line attached to the center of their backs

near shoulder level or above their heads. Also, the employer must ensure that the other end of the retrieval line is attached to a mechanical device or to a fixed point outside the permit space. A mechanical device must be available to retrieve personnel from vertical-type permit spaces more than 1.5 m (5 ft) deep.

In addition, if an injured entrant is exposed to a substance for which a MSDS or other similar written information is required to be kept at the worksite, that MSDS or other written information must be made available to the medical facility treating the exposed entrant.

This all may seem rather daunting, particularly in small systems, where there are one or two operators only. In situations like this, it is good practice to know the employees of surrounding towns and learn how to cooperate with them. With proper planning, two or three small communities may pool employees and do work that requires confined space entrance as a team, thereby staying within best safety practices, even in towns that have too few employees to be covered by OSHA regulations. This lowers any liability that may be faced by the employer.

Confined Space Regulations for Collection System Workers. Sewer entry differs in the following three vital respects from other permit entries: (1) there rarely exists any way to completely isolate the space (a section of a continuous system) to be entered; (2) because isolation is not complete, the atmosphere may suddenly and unpredictably become lethally hazardous (toxic, flammable, or explosive) from causes beyond the control of the entrant or employer; and (3) experienced sewer workers are especially knowledgeable in entry and work in their permit spaces because of their frequent entries. Unlike other occupations where permit space entry is a rare and exceptional event, sewer workers' typical work environment is a permit space. The following is a synopsis of 1910.146 Appendix E for sewer system entry (Permit Required Confined Spaces, 2005).

- Adherence to procedure. The employer should designate as entrants only employees who are thoroughly trained in the employer's sewer entry procedures and who demonstrate that they follow these entry procedures exactly as prescribed when performing sewer entries.
- Atmospheric monitoring. Entrants should be trained in the use of and be equipped with atmospheric monitoring equipment that sounds an audible alarm, in addition to its visual readout, whenever one of the following conditions are encountered: oxygen concentration less than 19.5%; flammable gas or vapor at 10% or more of the lower flammable limit; or hydrogen sulfide or carbon monoxide at or above 10 or 35 mg/L (10 or 35 ppm), respectively, measured as an 8-hour,

time-weighted average. Atmospheric monitoring equipment should be calibrated according to the manufacturer's instructions

- Although OSHA considers the information and guidance provided above to be appropriate and useful in most sewer entry situations, the agency emphasizes that each employer must consider the unique circumstances, including the predictability of the atmosphere, of the sewer permit spaces in the employer's workplace when preparing for entry. Only the employer can decide, based on his or her knowledge of and experience with permit spaces in sewer systems, what the best type of testing instrument may be for any specific entry operation.
- The selected testing instrument should be carried and used by the entrant in sewer line work to monitor the atmosphere in the entrant's environment, and in advance of the entrant's direction of movement, to warn the entrant of any deterioration in atmospheric conditions. If several entrants are working together in the same immediate location, one instrument, used by the lead entrant, is acceptable.
- Surge flow and flooding. Sewer crews should develop and maintain liaison, to the extent possible, with the local weather bureau and fire and emergency services in their area so that sewer work may be delayed or interrupted and entrants withdrawn when sewer lines might be suddenly flooded by rain or fire suppression activities or when flammable or other hazardous materials are released into sewers during emergencies by industrial or transportation accidents.
- Special equipment. Entry to large bore sewers may require the use of special equipment. Such equipment might include such items as atmosphere-monitoring devices with automatic audible alarms, escape self-contained breathing apparatus with at least a 10-minute air supply (or other NIOSH approved self-rescuer), and waterproof flashlights, and may also include boats and rafts, radios, and rope stand-offs for pulling around bends and corners as needed.

TRENCHING AND EXCAVATION SAFETY

This issue is one that is faced by collection system workers primarily and not by plant workers. However, because more than 60 deaths were caused in 2004 by trench collapses, it is worth mentioning. A trench or excavation is any digging that removes soil (a trench, by definition, is any excavation with a bottom less than 4.6 m [15 ft] wide.) Remember that soil is very heavy; 0.76 m^3 (27 cu ft) can weigh over 1400 kg (1.5 tons). As soil is removed from a ditch, the weight of the soil at the edge of the ditch presses against the ditch and can cause it to collapse. Any exposed trench face over 1.5 m (5 ft) in depth needs to be either shored or sloped back to prevent cave-in. Materials used for

trench boxes, sheeting, sheet piling, bracing, shoring, and underpinning should be in good condition and should be installed so that they provide support that is effective to the bottom of the trench. Timber must be sound and free from large or loose knots. Vertical planks in the bracing system should be extended to an elevation no less than 0.3 m (1 ft) above the top of the trench face. Inspections of cribbing, bracing, shoring, or slopes in the surrounding area must be performed at least daily. Be mindful that changing weather conditions may drastically change the soil's stability. It is the supervisor's responsibility to ensure that all workers on the crew are provided with a safe work area.

Rainfall and accumulating water present another hazard to workers. Employees must exit trenches during rainstorms. The trench area should be reinspected after a rain event. Protective measures, such as surface ditches to limit runoff, can be useful tools. When there is standing water in the trench, it should be removed using pumps. These need to be monitored by a competent person. Safety harnesses and lifelines should be used (in accordance with 29 *CFR* 1926.104 [Safety Belts, Lifelines, and Lanyards, 2005]).

Another hazard that seems obvious and has not yet been mentioned is falling into the excavation. Workers must be careful around an excavation, making sure not to stand too close the edge. It is important to be aware of slipping or tripping hazards.

Pedestrians must be kept away from excavations and trenches so that they do not get injured by falling or being hit by equipment. All excavations must be protected to prevent pedestrian traffic near the excavation site. Examples of minimally acceptable protection may include cyclone fencing, complete barricading, or OSHA standard railings around the entire site. Protection should be placed well away from the excavation or trench, if at all possible. Plastic barricade tape at the edge of an excavation is *not* acceptable site protection. Accident prevention warning signs or flashing barricades should also be placed adjacent to excavations.

When employees are required to be in trenches that are 1.2 m (4 ft) or more in depth, an adequate means of exit, such as a ladder or steps, must be provided and located so that no more than 7.6 m (25 ft) of lateral travel is required for a person to reach the exit structure. The trench should be braced and shored during excavation and before personnel are allowed entry. Cross braces and trench jacks should be secured in true horizontal positions and spaced vertically to prevent trench wall material from sliding, falling, or otherwise moving into the trench. Portable trench boxes (also called *sliding trench shields*) or safety cages may be used to protect employees instead of shoring or bracing. When in use, these devices must be designed, constructed, and maintained in a manner that will provide at least as much protection as shoring or bracing, and extended to a height of no less than 150 mm (6 in.) above the vertical face of the trench.

During the backfill operation, it is important to backfill and remove trench supports together, beginning at the bottom of the trench. Jacks or braces should be released

slowly and, in unstable soil materials, ropes should be used to pull them from above after employees have left the trench.

It is up to the supervisor or inspection engineer (legally, the competent person) to determine the soil classification. This is important because the soil classification determines the slope necessary for the trench or excavation. All previously disturbed soil is automatically classified as either Class B or Class C soil. If an excavation occurred to either replace or repair pipe, it is typically classified as Class C soil.

There are basic manual tests to be run by a competent person to determine the soil class. If a person pushes his or her thumb into the edge of the trench and it goes no further than the nail, it is probably Class B soil. If cracks are seen in the soil, it should be treated as class C soil. Bulging, sloughing, or water seepage, and excessive vibration from area traffic make the soil Class C also. If dry soils crumble freely, they are probably Class C soils; however, if they break into clumps, they have enough clay content to be Class B soils. If a moist soil sample can be rolled into a 0.318-mm (0.125-in.) thread approximately 50 mm (2 in.) long and it breaks, then the soils is probably Class B.

The soils classification defines how slopes at the edges of trenches and excavations may be made. If the soil is Class B, then a 1:1 slope on the edge of the trench or excavation is allowed. Class B soils may also be benched every 1.2 m (4 ft). A Class C soil cannot be benched and must have a 1:1.5 slope (34-degree angle from the bottom). This means much more excavation for safe working conditions. It is important to keep in mind that spoils must be kept back at least 0.6 m (2 ft) from the edge of the excavation.

One other factor not yet mentioned is the necessity of locating underground utilities before digging. It is common to see underground utilities torn up because they were either not located properly, or disregarded. In one case, a backhoe hit both an underground propane line and electrical line. What saved the operator was that the propane was so concentrated that it was above the UEL when the electrical lines were sparking. Locating utilities typically is included as part of the process of obtaining a permit for the excavation or trench. It is important to always check to see if a permit is needed, because some permits require specific safety requirements.

The atmosphere inside a trench should be routinely monitored for oxygen and explosive gases. Using a four-gas monitor as if the trench were a confined space is a good work practice. There are times a trench can become filled with exhaust fumes without the worker in the trench really noticing it because the change is so gradual.

LADDER SAFETY

Closely related to excavation safety is ladder safety. Typically, there are not that many uses for ladders in the wastewater field, except as ingress and egress from

trenches and excavations. Other uses are getting into storage areas, confined spaces, aeration basins, clarifiers, and digesters for maintenance and repair. Ladders leading to storage tanks may also be a common use. Falls are one of the most frequent causes of compensation injuries. The following is a list of safe practices to follow when using ladders; some of these standards are found in the OSHA Construction Standards (29 *CFR* 1926):

- Ensure that all ladders are equipped with approved safety shoes.
- Place the ladder so that the horizontal distance from its foot to the support it rests against equals one-fourth the length of the ladder.
- Do not allow working or standing upon the top two rungs of the ladder.
- **Never** splice two short ladders together.
- Never place a ladder against an unsafe support.
- Ensure that the ladder feet rest upon stable support. If the ladder feet are placed upon a platform, make sure that the ladder cannot slide or move off of the platform.
- Do not use ladders as scaffold platforms.
- Whenever possible, tie off the top of a straight ladder to a firm support.
- Ensure that a person holds a stepladder stable whenever someone is working at a height of 3 m (10 ft) or more.
- Make sure that any stepladder being use has its legs fully spread.
- When working near electrical lines, always use a nonconductive ladder.
- Avoid using stepladders as straight ladders.
- Extend stepladders at least 0.9 m (3 ft) above the top of the work platform to allow easy and safe ingress and egress.
- Routinely inspect ladders to make sure that they are in proper working order with no cracked or broken supports or steps.
- There should be a sticker on the ladder stating the weight limit on the ladder.
- Extension ladder sections must overlap. There should be a 0.9-m (3-ft) overlap in ladders up to 10 m (32 ft) long, 1.2 m (4 ft) for ladders 10 to 14 m (32 to 48 ft), and 1.5 m (5 ft) in ladders 14 to 18 m (48 to 60 ft).
- Always have three-point contact with the ladder (i.e., one hand and two feet).
- Never climb a ladder carrying tools. They should be put in a tool belt or lifted using a rope and bucket once the worker is at the desired height.
- If possible, use a fall protection system fastened to a secure place.
- Do not use a ladder on a windy day.
- Never leave a set-up ladder unattended.

LIFTING

Far too many people have back problems as they get older. Many back problems can be prevented by proper lifting. The following are guidelines for lifting that may prevent a lifetime of nagging pain caused by improper lifting:

- Be careful when lifting. The size, shape, weight, and texture can actually change how much can be lifted. A person should lift what can be handled comfortably and get help if needed.
- Look at the surface to be lifted and see if the are any metal of wood slivers protruding from the edges. Make sure the surface is not too rough or too slippery.
- Use solid footing and keep the feet wide enough to provide stability and balance. A sudden jerk from lifting something that is out of balance or unstable can wrench the back and cause a lifetime of problems.
- Move as close to the load as possible and bend your legs at approximately 90 degrees at the knee. Keep the back as straight as possible. Grip the object firmly. Lift by straightening the legs. When lowering the load, reverse the procedure. Do not lift by bending the back over the object and trying to tilt the back into an upright position. This will stress the lower back muscles and discs.
- Do not carry loads that block vision.
- If a worker needs help to lift heavy or awkward objects, he or she should be sure to be coordinated with the other person or persons. Miscommunication when lifting heavy objects as a group can place all the stress of the lift on one person, putting that person's back at risk.
- Keep hands, fingers, and feet away from any points that could expose them to pinching or crushing, especially when setting the object down or going through doorways.
- Make sure the path through which a person will be walking will be clear of oil, grease, and water that may cause a slipping hazard.
- Make sure the package itself is clean and not covered in grease or oil or is wet so that it is less prone to slip out of the hands.

LABORATORY SAFETY

There are many sources of injury and bacteriological contamination in a laboratory. While not all plants have much more than a rudimentary laboratory facility, the following are sound basic safety practices:

- Discard all chipped or cracked glassware. All glassware for disposal should be placed in appropriate containers.

- When using volatile chemicals that may cause an inhalation or atmospheric hazard, only use these under a ventilated hood.
- Store solvents or flammable liquids only in explosion proof cans or in a flammable storage locker. These are available from many suppliers of safety supplies or general contractor supply stores.
- When using acids that react violently with some organic materials (ammonia and nitric, acetic, and perchloric acids), take particular care to avoid possible fire or explosion.
- **Do not handle chemicals with bare hands.** Use gloves, tongs, spatulas, or whatever laboratory equipment may be best suited for the material and application being used.
- Provide an emergency eyewash station and shower in the laboratory. If in the field, make sure that if there is not immediate access to these items, there is an emergency eyewash bottle or two handy.
- Use suction bulbs on all pipettes. **Do not use the mouth.** It is much too easy for a worker to become distracted and ingest whatever substance he or she is trying to pipette, regardless of how practiced the worker may be.
- Wear a rubber apron when working with corrosive chemicals.
- Wear the appropriate face shield or chemical goggles when working with chemicals. Acids or bases in the eyes can cause a complete loss of vision in that eye. Safety glasses should be worn at all times in the laboratory.
- Clearly label all chemical containers, especially if transferring chemicals to smaller, more portable containers for use.
- Wear gloves when making rubber-to-glass connections.
- Properly ventilate to remove fumes and dust.
- Prohibit smoking, drinking, and eating in the laboratory.
- Workers must know where the fire extinguisher is and if it is usable. Routine inspections are necessary.
- Use tongs or insulated gloves to remove samples from hot places, such as hot plates, ovens, or muffle furnaces. Remember that ceramic wear remains hot to the touch for a very long time.
- Adequately shield centrifuges and caloric bombs.
- Make sure electrical outlets are properly grounded. Then make sure all equipment is plugged in properly. The male plug should have the appropriate grounding plug. If it has been removed, have it repaired.
- Thoroughly wash hands before eating, drinking, or smoking.
- Ensure that all laboratory faucets have either air gaps or vacuum breakers to prevent back-siphonage of toxic material to the water system. While this may

not deal particularly with laboratory safety, whenever a faucet is used in an application such as a polymer feeder or chemical feeder, it too should have an appropriate backflow preventer.
- Provide a spill kit for cleanup in case of spills.

FIRE SAFETY

It may seem rather odd to cover fire safety in a wastewater treatment manual, particularly if one is working in the plains and the plant consists mainly of lagoons. There are many places in modern plants where fires can start and spread, and, with the chemicals that can often be found in activated sludge or trickling filter plants, there is a basic need to know some fire safety. Important questions an operator should ask include the following:

- Where are the extinguishers?
- What other fire-retardant systems are in place?
- Have the extinguishers been routinely inspected and are they operational? Old water-type extinguishers, even if improperly maintained, can become shrapnel if used when weakened.
- Has the operator been trained to use them?

Before examining extinguisher types and their uses, it is important to examine the basics of fire or combustibles. The most popular description of combustion, known as the fire triangle, is shown in Figure 5.7.

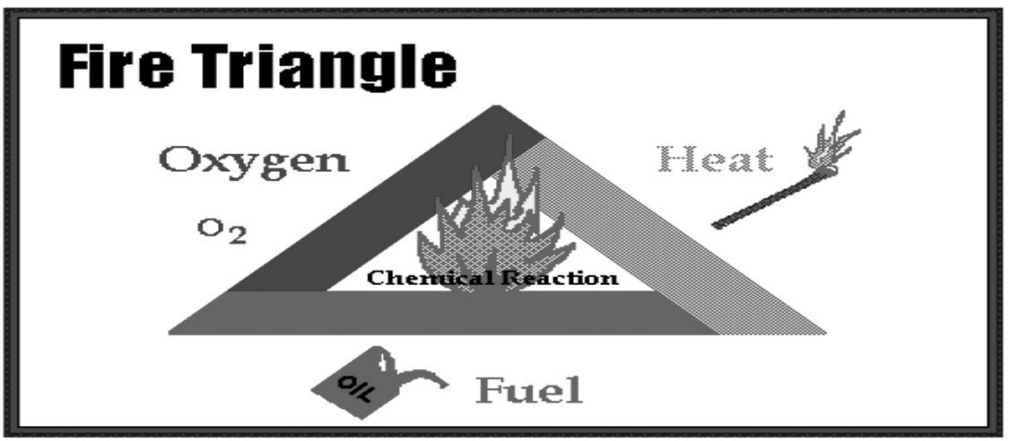


FIGURE 5.7 Fire triangle (http://www.pp.okstate.edu/ehs/MODULES/exting/Triangle.htm).

For an exothermic chemical reaction to occur (and fire is basically and exothermic reaction), there must be oxygen, fuel, and heat present. If any of the three components symbolized by the legs of the triangle (Figure 5.7) are taken away, then the fire will be extinguished. This is how fire extinguishers work. They take away one of the sides of the triangle. Dry chemical extinguishers take away the oxygen, smothering the combustion. Halon and carbon dioxide hopefully lower the temperature to below combustion parameters.

There are four basic designs of fire extinguishers. They are halon, carbon dioxide, water, and dry chemical extinguishers.

- Halon. These contain a gas that interrupts the chemical reaction that takes place when fuels burn. These types of extinguishers are often used to protect valuable electrical equipment because they leave no residue to clean up. Halon extinguishers have a limited range, typically 1.2 to 1.8 m (4 to 6 ft). The initial application of halon should be made at the base of the fire, even after the flames have been extinguished.
- Carbon dioxide. These are most effective on Class B and C (liquids and electrical) fires. Because the gas disperses quickly, these extinguishers are only effective from 0.9 to 2.4 m (3 to 8 ft). The carbon dioxide is stored as a compressed liquid in the extinguisher; as it expands, it cools the surrounding air. The cooling will often cause ice to form around the "horn", where the gas is expelled from the extinguisher. Because the fire could reignite, the agent should continue to be applied even after the fire appears to be out.
- Water. These extinguishers contain water and compressed gas and should only be used on Class A (ordinary combustibles) fires.
- Dry chemicals. These are typically rated for multipurpose use. They contain an extinguishing agent and use a compressed, nonflammable gas as a propellant.

The description of water-type extinguishers mentions Class A fires. Extinguishers are rated by the class of fire that they have the capability of extinguishing if they are used properly. The following are the four classes of fire.

- Class A, ordinary combustibles;
- Class B, combustible liquids and vapors;
- Class C, electrical fires; and
- Class D, combustible metals.

All extinguishers have the types of fire that they are capable of extinguishing posted on them. It is important to know what types of extinguishers are present before an emer-

gency. An emergency is not the time to find out that only a Class D extinguisher is available and the fuel is gasoline. The person who has the responsibility to order or prepare the site for safety should assess the possible dangers and have the proper extinguishers in place before an emergency to the extent possible.

While nothing can replace hands-on training using an extinguisher, there is a basic mnemonic rule for using an extinguisher. That memory device is PASS. It stands for the following:

- *Pull* the safety pin (so the trigger can be pulled);
- *Aim* at the base of the fire from approximately 2.4 m (8 ft) away;
- *Squeeze* the trigger, aiming the extinguisher at the base of the fire; and
- *Sweep* the nozzle back and forth at the base of the fire.

While all this seems easy on paper, when there is an emergency, adrenaline starts flowing and people sometimes try to do more than they should. It is important to consider the situation. If there is a fire near the chlorine room, for example, a worker should not try to put it out alone if it looks like it is going to get out of control. The local fire department should be called for help. While one person may be able to put out the flames if it is small, if it gets out of control, that person is in danger and the surrounding populace is also in danger. That one person may be the only chance to warn them and get proper emergency equipment on the scene.

MACHINE SAFETY

There are many different types of machinery that can be found in wastewater treatment plants, varying from pumps to belt filter presses. One thing that they have in common is moving parts. It is amazing how many moving parts there are and how damaging they can be to the human body.

The external moving arms that some primary sludge pumps use are mechanically related to the old piston rods and wrist pins of old-fashioned steamships. In past days, it was the job of an oiler to manually apply oil to the wrist pins and connecting rods (the connecting rods where often twice as tall as a man) amidst the heat of the steam engine. It was a job where one false move would cost the oiler his arm and sometimes his life. The working standards of the late 19th century should not apply to present-day workers.

Most pieces of machinery have guards that are designed to be in place over the moving parts. This is an engineering design feature that is meant to keep personnel from hazards. The guard encloses the danger. When a person comes across machinery

that he or she knows can be dangerous, it is important to make sure that the guards are there. This conscious pattern of thought should extend to all tools used. Table saws and circular saws have safeties to prevent career-ending injuries to hands. **Use them.** If a worker encounters machinery that may need safeties beyond the original design, he or she should make sure that the proper chain of command is notified and action is taken. Belts and pulleys, chains and sprockets, rotating coupling, and racks and gears are among some of the common items that should have guards over them.

This is common sense. But what happens when these guards need to be taken off for maintenance? The correct answer is not for employees to work at their own risk. Most people are aware of lockout/tagout programs. These are normally accepted as standards when electrical work is being performed. There is energy, called *latent energy*, that may be stored in hydraulic systems or other forms of mechanical energy storage systems. This can be released if improperly locked out, with possibly dire consequences.

LOCKOUT/TAGOUT PROGRAMS

In simple terms, a lockout/tagout program is a formalized program that has routine steps in it that will not allow anyone to turn on machinery that is being repaired or maintained. The main panel shutoff will have a lock placed on it by the person doing the work. In a place like a large wastewater plant, there could be electrical crews and maintenance and repair crews working on the same item at once. If, for example, there needed to be work on a clarifier drive, the supervisor may have the oil and flights worked on at the same time.

For this example, assume that there are three crews, each doing their particular jobs. The main shutoff for the clarifier would have a device that would fit through the hole in the main power shutoff, instead of the basic lock used if it were a one-man crew. Then locks from all three crews and the supervisor would fit into the holes of this device. There would be a tag stating "Do Not Use" if this is not printed on the device. When each crew has completed their project, their lock is removed from the device. When the job is complete, the supervisor would take the lock off of the device, remove the tag, and allow the device to be turned on. As a general rule, **never cut a lock off of a lockout device or a piece of equipment**. This could lead to serious injury. If someone were to quit without returning keys, suffer a long-term injury, or some other incident occurred that prevented that person from coming to work, then the decision to do something like cutting a lock becomes an administrative decision, where all consequences should be thoroughly considered. Illustrations of some common lockout devices are shown in Figure 5.8.



FIGURE 5.8 Illustrations of (a) 480v lockout device (courtesy of Lab Safety Supply), (b) circuit breaker lockout device (courtesy of Lab Safety Supply), (c) circuit breaker panel lockout device (courtesy of Lab Safety Supply), and (d) electrical panel lockout device (image courtesy of Brady® Worldwide Inc.) (http://www.labsafety.com/store/dept.asp?dept_id=5442).

In summary, a lockout/tagout program that meets OSHA specifications covers employee training in the three following aspects:

(1) The employer's energy control program,
(2) Elements of energy control programs that are relevant to the employee's duties, and
(3) Various requirements of the OSHA lockout/tagout standard.

The following are mandates that an employer must follow to protect employees:

- Develop, implement, and enforce an energy control program.
- Use lockout devices for equipment that can be locked out. Tagout devices can be substituted in lieu of lockout devices only if tagout devices can provide the same degree of protection.
- Ensure that new or overhauled devices are capable of being locked out
- If existing equipment cannot be locked out, develop a tagout program.
- Develop, document, implement, and enforce energy control procedures.
- Use only lockout/tagout devices authorized for the particular application and ensure that they are durable, standardized, and substantial.
- Ensure that lockout/tagout devices identify the individual users.
- Establish a policy that permits only the employee who applied the device to remove it (see 29 *CFR* 1910.147 (e)(3) [Occupational Safety and Health Hazards, 2005] for exceptions).
- Inspect and update energy control procedures annually.
- Provide effective training for all employees covered by the standard.

- Comply with the additional energy control procedures in OSHA standards when machines are tested or repositioned, when outside contractors work at the site, in lockout situations, and during shift and personnel changes.

TRAFFIC SAFETY

Traffic safety can fall into the following two basic categories: (1) general driving practices and (2) signage and traffic patterns that need to be maintained when people are out working in streets.

DEFENSIVE DRIVING. General driving practices can be casually summed up as driving defensively. It is important to make sure vehicles are in working condition. All blinkers and safety lights, brakes, and wipers should work and windshield washer fluid should be full (especially in mountainous terrain). Seldom is getting to a job a few minutes earlier a life-or-death situation, so it is important to take time and be careful. The term "road rage" has become increasingly popular in the past few years. There are many reasons for this. The electronic age has brought a faster-paced lifestyle, with almost constant access and pressure. There often is little time to relax. Traffic has gotten worse. Deadlines are constantly looming. The road is often seen as place to make up time, and aggression is taken out anonymously. These conditions can lead to problems on the road. It is important to remember that there is no need to be aggressive, especially in a company vehicle. It is important to just get the job done and be careful. In the wastewater treatment industry, if a person loses his or her license, he or she often loses the job also.

DRINKING AND DRIVING. The use of illicit substances and driving do not mix. Many places of employment have drug testing before employment starts and can have random drug testing at any time. Anyone who has DOT licensing can be subject to random drug testing and, if there is an accident, the driver must undergo mandatory drug testing. Legal blood alcohol levels continue to drop and, in many states, the level is currently 0.08. It is important to remember that all drivers have different metabolisms and susceptibility to alcohol and take different medications. Many of these can cause unwanted side effects and lack of coordination. Drinking and driving remains one of the leading causes of death in the United States.

CELL PHONE USAGE. Cell phones have been a blessing for making communication easy. For driving, they have become a problem. Many studies have linked cell phone use when driving to accidents (Helperin, http://www.edmunds.com/ownership/

safety/articles/43812/article.html [accessed January 2006]). Originally, it was thought that using the hands to dial resulted in worse driving; however, the driving actually worsens because the driver is distracted. The driver's concentration is no longer on guiding the automobile down the road, but on what the driver is doing or saying. This endangers others. If it becomes necessary to talk while driving, please try to pull over. Also, some areas have actually made it illegal to use a phone and drive at the same time.

SIGNAGE AND TRAFFIC PATTERNS. One of the more dangerous things that wastewater workers can do is to work outside the plant performing collection system maintenance and repairs. The best defense and protection for wastewater treatment workers would be totally cordoning off the work area or worksite behind impenetrable concrete barriers. Often, that is impossible. The next best thing that can be done is protecting workers with a traffic control zone. The workers will need to set up a means of guiding traffic through the work zone so that they will not be harmed. This means proper placement of signs, cones, and possibly a flag person to guide the traffic. Before working in the roadway, remember to contact the local police or district to determine whether traffic control is necessary. In some areas, a traffic control plan must be submitted before any work can be started.

Typically, when working in a district where there is only one worker, the roads generally are not that heavily trafficked, so there will not be a need for more than the truck, cones, and basic "Road Work Ahead" or "Detour" signs (remember, the truck can be a safety device and just by its bulk can be used behind cones as a mobile barrier). Following are the recommended distances for simple signs:

- A "Road Work Ahead" sign is typically placed 46 m (150 ft) minimum in front of any other signage.
- A "Lane Closed" sign is typically placed 30 m (100 ft) minimum in front of the work zone.
- A "High Level Warning Device" is placed at the beginning of the work zone. This can be a multiple flag type of device or a flashing sign. It is important to check local regulations to make that the proper type of device is being used.
- Cones are placed to direct traffic around the work zone.

There are some basic rules that need to be followed. All flag persons should wear orange vests or shirts. Recently, some areas began allowing a fluorescent yellow-green color also. Reflective belts, suspenders, or edges on the normal orange vest are necessary for night work. Proper use of signs that say "Slow" on one side and "Stop" on the

other are necessary. Flag persons should be positioned at least 30 m (100 ft) ahead of the work zone. The "Flagmen Ahead" sign should be approximately 152 m (500 ft) ahead of them. Flag persons are required where

(1) Workers or equipment will intermittently block traffic;
(2) One lane must be used for both directions of traffic (a flag person is required for both directions); or
(3) The safety of the public and/or workers requires it.

Local regulations should be checked for proper placement of signs. They may differ from area to area. Permits may be required at specific sites. Table 5.3 shows suggested distances between common warning devices.

The following are a few basic things to remember when working inside a cordoned-off area:

- Always use more than the minimum amount of warning signage.
- Anticipate unpredictable acts of drivers before setting up the traffic plan and then actualizing it. Cars and trucks are much larger than people, and, if poor driving is anticipated, it is much easier to protect workers from it, preventing accidents and injury.
- Keep all tools and materials behind the protected zones. If something were to fall into the flow of traffic, do not react and go after it without first looking and making sure that the area may be entered safely.
- The pedestrian, motorist, equipment, and work force need to be considered as traffic control plans are made.
- Finally, it is a good idea to review the safety plans with everyone on the worksite before work starts.

TABLE 5.3 Suggested distances between common warning devices.

	Speed (km/h [mph])	**Distance (m [ft])**
Traffic cones	0 to 48 km/h (0 to 30 mph)	3 to 6 m (10 to 20 ft)
	48 to 64 km/h (30 to 40 mph)	7.6 to 11 m (25 to 35 ft)
	72 to 88 km/h (45 to 55 mph)	12 to 15 m (40 to 50 ft)
High level warning devices	0 to 40 km/h (0 to 25 mph)	45 m (150 ft) before worksite
	40 to 56 km/h (25 to 35 mph)	76 m (250 ft) before worksite
	56 to 72 km/h (35 to 45 mph)	152 mm (500 ft) before worksite
	72 to 88 km/h (45 to 55 mph)	229 m (750 ft) before worksite

SAFETY CONSIDERATIONS IN PLANT DESIGN

When a new plant is designed or there are renovations made to an existing facility, possible safety hazards and design considerations must be taken into account by management to ensure a safe working environment. To encourage buy-in, management will invite the plant supervisor and operators to review the plans before the first piece of pipe is in the ground or before the concrete is poured. It is much easier and less expensive to change designs on paper than it is to change once the concrete has set. The following is a list of design considerations that should be considered before the construction process begins:

- Provide stairs instead of vertical ladders. If chemicals are to moved in that area, use a ramp instead of stairs.
- Provide nonskid floors and treads.
- Label all piping and color code it where possible.
- Maintain a minimum headroom of 2 m (7 ft).
- Provide guards on all accessible moving parts of machinery.
- Equip all stairs, openings, tanks, basins, ladder ways, and platforms with standard guard railings. If the railings and guards are at the base of an icy slope in mountainous terrain, make sure the guard is higher than minimum standard to prevent injury.
- Post appropriate warning signs in all hazardous areas.
- Provide adequate floor drains for washdown.
- Provide adequate lifting facilities.
- Isolate disinfection facilities from other buildings. Consider the use of alternative disinfection systems such as UV to lower the risk of using hazardous chemicals.
- If it is necessary to use gaseous chlorine and sulfur dioxide, provide leak detection systems and alarm systems.
- Provide combustible gas detectors, toxic gas detector, and oxygen-deficiency alarms and indicators where appropriate.
- Include SCBA in the plant equipment inventory. If the use of toxic chemicals can be lessened, then the maintenance costs and training may be eliminated from future operations budgets.
- Provide ship's ladders, stairs, or mechanical lifts for all installations deeper than 3.7 m (12 ft). A means of egress from aeration basin and aerobic digesters must be provided because the body loses buoyancy in aerated liquors.
- Provide adequate space for safe and efficient operation and maintenance of all equipment installed.
- Provide flush toilets, lavatories or wash fountains, hot and cold water, and showers.

- Provide adequate eating facilities with refrigerator, microwave, stove, and sink. This area should be out of the traffic pattern so that it may be maintained and adequately cleaned.
- Provide dressing rooms, benches, mirror, and metal lockers (two lockers is ideal so that work clothes may be kept separate from clean clothes).

ACCIDENT REPORTING AND INVESTIGATION

It is mandatory that any injuries be reported within 48 hours of occurrence to management. This record will ensure that proper medical treatment is provided and workman's compensation and insurance claims can be filed and handled promptly. A worker who is injured will want fast action on claims. If the injury is serious enough, management is bound to notify the designated emergency contact. If there is the need for special treatment, such as treatment for allergic reaction to medications or diabetes, this should be noted on emergency contact forms so that accidents that could cause complications do not occur. Records of illness and accidents need to be kept so that individual workers and treatment processes can be monitored.

If accident reporting is to be effective, then follow-up to the initial accident report should be made. This may help management determine if there is a process that is too dangerous and should be redesigned. It also helps show if any worker is accident-prone and may need special help.

If management is serious about having a safe work facility, there is an appointed safety officer who will make detailed notes on each accident. The investigator's notes should include answers to the following questions:

- Who was present, who should have been present, and was someone out of place?
- Were any guards, kick plates, or other protective equipment out of place?
- Was access and egress open or blocked?
- What happened and what damage occurred (an accident can involve equipment damage and personal injury)?
- Is anyone hurt?
- Who was in charge at the time of the accident?

Diagrams of the scenario, videotape, and pictures may be helpful tools in investigating the incident.

Figures 5.9 to 5.11 are sample supervisor's report of accident forms and employee accident/incident report forms. Investigators may ask for recommendations to help prevent these accidents from repeating. Then, any changes that are necessary in process or equipment can be presented to management so that they may find a means

Supervisor's Report of Accident
(Occupational Injury)

INJURED EMPLOYEE		EMPLOYEE #		AREA
DATE OF ACCIDENT	TIME	AM/PM	EMPLOYEE'S OCCUPATION	
PLACE OF ACCIDENT				
NATURE OF INJURY				
NAME OF DOCTOR				
NAME OF HOSPITAL				
WITNESSES (NAME AND ADDRESSES)				

FIGURE 5.9 Supervisor's report of accident.

to pay for the necessary changes and prioritize changes so that they may happen in a decent work flow. If violations occurred in disregard of safety policies and procedures, these should be recorded so that appropriate disciplinary actions may be taken. If chemical spills occur, these need to be dealt with in a safe manner. A good report documents all that happened in a manner that is easily understood and suggests ways to prevent these incidents from happening again.

OCCUPATIONAL SAFETY AND HEALTH ADMINISTRATION 300 LOGS

The OSHA 300 logs (Figures 5.12 to 5.14) are publicly posted records of accidents and lost work time that are mandated to be posted in the month of February where the labor force gathers. Typically, they are posted in either the lunch area or the time clock area. Please regularly check the log format on the OSHA Web site for changes, as they do change. Make sure the proper form is used and sent to the proper regulatory address and file.

SAFETY PROGRAMS AND ADMINISTRATION

There has been much information presented in this chapter concerning safety, including mandatory safety items and procedures. The question then is how this becomes something useful and cohesive. Most of these are laws from the U.S. Congress and need to be followed. Others are industry standards and are accepted practice. Typically, a *written* safety and health program is needed. This manual should contain

DESCRIPTION OF ACCIDENT

Information is to be used for preventing similar accidents. Answer questions specifically, not in generalities. The safety officer, as required, will conduct independent investigations of accidents.

1. **What job was employee doing?**

2. **What tools, materials, and/or equipment were being used?**

3. **What specific action caused the accident?**

4. **How did the employee contribute to the accident?**

5. **Were the proper safety protection devices being used?**

6. **What materials, tools, etc. were defective or in unsafe condition? How?**

7. **What work methods or acts caused the accident?**

8. **What safeguards should have been used?**

9. **What steps will you take to prevent similar injuries?**

10. **What other steps should be taken to prevent a recurrence?**

Figure 5.10 Description of accident.

safety and health policies, rules, emergency procedures, and emergency phone numbers. There is a need for ongoing safety training that will change and be updated as laws, standards, and the systems change. Wastewater treatment professionals working in a small plant may question the need for putting it all in writing, and then keeping it up-to-date. After all, there may only be one or two employees who know their jobs. However, what happens if someone leaves, retires or gets hurt? The replacement will not have the benefit of history and experience and could be overwhelmed. The town administration will need to know what to do.

11. Did you see the accident? □ Yes □ No

Date of Report _____ _____
Immediate Supervisor

Remarks Concerning Investigation

Age of Injured _____ Length of Service _____

For Safety Department Use

Date Investigated _____ By _____
Signature

Remarks Concerning Investigation

Figure 5.10 Description of accident (continued).

In fact, the leadership of compiling a health and safety program can come from a worker or from higher levels of administration. It is best to work with administration closely, regardless of who is taking the lead in formulating such a program. If the town administration is taking the lead, the worker or manager can convey to them different things that are necessary so that the budgetary considerations can be made. If a wastewater treatment professional is taking the lead, he or she should take advantage of the opportunity to educate those with whom he or she is working.

Regardless of who is in charge and how the program is formulated, the safety and health program should start with a mission statement. The mission statement defines the need for such a program and should help define the working conditions expected and the follow-through required. It frames that attitude within which administrators and employees are expected to work. A good statement will define the goals and objectives of preventing job-related injuries and illness and the disruptions that they may

EMPLOYEE ACCIDENT/INCIDENT REPORT

To be completed within 24 hours and sent to the Health and Safety Officer
Type or Print with Ball Point Pen

EMPLOYEE IDENTIFICATION

1. Name _____ 2. Street Address _____
3. City, State, Zip Code _____ 4. Home Phone _____
5. Work Phone _____ 6. Length of Employment _____
7. SS# _____ 8. Birth date _____
9. Job Title _____

INCIDENT INFORMATION (to be completed by Employee)

10. Date of Incident _____ 11. Time of Incident _____
12. Location of Incident:
    Inside Building (Building & Room #) _____ Outdoors (Description) _____
13. Was Supervisor Notified? ____Yes ____No
14. Date & Time Notified: _____
15. Name of Immediate Supervisor _____
16. Was injured person performing regular job duties at time of incident? ____Yes ____No
17. Did incident result in injury? ____Yes ____No
18. Did incident result in loss of property? ____Yes ____No
19. Complete description of incident _____
20. Circumstances that lead to incident, i.e., unfamiliar with task, lack of concentration, improper instruction, etc. _____
21. What measures could have been taken to prevent this incident? _____
22. If there was damage to property, describe the extent of loss to the best of your knowledge. _____
23. Witnesses ____Yes ____No

FIGURE 5.11 Employee accident/incident report.

24. Name, address and phone number of witness:

_____

_____

25. Bodily injury - Body part injured:

	Left	Right
hand elbow ankle	_____	_____
thumb shoulder foot	_____	_____
finger(s) thigh toe (s)	_____	_____
wrist knee eye	_____	_____
arm calf ear	_____	_____
face/teeth other	_____	_____
head	_____	_____
abdomen	_____	_____
back lower	_____	_____
back mid	_____	_____
back upper	_____	_____
groin	_____	_____
neck cervical	_____	_____
nose/throat/lungs	_____	_____

26. Nature of Injury:

laceration sprain other puncture strain _____

insect/animal bite fracture/dislocation _____

burn inhalation _____

abrasion, scrape foreign matter _____

contusion, bruise skin irritation _____

exposure to body fluids (bbp) _____

Other:

_____

_____

Describe:

_____

_____

_____

FIGURE 5.11 Employee accident/incident report (continued).

27. Was this incident the result of a slip, trip, or fall? ____Yes ____No

28. Was this incident the result of lifting? ____Yes ____No
    Approximate weight of object: _____ How high lifted? _____
    Was kind of work performed regularly? ____Yes ____No

29. Did injury appear immediately? ____Yes ____No Explain: _____
    _____

30. What was the length of time between the injury and your symptoms? _____

31. Were you treated by a doctor? ____Yes ____No

    If yes, name of doctor _____ Date treated: _____

32. Did you go to the hospital? ____Yes ____No

    If yes, name of hospital _____Date treated _____

33. Was first aid given? ____Yes ____No

    By whom (self - using first aid kit, paramedic, other): _____

34. Have you ever filed a Worker's Compensation claim? ____Yes ____No
    If yes, when and where:
    _____

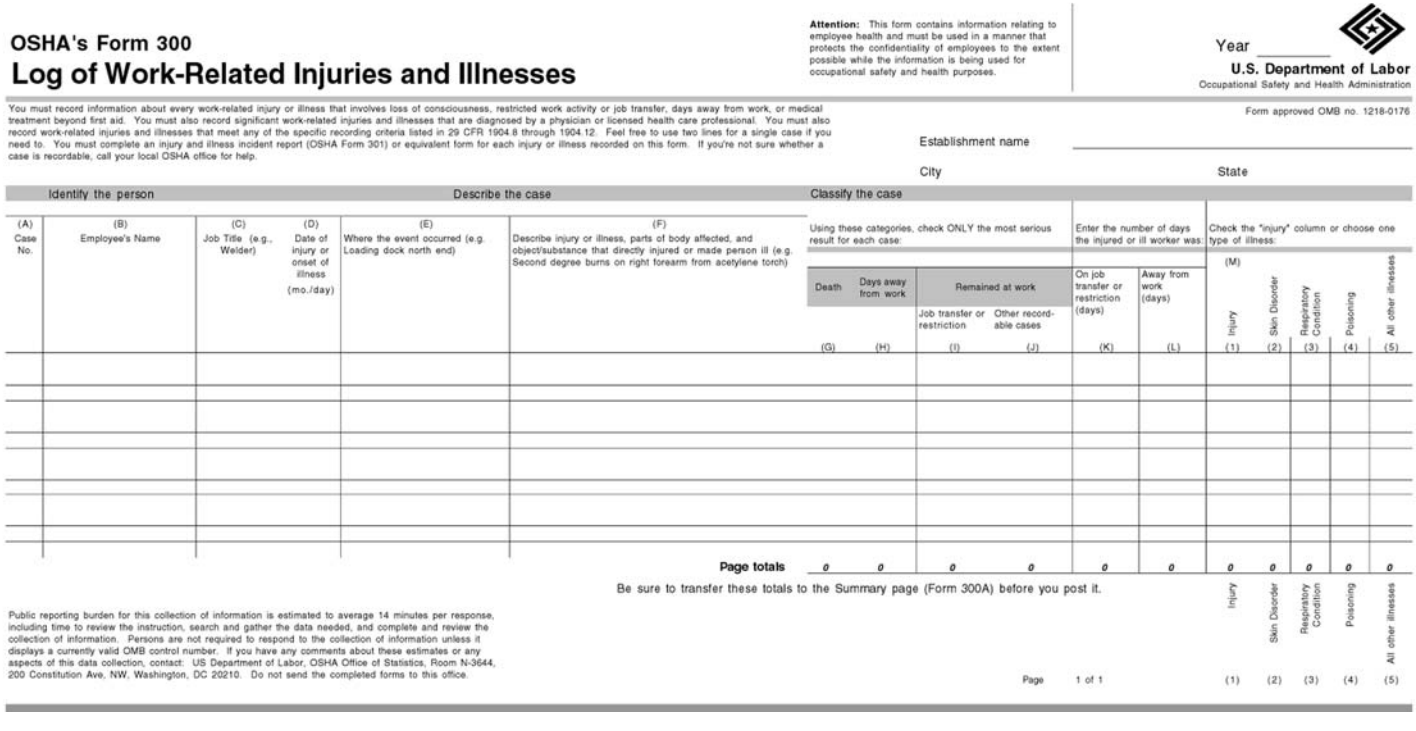
35. Nature of previous claim(s): _____

36. Is this injury an aggravation of an old injury? ____Yes ____No

I, the injured employee, herein certify that the information set forth above is true and correct to the best of my knowledge. By signing this form, I expressly waive all provisions of law which forbid any person or persons who heretofore did or who hereafter may medically attend, treat, or examine me or who may have information of any kind which may be used to render a decision in my claim for injury/disease of (Date)_____ from disclosing such knowledge to my employer and/or any other agency contracted by employer to investigate this health claim. A copy of this form will serve as the original.

Employee Signature _____Date: _____
Print Name _____

FIGURE 5.11 Employee accident/incident report (continued).



OSHA's Form 300

Log of Work-Related Injuries and Illnesses

Attention: This form contains information relating to employee health and must be used in a manner that protects the confidentiality of employees to the extent possible while the information is being used for occupational safety and health purposes.

Year _____

U.S. Department of Labor
Occupational Safety and Health Administration

You must record information about every work-related injury or illness that involves loss of consciousness, restricted work activity or job transfer, days away from work, or medical treatment beyond first aid. You must also record significant work-related injuries and illnesses that are diagnosed by a physician or licensed health care professional. You must also record work-related injuries and illnesses that meet any of the specific recording criteria listed in 29 CFR 1904.8 through 1904.12. Feel free to use two lines for a single case if you need to. You must complete an injury and illness incident report (OSHA Form 301) or equivalent form for each injury or illness recorded on this form. If you're not sure whether a case is recordable, call your local OSHA office for help.

Form approved OMB no. 1218-0176

Establishment name

City State

Identify the person				Describe the case		Classify the case										
(A) Case No.	(B) Employee's Name	(C) Job Title (e.g., Welder)	(D) Date of injury or onset of illness (mo./day)	(E) Where the event occurred (e.g. Loading dock north end)	(F) Describe injury or illness, parts of body affected, and object/substance that directly injured or made person ill (e.g. Second degree burns on right forearm from acetylene torch)	Using these categories, check ONLY the most serious result for each case:				Enter the number of days the injured or ill worker was:		Check the "injury" column or choose one type of illness:				(M)
						Death (G)	Days away from work (H)	Remained at work: Job transfer or restriction (I)	Remained at work: Other recordable cases (J)	On job transfer or restriction (days) (K)	Away from work (days) (L)	Injury (1)	Skin Disorder (2)	Respiratory Condition (3)	Poisoning (4)	All other illnesses (5)
					Page totals	0	0	0	0	0	0	0	0	0	0	0

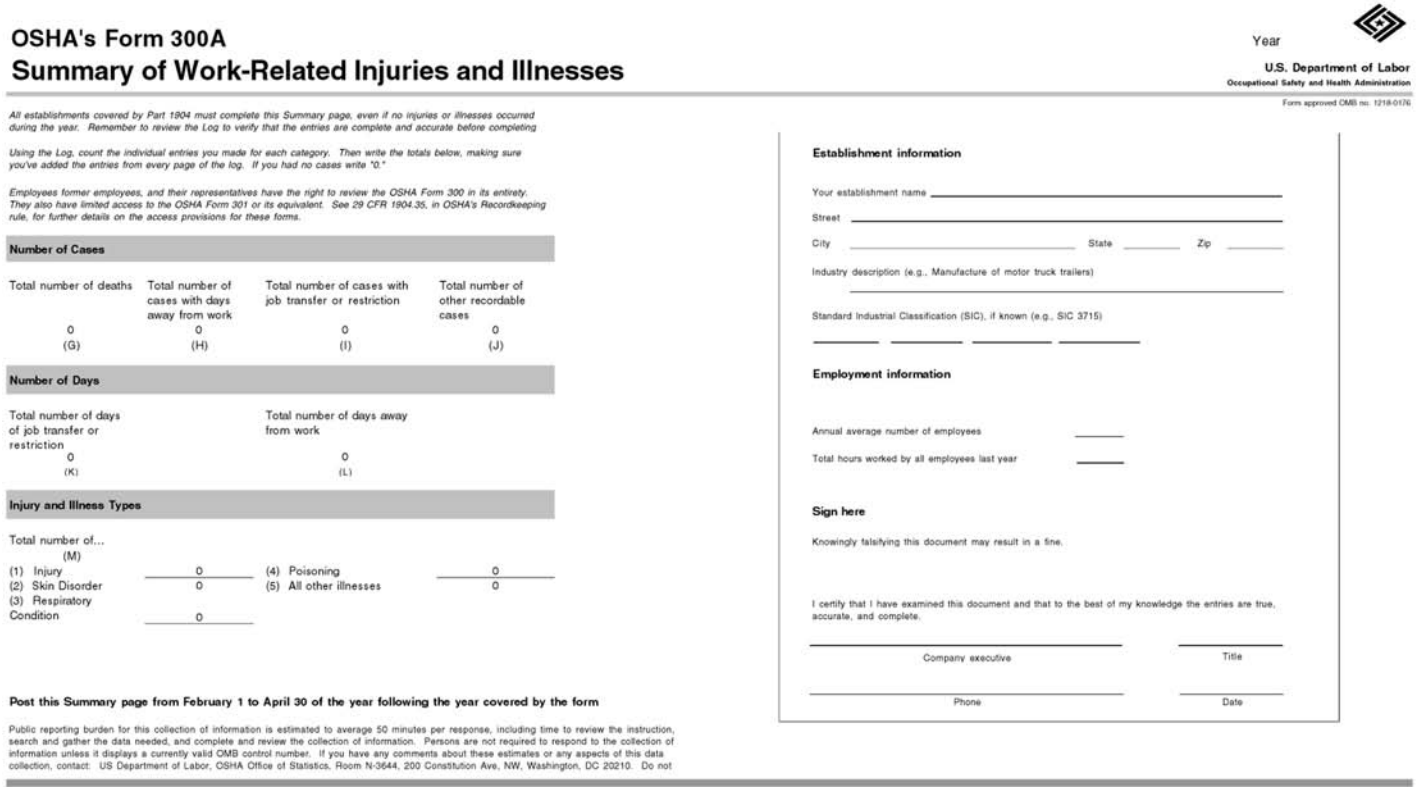
Be sure to transfer these totals to the Summary page (Form 300A) before you post it.

Public reporting burden for this collection of information is estimated to average 14 minutes per response, including time to review the instruction, search and gather the data needed, and complete and review the collection of information. Persons are not required to respond to the collection of information unless it displays a currently valid OMB control number. If you have any comments about these estimates or any aspects of this data collection, contact: US Department of Labor, OSHA Office of Statistics, Room N-3644, 200 Constitution Ave, NW, Washington, DC 20210. Do not send the completed forms to this office.

Page 1 of 1

Injury (1) Skin Disorder (2) Respiratory Condition (3) Poisoning (4) All other illnesses (5)

FIGURE 5.12 Log of work-related injuries and illnesses (OSHA form 300; http://www.osha.gov/recordkeeping/new-osha300form1-1-04.xls; accessed January 2006).



OSHA's Form 300A
Summary of Work-Related Injuries and Illnesses

Year

U.S. Department of Labor
Occupational Safety and Health Administration

Form approved OMB no. 1218-0176

All establishments covered by Part 1904 must complete this Summary page, even if no injuries or illnesses occurred during the year. Remember to review the Log to verify that the entries are complete and accurate before completing

Using the Log, count the individual entries you made for each category. Then write the totals below, making sure you've added the entries from every page of the log. If you had no cases write "0."

Employees former employees, and their representatives have the right to review the OSHA Form 300 in its entirety. They also have limited access to the OSHA Form 301 or its equivalent. See 29 CFR 1904.35, in OSHA's Recordkeeping rule, for further details on the access provisions for these forms.

Number of Cases

Total number of deaths	Total number of cases with days away from work	Total number of cases with job transfer or restriction	Total number of other recordable cases
0	0	0	0
(G)	(H)	(I)	(J)

Number of Days

Total number of days of job transfer or restriction	Total number of days away from work
0	0
(K)	(L)

Injury and Illness Types

Total number of...	(M)		
(1) Injury	0	(4) Poisoning	0
(2) Skin Disorder	0	(5) All other illnesses	0
(3) Respiratory Condition	0		

Establishment information

Your establishment name _____

Street _____

City _____ State _____ Zip _____

Industry description (e.g., Manufacture of motor truck trailers)

_____

Standard Industrial Classification (SIC), if known (e.g., SIC 3715)

_____ _____ _____ _____

Employment information

Annual average number of employees _____

Total hours worked by all employees last year _____

Sign here

Knowingly falsifying this document may result in a fine.

I certify that I have examined this document and that to the best of my knowledge the entries are true, accurate, and complete.

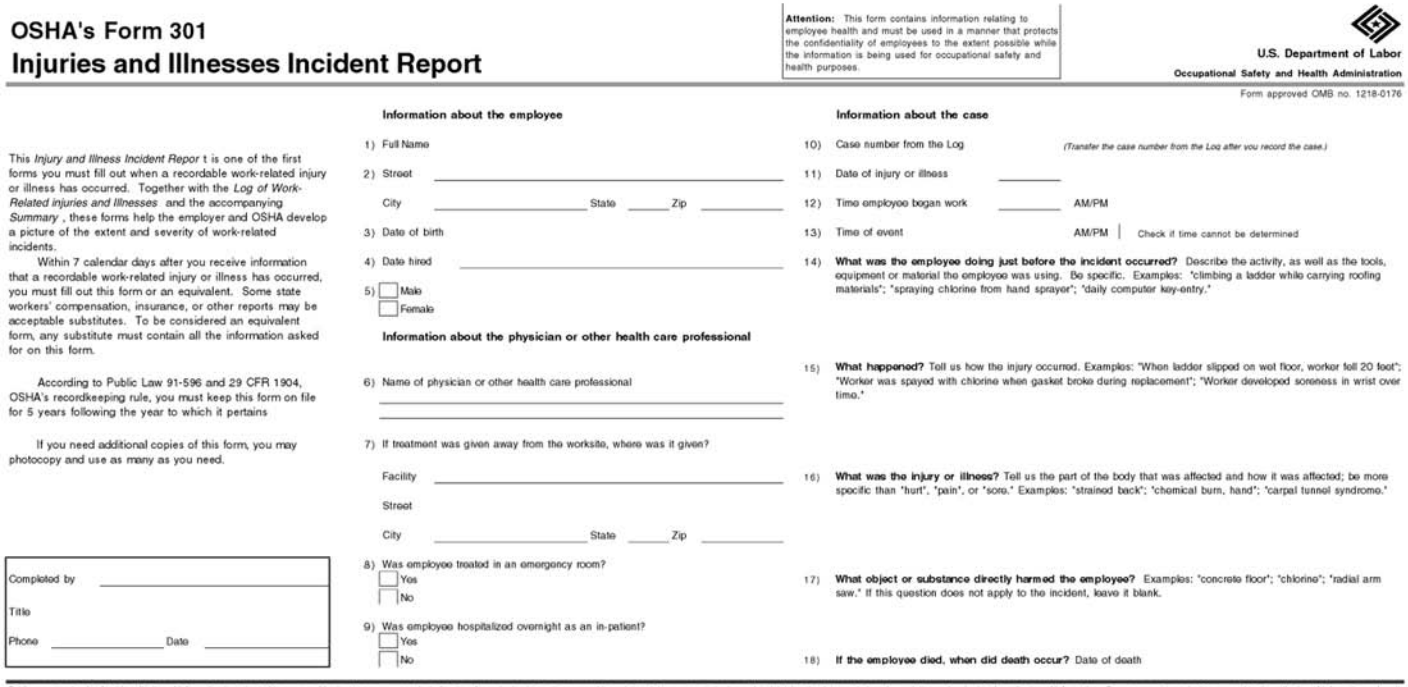
_____ _____
Company executive Title

_____ _____
Phone Date

Post this Summary page from February 1 to April 30 of the year following the year covered by the form

Public reporting burden for this collection of information is estimated to average 50 minutes per response, including time to review the instruction, search and gather the data needed, and complete and review the collection of information. Persons are not required to respond to the collection of information unless it displays a currently valid OMB control number. If you have any comments about these estimates or any aspects of this data collection, contact: US Department of Labor, OSHA Office of Statistics, Room N-3644, 200 Constitution Ave, NW, Washington, DC 20210. Do not

FIGURE 5.13 Summary of work-related injuries and illnesses (OSHA form 300A; http://www.osha.gov/recordkeeping/new-osha300form1-1-04.xls; accessed January 2006).



OSHA's Form 301
Injuries and Illnesses Incident Report

Attention: This form contains information relating to employee health and must be used in a manner that protects the confidentiality of employees to the extent possible while the information is being used for occupational safety and health purposes.

U.S. Department of Labor
Occupational Safety and Health Administration
Form approved OMB no. 1218-0176

This *Injury and Illness Incident Repor* t is one of the first forms you must fill out when a recordable work-related injury or illness has occurred. Together with the *Log of Work-Related injuries and Illnesses* and the accompanying *Summary* , these forms help the employer and OSHA develop a picture of the extent and severity of work-related incidents.

Within 7 calendar days after you receive information that a recordable work-related injury or illness has occurred, you must fill out this form or an equivalent. Some state workers' compensation, insurance, or other reports may be acceptable substitutes. To be considered an equivalent form, any substitute must contain all the information asked for on this form.

According to Public Law 91-596 and 29 CFR 1904, OSHA's recordkeeping rule, you must keep this form on file for 5 years following the year to which it pertains

If you need additional copies of this form, you may photocopy and use as many as you need.

Completed by _____
Title
Phone _____ Date _____

Information about the employee

1) Full Name
2) Street _____
City _____ State ____ Zip _____
3) Date of birth
4) Date hired _____
5) ☐ Male ☐ Female

Information about the physician or other health care professional

6) Name of physician or other health care professional _____
7) If treatment was given away from the worksite, where was it given?
Facility _____
Street
City _____ State ____ Zip _____
8) Was employee treated in an emergency room? ☐ Yes ☐ No
9) Was employee hospitalized overnight as an in-patient? ☐ Yes ☐ No

Information about the case

10) Case number from the Log *(Transfer the case number from the Log after you record the case.)*
11) Date of injury or illness _____
12) Time employee began work _____ AM/PM
13) Time of event AM/PM | Check if time cannot be determined
14) **What was the employee doing just before the incident occurred?** Describe the activity, as well as the tools, equipment or material the employee was using. Be specific. Examples: "climbing a ladder while carrying roofing materials"; "spraying chlorine from hand sprayer"; "daily computer key-entry."
15) **What happened?** Tell us how the injury occurred. Examples: "When ladder slipped on wet floor, worker fell 20 feet"; "Worker was sprayed with chlorine when gasket broke during replacement"; "Worker developed soreness in wrist over time."
16) **What was the injury or illness?** Tell us the part of the body that was affected and how it was affected; be more specific than "hurt", "pain", or "sore." Examples: "strained back"; "chemical burn, hand"; "carpal tunnel syndrome."
17) **What object or substance directly harmed the employee?** Examples: "concrete floor"; "chlorine"; "radial arm saw." If this question does not apply to the incident, leave it blank.
18) **If the employee died, when did death occur?** Date of death

Public reporting burden for this collection of information is estimated to average 22 minutes per response, including time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Persons are not required to respond to the collection of information unless it displays a current valid OMB control number. If you have any comments about this estimate or any other aspects of this data collection, including suggestions for reducing this burden, contact: US Department of Labor, OSHA Office of Statistics, Room N-3644, 200 Constitution Ave, NW, Washington, DC 20210. Do not send the completed forms to this office.

FIGURE 5.14 Injuries and illnesses incident report (OSHA form 301; http://www.osha.gov/recordkeeping/new-osha300form1-1-04.xls; accessed January 2006).

cause. It should assign responsibility for carrying out policy. Details that would be contained in the program itself and not necessarily in the mission or policy statement would be identifying hazards, ongoing training, developing disciplinary, rewards procedures, and personnel training. For more details, see *Safety and Health in Wastewater Systems* (WEF, 1994) or *Supervisor's Guide to Safety and Health Programs* (WEF, 1992).

In larger systems, the responsibility for health and safety programs are also shared by administration and labor and are often formalized into committees. The committee is a shared responsibility where the program is defined and refined, ongoing inspections take place, and material is updated for the program. Regardless of who is ultimately responsible, records should be kept for training and accidents. As mentioned earlier, accident investigations must be conducted.

MANAGEMENT RESPONSIBILITIES

As with any program, responsibility for creation, institution, and follow-through begins at the top. This can be the council, a commission, an administrator, or the plant superintendent. Leadership will set the policy and the attitude towards health and safety. The effectiveness of any program depends on the earnest concern of management. Management provides the control of the work environment and employee performance. Among management responsibilities are the following:

- Formulating a written safety and health policy,
- Enforcing the policy,
- Setting achievable goals,
- Providing adequate training, and
- Delegating authority so that the policy may be carried out.

These responsibilities typically are delegated to the line supervisor, crew chief, or foreman. It is his or her responsibility to make sure that labor has the proper tools to work safely and safe work practices are carried out, and that operators are using safe work practices and that proper training of labor has taken place. In larger cities, this responsibility is typically given to the safety director or equivalent position.

EMPLOYEE RESPONSIBILITIES

The following are responsibilities of employees:

- Be familiar with safety policies and rules and follow them.
- Recognize job-related hazards and report to the supervisor any that seem unusual or new.

- Report all injuries and accidents.
- Before operating equipment, receive adequate instruction.
- Observe speed limits, traffic signs, and drive defensively, anticipating problems, whether on- or off-site.
- Keep hand tools and the work area clean and orderly at all times.
- Use the correct tool for the right task.
- Use proper PPE.
- Avoid wearing loose clothing that may be caught in moving equipment. If a worker has long hair, he or she should make sure it will not get caught in moving equipment.
- If wearing jewelry (watches and rings), make sure they do not get caught in machinery.
- Smoke only where allowed.
- Observe rules of personal hygiene to avoid infection.
- Never report to work under the influence of controlled substances or bring them on-site.
- Avoid practical jokes that could result in injury.
- Do not bring firearms to the worksite.
- Do not compromise safety for speed, regardless of circumstance.

TRAINING

The first thing necessary for successful training, no matter how good the prospective program, is the proper attitude. The material could be great and the presentations awe-inspiring, but if management is not serious about its application, no improvements will occur. If there is not enthusiasm or financial backing for programs (including bonuses for safe work performance), then there will not be acceptance by the work force. They will know they are being trained in safety only because of liability issues. Leadership is one of management's primary responsibilities.

Safety and prevention of accidents do not occur by some random chance. These conditions prevail when they are topics accepted enthusiastically and, because of that enthusiasm, a systematic study of all hazards, illnesses, and accidents occurs. Then, ways to prevent these occurrences are applied to the particular facility.

All new employees must have basic safety training. They need to know where the health and safety manual is in case they are not presented with their own copy (in these days, with the availability of copiers and electronic storage, employees should be provided with their own copy). When new equipment is purchased, training must be held to uphold the standards that are being set in the general workplace. If there

are continued injuries in one process, then a reassessment of the process needs to be made. Routine quality assurance/quality control inspections need to include safe working habits. Management observance of workers may also show unsafe working habits or careless attitudes. One of the worst things that can happen as a manager is to allow these attitudes to persist.

The following are some items that are included in a training program:

- Wastewater facility hazards, both general and site-specific;
- Employee health and industrial hygiene;
- Personal protective equipment, including respiratory protection;
- Materials handling and storage;
- Safe use of power and hand tools;
- Fire prevention and fire safety;
- Possibly first aid and CPR;
- Lockout/tagout;
- Confined space and entry;
- The MSDS and its use;
- Employee and community right-to-know;
- Emergency planning and response; and
- Chemical handling and storage.

Training serves as a preventative measure against accidents and job-related illness. It starts when a new employee comes on board and really never ends, when done correctly. Safety is a joint effort between management and labor and requires a commitment from both.

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INTRODUCTION

Data requirements at wastewater utilities have exploded in recent years and are expected to grow exponentially for the indefinite future. Operators need data to confirm their observations and judgments on how to control, adjust, and modify wastewater treatment processes. Regulators need periodic reports on utility operations so they can see whether public and environmental health are protected. Utility managers need data to determine whether to adjust sewer rates or upgrade the facilities. Lawyers need data

to prove that the utility is operating in accordance with applicable laws and regulations. Outreach personnel need data to show the public why wastewater management is important.

Effectively collecting, querying, analyzing, reporting, distributing, storing, and archiving data—whether electronic, paper, audio, image, or video—have become key to effective and efficient operations. They are an important part of a utility manager's responsibilities. Today, most utilities could not operate for long without effective information technology (IT) support.

MANAGEMENT INFORMATION SYSTEMS

Paper-based records require little equipment, but producing and updating them is labor-intensive. Accessibility and data sharing is limited, so people make copies of the paper and create duplicate files. Updates and additions are inconsistent, causing more work reconciling the differences. Data analysis is painstaking, time-consuming, and sometimes virtually impossible. Nevertheless, paper-based systems are still common.

Properly designed computer systems offer important advantages. They should help utility staff make better, faster decisions; automate routine tasks cost-effectively; and minimize risks. The utility's administrative and operations and maintenance (O&M) personnel should be involved in planning management information systems to ensure that they can get the information they need. With a good system, utility staff can

- Enter data once and use it for multiple purposes;
- Easily select, sort, manipulate, and print data in a variety of ways for various purposes;
- Easily display data graphically for analysis;
- Attain better data accuracy via range checking and other editing techniques;
- Automate routine tasks (e.g., automatically re-ordering materials and supplies when the stock falls below a certain level) to make them more consistent;
- Track data changes;
- Organize and store data securely;
- Improve customer service;
- Know the plant's operating status at a glance; and
- Effectively and rapidly communicate with colleagues and external stakeholders.

The information technology industry changes rapidly, making it a challenge for utility managers and staff to stay current. Even the name of the utility's "computer department" is evolving: staff may call it Data Processing (now generally considered

outdated), Management Information Systems (MIS), Information Services, or other names. (In this chapter, the term *information technology* refers to information systems, hardware, software, and the associated business processes required to select, implement, and manage the technology.)

Basically, management information systems can be divided into four categories: hardware, software, data, and supporting business processes. *Hardware* refers to the physical devices used to input, store, process, and exchange data [e.g., mainframes; servers; routers, switches, and other network devices; and personal computers (PCs), personal digital assistants (PDAs), printers, copy machines, private branch exchanges (PBXs), video cameras, and programmable logic controllers (PLCs)]. Hardware's lifespan varies but typically ranges from 3 to 7 years. *Software* is any program that runs on the hardware. Its typical lifespan ranges from 3 to 10 years or longer. Software upgrades (often called "maintenance") extend this lifespan. *Data* are the content manipulated by the computer system. The lifespan of data is often very long—sometimes 100 years or more—spanning multiple generations of hardware and software. *Integration* is the concept of a unified system of hardware, software, and data (from a user's perspective).

Many wastewater utilities still have fairly primitive information management systems, and many of those with sophisticated systems have yet to truly leverage the benefits. The utilities that effectively manage their information and supporting technologies will be better positioned for future success (AWWA, 2001).

For management information systems to be effective, a utility's business processes (the way that work gets done) and its software must be aligned in the following eight areas (AWWARF, 2004):

- Overall/common (practices not unique to MIS, such as developing and training staff, managing and measuring performance, and handling customer feedback);
- Applications and integration;
- Data (practices related to data definition, standards, analysis and reporting, management, and quality);
- IT infrastructure management (IT assets, architecture, and help-desk practices).
- Service delivery and sourcing (service delivery alternatives, service level management, and software life-cycle management);
- IT organization, direction, oversight, and planning (governance and policy definition, budgeting, total cost of ownership, and business continuity);
- Program and project management (program management, project management, quality control, and testing strategies); and
- Security [risk-management and security issues (e.g., personnel security, production controls, and audit trails)].

TYPICAL SOFTWARE APPLICATIONS. Today, wastewater utilities typically use a number of software applications [e.g., e-mail, word processors, spreadsheets, graphics applications, Laboratory Information Management Systems (LIMSs), and financial management systems]. To reduce the costs of integration, these applications should be based on common standards.

Following are some typical software applications found at wastewater utilities.

Computerized Maintenance Management System. A computerized maintenance management system (CMMS) [also called a computerized work management system (CWMS) or a work management system (WMS)] enables utilities to manage maintenance work and minimize equipment downtime cost-effectively. The system is designed to plan, schedule, and manage maintenance activities; control parts inventories; coordinate purchasing activities; and help prioritize long-term asset investment needs.

A CMMS typically consists of the following six components:

- Work management (corrective, preventive, and predictive maintenance scheduling, activities, and procedures);
- Equipment inventory (an inventory and description of equipment and support systems requiring maintenance, along with other technical or accounting information);
- Inventory control, tools, and materials management (materials, tools, and spare parts management, scheduling, and forecasting);
- Purchasing or procurement (maintenance-related requisition, procurement, and accounting);
- Reporting and analysis (standard and ad hoc reports); and
- Personnel management (staff skills, wages, and availability).

Effective CMMSs range from single-user PC systems to comprehensive networked client–server-based systems for utilities with several hundred maintenance personnel in multiple locations. While a manual maintenance system may seem adequate for small treatment plants, they should consider converting to a PC-based CMMS to enhance record accessibility, sharing, and security.

Relatively new to the wastewater treatment industry, CMMSs are used extensively in other industries. The rising popularity of CMMSs at treatment plants is the result of concerns about deteriorating infrastructure, the need for better asset management, and related new regulations [e.g., Governmental Accounting Standards Board (GASB) 34 and the capacity, management, operations, and maintenance (CMOM) rule].

The information from a CMMS, especially that pertaining to major equipment and work history, is an integral part of an asset management plan.

Some utilities connect key assets directly to the CMMS, so it can automatically create work orders based on vibration analysis, lubricant analysis, thermography, and other real-time data. Some connect the process control system (PCS) to the CMMS, so it can automatically generate work orders based on equipment run time.

Geographic Information System. According to Huxhold (1991), at least 80% of data collected and used for utility and environmental information systems are related to geography. Geographic information systems (GISs) allow users to link databases and maps to better see topographical-related patterns and trends. These systems are often at the center of a utility's data integration strategy because they are data-intensive, can use data from many sources, and can be specialized to meet specific utility needs.

Laboratory Information Management System. According to *Good Automated Laboratory Practices* (GALPs) (U.S. EPA, 1995), a LIMS is an automated system that collects and manages laboratory data. It typically connects the lab's analytical instruments to one or more PCs that are part of the utility's overall network. (Sometimes the interface software is custom and complex.) A full-featured LIMS can track chain-of-custody forms, print bar codes for sample containers, hold data in the queue until all validations are completed, generate various trend charts and reports, perform on-the-fly sample cost analyses, bill customers, monitor quality assurance and quality control activities, track instrument calibration and maintenance, and control inventory. Various levels of security and access are available.

There is virtually a limitless range of possible configurations for LIMSs. However, not all automated laboratory systems are LIMSs; those that record data but do not allow changes (e.g., analytical balances) are not LIMSs (Figure 6.1). The agency's GALPs are intended for comprehensive LIMS configurations in which data are entered, recorded, manipulated, modified, and retrieved.

When implementing a LIMS, laboratory managers should ensure that

- Personnel, resources, and facilities are adequate and available as scheduled;
- Personnel clearly understand the function(s) they will perform on the LIMS;
- Each applicable GALP is followed;
- There are standard operating procedures (SOPs) to protect raw LIMS data integrity;
- A quality assurance unit (QAU) monitors LIMS activities;
- Any deviations from SOPs and applicable GALPs are corrected and both the deviation and correction are appropriately documented;

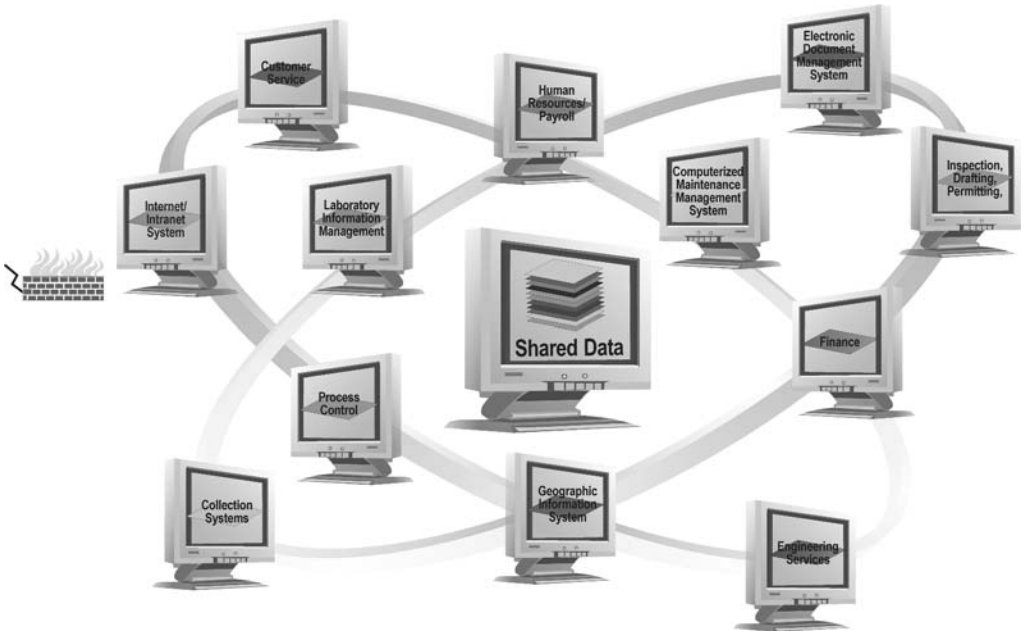


FIGURE 6.1 An integrated system makes data available across systems.

- Appropriate changes are subsequently made to SOPs; and
- Any data deficiencies noted in LIMS QAU inspection reports or audits of raw LIMS data are promptly corrected.

Human Resources Management System. A comprehensive human resources management system (HRMS) can provide flexible, accurate control over payroll accounting and all employee personnel records, as well as in-depth inquiry and reporting capabilities. It also includes payroll, benefits administration, and pension administration. Advanced HRMSs often support career development, training, and succession planning. They are sometimes supplemented by a training information management system (TIMS), which tracks personnel training.

Financial Information System. A financial information system (FIS) typically includes modules on general ledger, budgeting, accounts receivable, accounts payable, project management, investment tracking, and job costing. (Many wastewater utilities do not use the accounts receivable module because their needs are too simple for it to be practical.) Ideally, the FIS should be interfaced with the CMMS and other applications involving inventory management, fixed-asset management, and other cost-related issues.

Process Control System and Supervisory Control and Data Acquisition System. Process control systems and supervisory control and data acquisition (SCADA) systems automatically monitor and can control wastewater collection, treatment, and disposal processes in real time. Except for the instrumentation used to collect field data and control equipment (e.g., start or stop a pump), their hardware and software components are basically the same as those used in business information systems. In fact, both PCSs and SCADA systems can interface with business systems to promote cost-effective operations (e.g., enable plants to calculate up-to-date energy, chemical, labor, and other costs so control algorithms can be adjusted, if possible).

The hardware has become relatively inexpensive and simple to install, program, and maintain, so even the smallest wastewater treatment plants can afford to automate their processes (WERF, 2002). Some large wastewater utilities connect their PCSs or SCADA systems to dynamic models, so they can continually predict how influent conditions will affect performance and automatically adjust key operating parameters as needed (WERF, 2002).

The same security considerations that apply to other business systems also apply to PCSs and SCADA systems.

Personnel Productivity Applications. There are many applications available to enhance utility personnel's productivity (e.g., word processors, spreadsheets, graphics software, e-mail, and calendars).

Collaboration Software. Web-based software (e.g., wikis, blogs, and virtual meeting software) allows staff, vendors, consultants, and regulators to share ideas, solve problems, and jointly develop or review reports from any location at any time.

Other Support Systems. Many utilities have electronic controls for heating, ventilation, and cooling (HVAC); interior lighting; and emergency and security systems (e.g., fire alarms, electronic key access, motion sensors, and closed-circuit television cameras). To help reduce energy costs, the heating and cooling controls should be optimized based on work schedules.

In addition to these core applications, there are a number of other software applications that wastewater utilities require, depending on their size and complexity. Wastewater models, for example, can predict inflow and precisely describe combined sewer overflows (CSOs) from collection systems into receiving waters. Capital projects planning and management systems help utility staff manage construction budgets and schedules. Many utilities use an electronic document management system to manage all the documents generated as part of conducting business. These systems, which can convert paper documents into electronic format, allow multiple users in multiple loca-

tions to "share" the same document. Their capabilities typically include check-in and check-out, version control, categorization, search, and archive. An electronic document management system is similar to a records management system, which provides a centralized location to store, access, and retrieve critical information sources in compliance with legal requirements. All of these applications are commercially available, and most wastewater utilities have adopted or are migrating to a strategy of procuring them from vendors rather than developing custom applications.

In addition, many utilities now have developed custom Web-enabled systems that may be used via intranet (internal communications) or Internet (external communications). These Web-enabled systems consist of various technologies (e.g., relational databases, user interfaces, and messaging systems) and allow varying levels of integration with other utility systems. They may provide a portal to other systems.

Most wastewater utilities have implemented a local area network (LAN), which allows users at different computers to share data, and have connected to a wide area network (WAN), which links multiple LANs. Utilities also typically are connected to the Internet and can electronically communicate with others, regardless of their location. The clear trend is for utilities to exchange data electronically with individuals (via e-mail and a utility's Web site) and other businesses (e.g., electronic banking between the utility and its bank). As utility Web sites become richer and offer more capabilities (e.g., allowing significant users to enter their own data), the utility's internal business processes must become more streamlined and reliable. This typically involved redesigning the business processes.

The U.S. Environment Protection Agency (U.S. EPA) is moving toward accepting electronic reports via the Cross Media Electronic Reporting and Recordkeeping Rule [40 *CFR* 3 (New) and 40 *CFR* 9 (Revision)], which provides a legal framework for electronic reporting and recordkeeping under the agency's environmental regulations. The intent is to provide a uniform, technology-neutral framework for electronic reporting and recordkeeping across all U.S. EPA programs. The final rule, which was published in the *Federal Register* in October 2005, does not mandate electronically submitted reports or records but does

- Modify requirements in the *Code of Federal Regulations* to remove any obstacles to electronic reporting and recordkeeping;
- Allow regulated entities to submit any report or maintain any record electronically once U.S. EPA announces that electronic reporting or recordkeeping is available for that document;
- Require electronic reports to be submitted via U.S. EPA's central data exchange (CDX) or another designated report-submittal system;

- Require validation of electronic signatures on reports submitted electronically (valid electronic signatures have the same legal force as their "wet-ink" counterparts); and
- Set forth electronic-reporting requirements that U.S. EPA-authorized programs must satisfy and provide a streamlined process for the agency to approve of electronic-reporting implementations.

A utility's software applications may reside at a variety of locations. For example, the FIS may be in the municipal administration building downtown, the GIS may be distributed across multiple locations, and some parts of the CMMS may be implemented via wireless devices used by mobile maintenance staff.

The software applications may be supported and maintained via utility staff, staff augmented by contractors or consultants, a third-party vendor, or another outsourced arrangement.

Integrating these applications is a major management issue for many utilities. Integration has many advantages but can be expensive (Figure 6.1). There are a number of strategies that can be adopted to integrate systems, each with advantages and disadvantages.

Cost-effectively implementing, using, and supporting all these systems includes making sure business processes are aligned with technology, ensuring the technology addresses overall business requirements (not individual needs), adequate training for end-users and support personnel, sufficient support resources, and standardization. Successful technology deployment requires addressing not only technology issues, but also organizational issues and business processes.

Particular challenges often include issues related to integration, data management, governance, and staff skills.

INFORMATION TECHNOLOGY GOVERNANCE

Effective governance ensures that a utility's IT investment meets its business requirements and produces expected results. A good governance method should ensure that the

- Goals are clearly defined,
- Business and IT strategies are aligned,
- IT issues are understood,
- Strategies can be implemented efficiently,
- Related risks are managed, and
- Progress is tracked and reported.

Effective governance means that technology decisions and investments are based on good business practices. In other words, the "customer's" needs are addressed, managers receive regular feedback, technology investments are planned, the desired results are clearly identified before final signoff, and the resulting process is audited after the technology has been implemented.

PLANNING AND ORGANIZING. Every wastewater utility should have an IT strategy. Developed by a cross-functional team with strong management support, the strategy should set the overall direction, establish key standards, identify and prioritize major projects (including each project's purpose, schedule, and estimated costs), and account for utility-support issues (e.g., training, required resources, and reporting requirements). The strategy also should specify how various applications will work together so users can easily enter, access, and use the utility's data. It should be updated annually and completely overhauled every 3 to 5 years (or whenever a major shift occurs in the utility's strategies).

In addition to technical and financial issues, the IT strategy should address organizational issues (e.g., centralized, distributed, matrixed, or some combination) and personnel needs. The utility's IT staff must have the skills to implement the strategy, or else the strategy should provide a mechanism for them to acquire the necessary skills. Also, staff retention is becoming important as the baby boom generation begins retiring.

Each year, the utility should create an IT operations plan that specifies which IT strategy elements staff will accomplish. Then at the end of the year, utility staff should review the related accomplishments and lessons learned, and then generate a new, appropriate IT plan for the upcoming year.

When working on the strategy, team members should be judicious in requesting custom software. Historically, all IT departments wrote custom software for their organizations, but now many more applications are commercially available. Software should only be custom-developed when no viable commercial off-the-shelf (COTS) package meets the utility's need.

As a result of the shift from custom to COTS applications, IT jobs are now primarily about project management rather than software development. So, the strategy should account for the training that existing staff need to become effective project managers. (Managing IT projects is similar to managing any other project; it requires clear charters, teams, timelines, and costs, as well as involvement by key stakeholders.)

ACQUISITION AND IMPLEMENTATION. To ensure that any new information technology will meet the utility's business needs and deliver the required results, the

project team should first define the goals and requirements. Team members also should become familiar with the possibilities and limitations of the available COTS technology, so they can make the best decisions.

In addition, the team should examine the business process that will be affected by the new technology. Often, this business process needs to be redesigned when the new technology is deployed or else the workload will increase because employees are struggling to do things the old way, while the system requires things to be done in a new way. The struggle typically results in a failed technology, or at best, its anticipated benefits fail to materialize.

The project team also must decide which procurement option is preferred. Software may be "purchased" (i.e., utilities may purchase licenses to use the software), leased from a vendor, or run on a third-party's Web site [i.e., rented, using an application service provider (ASP) model]. Software financing and licensing approaches vary significantly and change frequently, so the team should evaluate the options carefully when selecting a new technology.

Commissioning the system requires as much focus as selecting it. There are several key steps:

- Documenting the new system and how it will be used,
- Training technical staff and others to use it,
- "Cleansing" the data,
- Developing the necessary reports, and
- Conducting a postimplementation audit (i.e., assessing whether the desired results were achieved and whether more benefits can be gained).

Data cleansing is the process of improving data quality when migrating data from an old application to a new one. The team should evaluate the existing data for quality problems (e.g., missing, incorrect, incomplete, or redundant data) and take the necessary steps to solve them. Often overlooked, data cleansing ensures that the new system has correct and complete data expected by users.

ONGOING SUPPORT. Once implemented, the new technology will require ongoing support from both the vendor and the utility's IT staff to function properly and optimize its effectiveness.

Support Services. Utilities should establish the minimum level of support services expected from the technology vendor or on-site IT staff. If the utility signs a Service Level Agreement (SLA) with the vendor, the minimum service levels should be well-defined

to ensure that the utility gets what it pays for. Aspects to consider include vendor response time, escalation procedures, the problem tracking mechanism, frequency of upgrades, upgrade documentation, training requirements, and duration of the support contract. Some utilities avoid vendor SLAs because they do not think the services provided are worth the costs involved. They prefer to develop an in-house SLA, which enables technology users and IT staff to jointly define expectations and discover the cost implications of a particular level of support.

Poorly executed SLAs can result in antagonistic relationships between the service provider and the service receivers. A well-executed SLA requires significant management involvement. For example, expected and actual service levels should be regularly compared, reported, and adjusted as necessary.

Training. Training should be provided on a "just-in-time" basis. Staff new to a technology cannot absorb expert-level training because they are simply trying to understand the basics. However, the training can be very valuable later, when staff gain more experience. Follow-up training helps reinforce new concepts, resolve misunderstandings, and promote acceptance of the new technology.

Ongoing Technology Management. Technology management involves adapting reports or creating new ones as users gain experience, changing configurations, addressing problems and complaints, and other user-driven support needs.

Maintenance. Technology maintenance includes backing up files (and occasionally restoring some part of the system to ensure that the correct files have been backed up and that the backup/restore system operates as expected); applying software patches and updates; tuning the databases, operating system, and hardware; and ensuring license compliance as users are added.

Security. Information security should be a part of a utility's overall security strategy. Appropriate security measures should be defined and implemented in tandem with the new technology itself, and everyone must follow proper IT security practices (e.g., password maintenance; no shared passwords; and appropriate security updates as people leave the utility, take on new roles and responsibilities, etc.). Also, the security system should be audited periodically to confirm that it is appropriate and effective. For mission-critical systems, this may include probes and attacks to prove that the protection works.

MONITORING. Monitoring ensures that the new technology is delivering intended results, that risks are mitigated, and that issues are managed appropriately. Effective monitoring is a matter of measuring and regularly reporting on appropriate perfor-

mance indicators—perhaps in the form of scorecards (e.g., the Balanced Scorecard, customer-satisfaction assessments, management reporting, and external assessments). Monitoring reports should illustrate the technology's current effectiveness and recommend improvements, as needed.

TYPES OF RECORDS

What is a record? According to 44 U.S.C. Chapter 33, Section 3301, *records* include "all books, papers, maps, photographs, machine-readable materials, and other documentary materials made or received by a U.S. government agency under federal law or in connection with the transaction of public business and preserved or appropriate for preservation by that agency or its legitimate successor as evidence of the organization, functions, policies, decisions, procedures, operations, or other activities of the government or because of the informational value in them." So, records can take many forms (e.g., printed or "hard" copy, electronic or "soft" copy, and even e-mail and voicemail).

Records are the backbone of all management systems. Capturing and managing records are not only regulatory requirements, but also vital to well-run operations. Each record houses important information for a multitude of "lookup" uses. When linked with other records and organized chronologically, spatially, or in some other pattern, they enable utility staff to analyze the age, condition, and many other attributes of the facilities and make highly informed decisions. Therefore, records should be accurate, accessible, and yet secure to ensure that utility have the best information available.

Following are the types of records that most wastewater utilities need to manage.

PHYSICAL PLANT RECORDS. Utility staff should always have easy access to current records of the physical treatment plant. Such records typically include construction specifications; the engineer's design report; as-built drawings of the wastewater treatment, pumping, and collection facilities; a map of the collection system; an O&M manual; equipment descriptions; shop drawings; manufacturers' literature; and manufacturers' O&M instructions.

Records of existing facilities and equipment are not only invaluable to O&M staff handling day-to-day operations, but also to managers scheduling services, regulators evaluating permit compliance, and engineers and contractors designing and constructing facility improvements or additions. The format and content of these records should remain as consistent as reasonable, while allowing for useful improvements. For example, paper-based O&M manuals typically did not include record drawings because they were too large. Instead, the drawings were stored in bins, file drawers, or plan

racks. However, electronic record drawings [produced via computer-aided design (CAD) software] can be linked to electronic O&M manuals and continually updated by engineers.

Record Drawings. Record (as-built) drawings of a wastewater collection and treatment system provide a concise, illustrated record of each item of equipment, its location, and its relationship to other pieces of equipment. They typically include a hydraulic profile, flow schematics, valve tables, and diagrams. The drawings are categorized as mechanical, electrical, civil or structural, architectural, instrumentation and controls, and landscaping. A large wastewater utility may have to manage several thousand of them.

Record drawings are used by engineers, O&M staff, consultants, and contractors for planning; project design, development, and management; procurement of equipment and materials; construction management; and O&M support. They typically are produced toward the end of a new construction project and should be updated whenever the project is rehabilitated or undergoes major repairs. The drawings or updates should be completed and checked before project closeout.

Plant engineers may establish utility-specific standards for submitting, updating, indexing, or layering record drawings. Typically, engineers note significant modifications or additions on the appropriate tracings (or electronic CAD files) and revise the record drawings accordingly. Doing this simplifies future repairs, modifications, or additions considerably.

Operations and Maintenance Manual. The O&M manual describes each basic piece of equipment and explains its function, capabilities, and effect on other units, as well as the factors that affect its operation (Table 6.1). It also should include technical information (e.g., vendor-provided specifications), model and serial numbers, and graphics or photographs (especially if the equipment is submerged or buried).

The manual should serve as an instruction manual for inexperienced personnel and a useful reference for experienced ones, so the information must be clear and easy to find. A properly written O&M manual also should help operators establish SOPs—documented, utility-specific methods for performing various O&M activities. The procedures also should note all related safety measures (e.g., emergency procedures, hazardous materials and waste-handling procedures, and lockout or tagout procedures) and reflect the degree to which the PCS and the CMMS are integrated.

Operations and maintenance manuals should be electronic whenever possible so they can be updated easily. When paper-based O&M manuals are converted into an online interactive document, they should include search engines to help staff find information quickly. Forms available electronically should have links to the related

TABLE 6.1 Topics an operations and maintenance manual should cover.

1. Managerial responsibility, effluent quality requirements, and plant description.
2. Copies of water quality standards and permits.
3. Operation and control of wastewater treatment facilities.
4. Operation and control of sludge handling facilities.
5. Personnel qualifications and requirements and number of people to be employed.
6. Laboratory testing.
7. Records.
8. Safety.
9. Maintenance.
10. Emergency operating response program.
11. Utilities.
12. Electrical system.

SOPs so staff can print them or access them on portable devices (e.g., PDAs or notebook computers) that can be used in the field, thereby encouraging better plant performance and asset preservation.

Manufacturers' Literature. Manufacturers' literature is the best source of detailed information on a particular piece of equipment. It typically includes shop drawings with fabrication and construction details, installation directions, recommended operating guidelines, and suggested lubricants and maintenance instructions. It also may include exploded views and parts lists; shop drawings; recommended O&M schedules; data on each part (e.g., names, model numbers, types, sizes, certifications, and warranties); and suppliers' names, addresses, and phone numbers.

This information is often accessible via the CMMS for ongoing maintenance and asset management purposes, and via the PCS to support ongoing operations.

Equipment Descriptions. An equipment description typically is a 1-page form in the O&M manual that provides key information on a piece of equipment, a checklist of routine maintenance activities, and a record of repair and overhaul services done. It also may include a list of tools, parts, and consumable items (e.g., filters and lamps) needed for routine maintenance and emergency repairs.

Specifications. *Specifications* provide a detailed description or assessment of the requirements, dimensions, materials, and so on needed for a construction project. The specifications accompanying utility construction drawings typically include the following data:

- Descriptions of equipment and their capacities (e.g., pumping capacity);
- The proper materials (e.g., polyvinyl chloride pipes for chemical solution lines and ductile iron pipe for pressure lines) needed;

- Details about the quality of materials, workmanship, and fabrication required;
- Details about related appurtenances and chemicals;
- Descriptions of the construction procedures (e.g., proper pipe bedding and backfilling procedures) to be used;
- A program for keeping existing services in operation during construction;
- A shutdown schedule (if service must be interrupted);
- An outline of the performance tests needed to ensure that the completed work meets design standards; and
- Other data not included in the construction drawings.

Utility staff should keep copies of the specifications for each construction project. Addenda often supersede parts of the specifications, so they should be filed in the same place.

Design Engineer's Report. Essentially, the design engineer's report should justify the project team's design selections. It typically includes brief descriptions of the project and the existing conditions, discussions of design parameters and testing results, justifications of the design recommendations, and the engineer's cost estimate. It should also note the project's service areas, their projected populations, the design capacities and parameters used, and the basis on which the facility was designed.

COMPLIANCE REPORTS

Discharge Monitoring Reports. Under the 1972 Clean Water Act (CWA), wastewater treatment plants must have National Pollutant Discharge Elimination System (NPDES) permits. These 5-year permits limit the volume of effluent that may be discharged and the concentration of pollutants that it may contain. They also dictate how often the wastewater must be tested (e.g., daily, once a week, or twice a week) and what types of samples (e.g., grab, 8-hour composite, or 24-hour composite) must be analyzed.

In addition, the CWA requires wastewater utilities to submit monthly NPDES monitoring reports [called *discharge monitoring reports* (DMRs)] to U.S. EPA and state regulators. (Some small treatment plants may submit DMRs quarterly as required by permit.) The report forms, which note all effluent limits, are prepared by the U.S. EPA in accordance with each treatment plant's permit.

There are applications that enable operators to generate DMRs quickly. If the treatment plant's monitoring information is already stored electronically, then DMRs can be generated via templates, which contain the permit limits and calculation logic needed to generate DMR results. These results can be reviewed, refined, and approved as necessary before utility personnel print the final DMR for submission. Some

utilities now submit computer-generated versions of DMRs—or just the data itself—electronically.

Occasionally, questions arise about permit limits, sampling requirements, reporting frequency, or contact information. So, NPDES permit limits and related information should be kept current and made readily available and searchable online.

Wasteload Management and Projection Reports. Wasteload management and projection reports help utilities predict influent organic and hydraulic loadings 5 years into the future to determine whether they will exceed those of a treatment plant, pumping station, or collection system. The information enables utility managers to make practical decisions about extending collection systems and expanding treatment plants. The reports typically are filed with regulators and updated annually.

Utility staff begin by calculating the annual average flow, three consecutive maximum monthly average flows, and the biochemical oxygen demand (BOD) contribution per person. This information can be determined from reliable influent BOD, flow, and service population data. Statistics show that the per-person BOD contribution is approximately 0.07 to 0.09 kg/cap (0.15 to 0.2 lb/cap), and the average wastewater flow per capita ranges from 0.3 to 0.5 m^3/d (75 to 125 gpd). Comparing the utility's data to established norms will show staff whether there are significant differences that should be investigated.

Staff can obtain the capacities of pumping stations, treatment plants, and collection systems from the design engineer's reports or the NPDES permit applications. They then should predict the future population based on census data and known growth patterns. (Between censuses, staff should use approved developer plans and issued building permits to predict population changes.)

Staff then make wasteload projections based on population projections and estimated per-capita hydraulic and organic loadings. If the 5-year wasteload projections exceed the facilities' capacities, staff should take steps to plan appropriate facility expansions or restrict growth in the relevant area(s).

Pretreatment Program Reports and Records. Pretreatment programs are designed to control discharges of "known" priority pollutants to wastewater utilities so they do not endanger utility employees, damage biological treatment processes, or accumulate in biosolids or receiving waters (U.S. EPA, 1983). (For more information on pretreatment programs, see Chapter 4.)

Pretreatment program records typically include the following information:

- The program development report, which contains a pretreatment ordinance based on U.S. EPA's model pretreatment ordinance;

- Industrial wastewater permit applications;
- Copies of permits issued, including special conditions;
- Administrative records on sampling and testing costs;
- Inspection records;
- Enforcement records;
- Compliance schedules; and
- The annual pretreatment program report required by U.S. EPA.

A separate file must be maintained for each industrial discharger. Utilities should seriously consider an electronic information management system for this program because of the large amount of data and recordkeeping involved. Over time, the accumulated data can help utility staff troubleshoot malfunctioning processes and improve process-control efficiency.

There are applications available to manage industrial discharge permits (e.g., calculate draft limits, track permit revisions, generate permit documents, and enable the contents of these documents to be searched). They also can generate self-monitoring report (SMR) forms for pretreatment program participants to use. Once the sampling results or completed SMRs have been added to the database (manually or imported from a LIMS or Internet-based SMR module), the applications can automatically detect noncompliance events and notify both utility and industrial staff via e-mail. Another important application feature to consider is automated evaluations of significant noncompliance, according to a U.S. EPA guidance document (U.S. EPA, 2002). Whenever this feature detects a violation, it would record the incident for further action and issue a Notice of Violation.

Toxics Reduction Evaluation Records. The U.S. Environmental Protection Agency requires that the toxics (also called *priority pollutants*) discharged to wastewater utilities be regulated. Whenever NPDES permits are being renewed, utilities with industrial customers (e.g., manufacturers, hospitals, medical centers, and water purveyors) must test treatment plant influent and effluent for toxics. (For a list of identified toxics, see CWA §307.) If toxics are found, the NPDES permitting authority will set effluent toxics limits for the treatment plant.

To achieve these limits, the utility must begin with a *toxics reduction evaluation* (TRE)—sampling and analysis of potential on-site and off-site sources to determine how the toxics are entering the system. These evaluations should be coordinated by a multidisciplinary team of toxicologists, chemists, engineers, and plant personnel. The overall goals of a TRE are to

- Sample potential sources of toxics,
- Characterize any toxics found in a sample,

- Pinpoint the source(s) by evaluating changes in toxicity after various chemical and physical processes, and
- Implement measures to reduce and eliminate the toxics.

In the process, the team must compile extensive records of each sample; these records include field collection sample forms, chain of custody forms, and quality assurance project plans. Team members examine these testing records to determine the significant contributors of toxics. Depending on the source, the toxics then can be abated via an in-house pollution prevention program, new pretreatment facilities, or household-chemical regulations (implemented by U.S. EPA). The identified toxics also are continuously monitored via NPDES reporting.

Risk Management Program Reports. Clean Air Act §112(r)(7) requires U.S. EPA to develop a Risk Management Program (RMP) to help prevent accidental releases of regulated substances (e.g., chlorine gas, methane, and various flammable compounds) and reduce the severity of a release if one occurs. So, utilities and other organizations must develop and implement RMPs in accordance with the agency's accidental release prevention regulations (40 *CFR* 68).

For more information on RMP guidance and related records such as air-dispersion modeling results and storage records see http://yosemite.epa.gov/oswer/ceppoweb.nsf/content/EPAguidance.htm#Wastewater and http://yosemite.epa.gov/oswer/ceppoweb.nsf/content/RMPS.htm.

Capacity, Management, Operations, and Maintenance Compliance Reports. Under U.S. EPA's draft proposed Sanitary Sewer Overflow (SSO) Rule, collection system utilities must meet five performance standards:

- Properly manage, operate, and maintain all parts of the collection system;
- Provide adequate conveyance capacity;
- Reduce the effect of any SSOs;
- Notify parties who may be exposed to an SSO; and
- Document the CMOM program in a written plan.

The CMOM program is a structured framework designed to help utility staff properly manage the collection system to optimize system performance, maintain facilities and capacity, and respond appropriately to any overflows. Currently, most wastewater utilities are developing strategies to meet anticipated CMOM requirements, and some are implementing them.

Training and recordkeeping are important aspects of a CMOM program. One best management practice is ensuring that O&M staff have the necessary knowledge and

skills to keep the collection system functioning optimally. Each employee should be trained as is appropriate for his or her roles and responsibilities, and the O&M staff should keep staff-training records.

Another important aspect is an overflow response plan (a preparedness plan to deal with sewer overflows or line breaks). *Preparing Sewer Overflow Response Plans: A Guidebook for Local Governments* (APWA, 1999) is designed to help municipalities prepare overflow response plans. The guidebook's model plan includes objectives and organization, overflow response procedures, public advisory procedures, regulator notification procedures, media notification procedures, and steps to distribute and maintain the plan.

The overall goal of a CMOM program is to create a regular and consistent cycle, a more proactive approach to collection system maintenance. To ensure future CMOM compliance, utilities should optimize their collection systems, focus on eliminating preventable SSOs, and train their O&M staff appropriately. To determine how well the CMOM program is working, utilities should identify performance measures that correspond to program goals and track them. The following are commonly used performance measures:

- Number of customer complaints,
- Number of overflows,
- Number of blockages per mile,
- Number of pump station failures,
- Ratio of base flows to peak wet weather flows,
- Number of manholes inspected, and
- Miles of sewer cleaned.

The information needed to create a CMOM plan and monitor compliance can be found in the following documents:

- Collection system maps,
- Collection system design and construction standards,
- Complaint logs,
- Work orders,
- Sewer assessment reports,
- Standard maintenance procedures,
- SOPs,
- Typical forms used by field and office personnel,
- Organization charts, and
- Safety and training program manuals.

Air Pollution Control Permit Reports. Local or regional air-pollution-control districts may regulate ambient air emissions from some wastewater utilities. The permits they issue may require utilities to report odor-control equipment outages, unusual plant conditions, unusual wastewater or biosolids characteristics, and complaints from the public or other agencies. Traditionally, the related recordkeeping was paper-based, but SCADA systems, CMMSs, and Customer Information Systems provide automated alternatives.

OPERATING RECORDS. Operating records consist of daily logs, weekly operating reports, monthly operating reports, and laboratory records. All of the data involved should be pertinent and useful because recordkeeping—especially manual recordkeeping—can be expensive and time-consuming. Traditionally, most recordkeeping was paper-based, but now most treatment plants are implementing computerized recordkeeping systems.

An operations management system (OMS) collects both plant operating data and laboratory test results. It also enables users to analyze the data and produce regulatory and other routine reports. There are many types of OMSs available. Some integrate real-time PCS or SCADA system data with water quality, flow, and related data. Some also address safety, quality control, and environmental management requirements. Many are intranet-based, so utility employees can access it directly via a WAN and remotely via dial-in facilities. All are updated regularly—so users typically have access to current information—and include links to SOPs, regulators' home pages, and O&M, health, safety, and other reference documents.

All of the records in this section can be directly integrated into an OMS. Operators should only keep those that are pertinent to wastewater processing, management, and administration. Any data that are not needed to control treatment processes or determine their efficiencies should not be entered into the system. [For more information on process control testing, see *Activated Sludge* (WEF, 2002).]

Because only laboratory test results can illustrate final effluent quality, all results—both good and bad—must be secure and reported accurately, even if the permitted parameters are monitored more frequently than regulators require. The NPDES permit requires that all results obtained via NPDES testing must be reported.

Daily Operating Records. There are typically three forms of daily records—plant logs, daily bench sheets, and routine reports—and they may be paper- or computer-based. The data in these records include wastewater and treatment process measurements, power used, weather (e.g., temperature, rainfall, and other hydrological data), and

other physical information. These data may be collected every few seconds, minutes, or hours, or only when the parameter has changed by at least a preset interval. They may be entered manually or via a PCS or SCADA system.

Daily administrative data include routine reports on personnel, payroll, small purchases, and related information that may or may not be part of an OMS.

In addition, a plant log may contain data on the progress of construction or maintenance work, equipment failure(s), employee accidents, floods or unusual storms, process bypasses, complaints registered, the names and affiliations of all visitors, and other matters. These data are valuable references.

These daily operating records can be the first step in a performance improvement program.

Weekly and Monthly Operating Reports. In addition to the data in daily operating records, weekly and monthly operating reports contain pertinent information on wastewater treatment operations (e.g., sedimentation, aeration, disinfection, digestion, and solids management). Such process-control data include air application, centrifuge test, chemical dosages, clarifier loading, digester gas production, influent flow, mixed-liquor volatile suspended solids, organic loading, sludge age, mean cell residence time, microscopic analyses, return sludge flow, sludge blanket levels (via sludge judge or instrumentation), sludge settleability (via settleometer), sludge volume index, wastewater flow, and waste sludge quantity (yield).

Monthly operating reports should contain a summary of all data collected daily or weekly. Calculating monthly averages of useful process-control parameters can help reveal trends (e.g., consistent performance or changing conditions).

The reports should be printed on good-quality paper so they are suitable for submission to local regulators. (For samples of reports formatting and the types of data required, see Figures 6.2 through 6.7.)

Analyses of weekly and monthly report data will show any departures from previously established norms—especially when graphing both test results and operating parameters. For example, comparing a plot of mixed-liquor suspended solids versus time with a 7-day moving average versus daily data can reveal whether the amount of solids under aeration is adequate for treatment and if the wasting rate is correct. [For more information, see *Activated Sludge* (WEF, 2002).]

Laboratory Records. Laboratory data must be recorded—at the very least, on printed bench sheets or in lab notebooks. Because there are no standard forms, most wastewater utilities develop their own data sheets for recording lab test results and calcula-

MONTH_____ 19____ Report Form for Treatment Plant Miscellaneous Data OPERATOR _____

Date	Weather				Raw Wastewater				Grit (cu. ft./ mil gal.)	Screening (cu. ft./ mil gal.)	Plant Effluent, Coliform Density (MPN/100 ml)	Chlorine (lb)	Power (kw-hr.)	Aux. Fuel†	Remarks
	Precip. (in.)	Temp. (°F) (max)	Temp. (°F) (min)	Type*	Temp. (°F)	Flow (mgd) Avg.	Flow (mgd) Max.	pH							
1 through 31 Average															

*C—Clear; W—Windy; CL—Cloudy; CA—Calm; R—Rain; S—Snow †Indicate kind and unit of volume

FIGURE 6.2 Report form for wastewater treatment plant miscellaneous data.

MONTH_____ 19____ Report Form for Treatment Plant Primary Treatment Data OPERATOR _____

	5-Day BOD					Suspended Solids					Suspended Volatile Solids				Remarks
	Influent		Effluent		Removal	Influent		Effluent		Removal	Influent		Effluent		
	(mg/L)	(lb)	(mg/L)	(lb)	(%)	(mg/L)	(lb)	(mg/L)	(lb)	(%)	(mg/L)	(lb)	(mg/L)	(lb)	
1 through 31 Average															

FIGURE 6.3 Report form for wastewater treatment plant primary treatment data.

VOLUME (cu. ft.) _____ MONTH _____ 19____ Report Form for Treatment Plant Trickling Filter Data RECIRCULATION PATTERN _____ OPERATOR _____

Date	R*	5-Day BOD					Suspended Solids					Suspended Volatile Solids		Removal		Remarks
		Primary Effluent (lb/day/ 1,000 cu. ft.)	Final Tank Effluent (mg/L)	Final Tank Effluent (lb)	Removal (%)	Removal (lb/day/ 1,000 cu. ft.)	Primary Effluent (lb/day/ 1,000 cu. ft.)	Final Tank Effluent (mg/L)	Final Tank Effluent (lb)	Removal (%)	Removal (lb/day/ 1,000 cu. ft.)	Final Tank Effluent (mg/L)	Final Tank Effluent (lb)	Total Plant BOD (%)	Total Plant Suspended Solids (%)	
1 through 31 Average																

*R= Filter Influent / Plant Influent

FIGURE 6.4 Report form for wastewater treatment plant trickling filter data.

Report Form for Treatment
Plant Activated Sludge Data

MONTH_____ 19____ OPERATOR _____

Date	Air Applied			5-Day BOD			Suspended Solids		Suspended Volatile Solids		Removal		DO Final Effluent (mg/L)	Mixed Liquor				Return Sludge		Waste Sludge (1,000 gal.)	Remarks
	(hr)	(cfm)	(cu. ft/lb BOD Rem.)	Primary Effluent (lb/day/ 1,000 cu. ft.)	Final Effluent		Final Effluent		Final Effluent		Total Plant			MLSS (%)	Settled Sludge Volume @ 30 min (SSV_{30})	Sludge Volume Index	DO (mg/L)	Q_{RAS}	SS (mg/L)		
					(mg/L)	(lb)	(mg/L)	(lb)	(mg/L)	(lb)	BOD (%)	SS (%)									
1 through 31																					
Average																					

FIGURE 6.5 Report form for wastewater treatment plant activated sludge data.

Report Form for Treatment
Plant Anaerobic Digester and Sludge Data

MONTH_____ 19____ OPERATOR _____

Date	Raw Sludge					Supernatant						Sludge near Bottom					Temp. (°F)	Gas		Remarks (include gal. of sludge to beds)
	(gal)	Loading (lb/1,000 cu. ft.)	pH	Total Solids (%)	Volatile Solids (%)	(gal)	pH	Total Solids (%)	Volatile Solids (mg/L)	Suspended Solids (mg/L)	5-Day BOD (mg/L)	Total Solids (%)	Volatile Solids (%)	Volatile Acids (mg/L)	pH	Alkalinity		Produced (cu. ft.)	Wasted (cu. ft.)	
1 through 31																				
Average																				

FIGURE 6.6 Report form for wastewater treatment plant anaerobic digester and sludge data.

Report Form for Treatment Plant
Aerobic Digestion and Sludge Data

MONTH_____ 19____ OPERATOR _____

Date	Raw Sludge							Digesting Sludge							Digested Sludge			Supernatant	
	Volume (gal.)	Leading (lb/1,000 cu. ft.)	pH	TS (%)	VS (%)	COD (mg/L)	N (mg/L)	pH	TS (%)	VS (%)	COD (mg/L)	N (mg/L)	DO (mg/L)	pH	TS (%)	VS Reduction (%)	N (mg/L)	TS (%)	N (mg/L)
1 through 31																			
Average																			

FIGURE 6.7 Report form for wastewater treatment plant aerobic digester and sludge data.

tions. The sheets should be designed to simplify the process of recording, reviewing, or recovering data.

A more sophisticated option would be LIMS software, which can automatically acquire data from instruments, manage lab work data, and store and print test results. [For more information on LIMS, as well as sound data management advice, see *Good Automated Laboratory Practices* (U.S. EPA, 1995).]

Laboratory records contain information related to the sample chain of custody, the test(s) performed on the sample, and the test results.

Industrial Waste Management Records. When industrial and domestic wastewater have similar characteristics, they typically are treated together because it is considerably less expensive to treat them jointly than separately. Municipalities that operate wastewater utilities typically have ordinances specifying the parameters that industrial wastewater must meet to be accepted by the utilities. Otherwise, the utilities' biological treatment processes could be damaged.

To ensure that the ordinances' requirements are met, municipalities periodically sample and test wastewater from nondomestic sources. They also should confirm that the industrial wastewater can be biologically treated.

So, industrial waste management records should include the following information:

- The industrial wastewater permit application and permit;
- The required sampling, analyses, and chain-of-custody records;
- Test results (preferably certificates of analyses issued by certified testing laboratories);
- Notices of ordinance violations, consent decrees, and other enforcement actions;
- Surcharge calculations for industrial wastewater discharges that were biologically treatable but stronger than domestic wastewater (e.g., higher concentrations of total dissolved solids, soluble BOD, BOD, total suspended solids, phosphorus, and ammonia-nitrogen);
- Compliance schedules (with milestone dates); and
- A record of all costs associated with the sampling and testing (suitable for billing purposes).

Industrial sources subject to pretreatment-program reporting requirements must maintain readily available, monitoring-related records for at least 3 years (longer if in the midst of litigation). All pretreatment activities should be documented and maintained in the manner prescribed by the utility.

The industrial pretreatment program authority should maintain the following records:

- Industrial waste questionnaire;
- Permit applications, permits, and fact sheets;
- Inspection reports;
- Industrial source reports;
- Monitoring data (e.g., laboratory reports);
- Required plans (e.g., slug control, sludge management, and pollution prevention);
- Enforcement activities;
- All correspondence to and from the industrial source;
- Phone logs and meeting summaries;
- Program procedures; and
- Program approval and modifications of the utility's NPDES permit(s).

A computerized data management system can make it easier for pretreatment program staff to track due dates, submissions, deficiencies, notifications, and so on, and calculate noncompliance with effluent limits. Many also use standard forms (e.g., inspection questionnaires, chains-of-custody, and field measurement records) and procedures (e.g., sampling and periodic compliance report reviews) to help organize data and ensure that they are consistent.

Program staff also must annually publish—in its area's largest daily newspaper—a list of industrial sources that were in significant noncompliance with their requirements at any time during the previous 12 months. In addition, 40 *CFR* §403.12(I) requires them to submit annual reports to the NPDES permitting authority. The reports must document the program's status and describe all activities performed during the previous calendar year.

All laboratory records must be based on U.S. EPA-approved analytical tests. Many of these tests can be found in the most recent edition of *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 1998).

Some pretreatment programs also develop local limits for pollutants (e.g., metals, cyanide, 5-day BOD, total suspended solids, oil and grease, and organics) to prevent interference, pass-through, sludge contamination, or worker health and safety problems at the wastewater treatment plant. Typically, these limits are imposed at the "end-of-pipe" discharge from an industry (i.e., where the company's discharge pipe connects to the plant's collection system).

Relating Recordkeeping to Operations. The analysis results that a utility chooses to record should reflect the treatment plant's operating conditions (e.g., influent flowrate, influent wasteload, the wastewater's characteristics and treatability, and effluent concentrations). With these data, operators should be able to determine how efficient each treatment process is and predict how the plant's effluent will affect receiving waters.

If the data are entered into a computerized OMS database, utility staff can analyze various trends more easily. Varying results, for example, would alert staff to expect difficulties in plant operations. Uniformly increasing loads could be evaluated to determine when wastewater loads will reach the plant's capacity. Sudden variations in results may reveal accidental discharges, collection-system damage, or other incidents.

Energy Management. Energy (e.g., electricity, gas, and fuel oil) is a significant line item in a treatment plant's operating budget. Many utilities' operating reports include a standard report or graph on energy use.

To manage energy costs, utilities should monitor the price and use of each form of energy via a PCS, SCADA system, or special monitoring equipment, so they can plot monthly trends and note changes. A formal energy audit, based on monitoring data and historical records, would show staff precisely how power is used on-site and how use varies throughout the day, week, and seasons. Utility staff also can determine the energy efficiency of each treatment process if they collect energy use, energy cost, and process volume statistics and plot daily or monthly trends (expressed as energy use or cost per million gallons treated). Once personnel have baseline information about each process' energy consumption, they can make changes (e.g., automate controls) to improve energy efficiency and measure resulting improvements.

Electricity's demand charges and other characteristics (e.g., lower-than-desired power factor) can be significant, so staff should be familiar with the electricity rate schedule. Operators could even have a list of equipment—chosen based on monitoring and energy audit data—that they could shut down during peak demand times without impairing treatment results.

PREVENTIVE AND CORRECTIVE MAINTENANCE RECORDS. Maintenance has become more important as permit limits become stricter and utilities become more automated. The former emphasis on *corrective maintenance*—fixing equipment when it breaks—is shifting to *preventive maintenance*—keeping equipment in good working order—and ultimately to comprehensive asset management to maximize the equipment's lifespan.

As a result of these changes, utilities need a dedicated, well-trained maintenance staff to keep their facilities in satisfactory repair. They also need a comprehensive maintenance management system to keep track of their activities.

Whether the maintenance system is computerized or manual, it should include equipment-, storeroom-, and inventory-management records; work-schedule records; budget records; and maintenance-cost records. The samples shown in Figures 6.8 through 6.11 illustrate the information typically needed to ensure that the equipment maintenance history is up to date.

Predictive Maintenance. A method for protecting valuable items, *predictive maintenance* involves testing equipment to identify incipient problems and scheduling whatever maintenance is needed to avoid them. The most common predictive maintenance methods are infrared thermography, vibration analysis, oil analysis, and surge testing. The equipment can sometimes be tested while in operation. (For more information on predictive maintenance methods, see Chapter 12.)

Work Order No. _____ Date _____

Location	Requested by: (Phone)	Priority:

Equipment Name	No.

☐ Inspect ☐ Replace ☐ Service

☐ Repair ☐ Overhaul ☐ Paint

Work Description

Work Performed/Comments

Job Estimate

Labor $ _____

Material $ _____

_____
Shift Operator

_____
Maintenance Superintendent

WORK ORDER

Personnel Assigned	Manhours	Date	Work Done	Parts & Materials
Total				

Work Completed By _____ Date _____

Work Accepted By _____ Date _____

FIGURE 6.8 Sample work order form.

Plant No. _____ MACHINE NO. _____ INVENTORY NO. _____ MOTOR NO. _____

H.P. _____ MANUFACTURED BY _____

SERIES SHUNT COMPOUND SYNCHRONOUS INDUCTION

TYPE FRAME SPEED VOLTS AMPERES

PHASE CYCLES TEMP. RISE EXCITATION AMPS. ROTOR OR ARM. SER. NO.

MODEL NO. FORM NO. STYLE OR S.O. NO. SERIAL NO.

MFGRS. ORDER NO. OUR ORDER NO.

CONNECTION DIAGRAM—ROTOR OR ARMATURE

SPECIFICATION	BEARINGS	SHAFT EXTENSION	PULLEY	GEAR	V BELT DRIVE
OPEN ☐	SLEEVE ☐	DIA. _____	DIA. _____	TEETH _____	NO. GROOVES _____
EXP. PROOF ☐	BALL ☐	LENGTH _____		PITCH _____	PITCH DIA _____
DRIP PROOF ☐	ROLLER ☐	KEYWAY _____	FACE _____	FACE _____	BELT SECTION
TOTALLY ENCL. ☐					☐ A-1/2x11/32
VERTICAL ☐					☐ B-21/32x7/16
_____ ☐					☐ C-7/8x17/32
					☐ D-1-1/4x3/4

MOTOR SERVICE RECORD

DATE INSTALLED	LOCATION	APPLICATION

DATE REPAIRED	REPAIRS OR PARTS REPLACED	CAUSE	REPAIRED BY	TOTAL COST

FIGURE 6.9 Sample motor service record—form 1.

MOTOR H.I. | A.C. | D.C. | TYPE | FRAME | R.P.M. | PHASE | CYCLES | VOLTS | DIVISION | SECTION

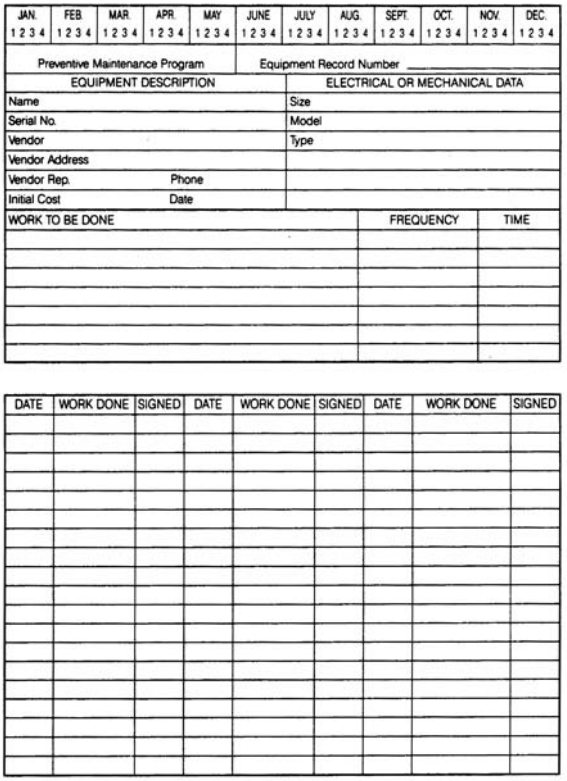
WINDING | TOOL NO. | STYLE NO. | SERIAL NO. | LOCATION-SECTION | COL. NO.

DATE INSTALLED	DATE IN STORAGE	DATE INSTALLED	DATE IN STORAGE	DATE INSTALLED	DATE IN STORAGE
DRIVES MACHINE	TOOL NUMBER	DRIVES MACHINE	TOOL NUMBER	DRIVES MACHINE	TOOL NUMBER

DATE	BLOWN OUT	BEARINGS	END PLAY	BRUSHES & HOLDER	COMMU.	MEGGER	GENERAL CONDITION	INSPECTED BY

DATE TAKEN OUT OF SERVICE _____ DATE SCRAPPED _____

FIGURE 6.10 Sample motor service record—form 2.



JAN. 1 2 3 4	FEB. 1 2 3 4	MAR. 1 2 3 4	APR. 1 2 3 4	MAY 1 2 3 4	JUNE 1 2 3 4	JULY 1 2 3 4	AUG. 1 2 3 4	SEPT. 1 2 3 4	OCT. 1 2 3 4	NOV. 1 2 3 4	DEC. 1 2 3 4

Preventive Maintenance Program	Equipment Record Number _____
EQUIPMENT DESCRIPTION	ELECTRICAL OR MECHANICAL DATA
Name	Size
Serial No.	Model
Vendor	Type
Vendor Address	
Vendor Rep. Phone	
Initial Cost Date	

WORK TO BE DONE	FREQUENCY	TIME

DATE	WORK DONE	SIGNED	DATE	WORK DONE	SIGNED	DATE	WORK DONE	SIGNED

FIGURE 6.11 Sample equipment record card.

Predictive maintenance records are simple (e.g., a vibration analysis printout of a bearing check, an infrared image of electrical facilities, or a surge-testing photograph of motor windings). They should be linked with the corresponding equipment record and kept as long as the asset is in service.

Equipment Management. Before creating an equipment management system, utility staff should decide how to number each piece of equipment (for identification purposes, quick digital access, and links among related records). The simplest method is to "count off" each area or building by thousands (e.g., the headworks is 1000, the primary treatment area is 2000, and the primary clarification area is 3000) and then number each piece of equipment within the area or building appropriately (e.g., the first bar screen is 1001, the second is 1002, and the third is 1003). There should be plenty of unassigned numbers left for equipment added later. Complex wastewater treatment facilities may require a more sophisticated approach to identification, in which case some CMMSs can help generate and organize unique equipment identifiers.

In addition to alphanumeric identifiers, each equipment record should include the

- Equipment's name, description, and location;
- Name and address of its manufacturer, supplier, or builder;
- Cost and installation date;
- Type, style, and model;
- Capacity and size rating;
- Mechanical and electrical data;
- Serial code;
- Preventive maintenance requirements (procedures and frequency);
- Proper lubricants and coatings; and
- Link(s) to the list of spare parts.

Over time, each record also should accumulate a history of the corrective and preventive maintenance work performed on the equipment. This should include related problems, scheduled tasks, completed tasks, the initials of the person(s) who did each task, and the costs, materials, and hours involved.

Maintenance Schedule. Utilities schedule maintenance work to reduce equipment failure, enhance asset performance, comply with manufacturer warrantees, prioritize tasks, minimize idle time, and reduce overtime. Preventive and corrective maintenance scheduling also should take into account the maintenance group's size, each employee's capabilities, and all of the equipment's daily, weekly, monthly, quarterly, semiannual, and annual maintenance requirements. Seasonal weather patterns also should be taken into account when scheduling certain tasks (e.g., painting and tank cleaning) to improve the likelihood of prompt completion.

At a small treatment plant (i.e., less than 1890 m^3/d [0.5 mgd]), depending on treatment system complexity, one employee may be responsible for scheduling, tracking, and perhaps performing much of the work. Small plants may use paper-based work order forms to assign maintenance and repair work (Figure 6.8). These forms should note the task, the personnel assigned, the parts and tools needed, the steps involved, and any safety issues. For example, an equipment-lubrication work order should note the manufacturer's recommendations, points of lubrication, frequency of lubrication, and the need to follow lockout/tagout procedures before beginning the task.

Once completed, labor and materials costs also should be noted on the form. Utility staff can use this information to better prepare maintenance budgets and determine whether a particular piece of equipment is cost-effective.

Staff at medium and large treatment plants (i.e., greater than 1890 m^3/d [0.5 mgd]) typically rely on CMMSs, which integrate work orders, scheduling, performance, cost, equipment history, workforce requirements, budgets, parts inventory, and maintenance work backlog into one comprehensive equipment-management process. Staff input all the equipment's preventive maintenance schedules, along with time and materials estimates, into the CMMS. The system then establishes a calendar of tasks and issues work orders. Data on completed work orders are entered into the CMMS by either clerical staff or the staff who did the work.

Computerized maintenance management systems can automatically provide reports on work schedules, labor and parts costs, maintenance history, and workforce requirements. They also can provide information on work order backlogs and available resources.

Managers should analyze maintenance reports periodically to ensure that the system is operating efficiently. For example, they should review the daily list of work order requests. At the beginning of each month, two work order reports should be produced: one on work completed the previous month and one on the work order backlog [noting the reason(s) for noncompletion and schedule deviation]. Both reports should include statistics (e.g., type, priority, and age of the work order). Managers should evaluate these reports, compare them with those for previous months, and note any trends or problems with receiving parts or supplies.

Storeroom and Inventory Management. As a minimum, inventory records should include the part or material description, number, quantity, reorder level, purchase date, cost, and vendor(s). They also should note when items were used and for what purpose so staff can properly monitor inventory and schedule re-orders. Staff also should maintain a complete catalog of parts and equipment in stock, and always keep storeroom and inventory system records up to date.

A CMMS typically includes a module for automating all inventory transactions. To ensure that this inventory module remains accurate and orders replacements appropriately, staff should promptly note when each part or material is used or received. They also should manually count parts and materials periodically and compare their results with the inventory module's records.

Utility staff should use a purchase-order system to track orders (e.g., item ordered, quantity, cost, vendor, date ordered, date received, and date invoice paid). This system may be part of a CMMS or a financial software suite. If part of the financial software, there should be a bi-directional interface between it and the CMMS purchase-order module.

Budgets and Maintenance Costs. Complete maintenance records can help staff prepare accurate budgets. To do this, the records should distinguish between preventive-maintenance and corrective-maintenance costs. They also should note the costs of both personnel's and contractor's efforts.

ADMINISTRATIVE REPORTS

Annual Operating Reports. When projects are financed via municipal bond issues, financial institutions require the utility to publish an annual report that summarizes the current status of the facilities and developments that occurred during the previous year.

The report should have four sections: general, operations, maintenance, and improvements. The general section should outline the scope of the report and list the names and addresses of persons associated with the facility. It also should note the facts about the project financing, the facility's financial status (e.g., O&M costs, construction costs, and remaining debts), and estimated completion dates for construction projects.

The operations section should briefly describe the wastewater treatment system and how it works. It should contain flow data and graphs comparing hydraulic capacities and loadings (past, present, and 5-year projections). It also should discuss the past year's flow data and operating efficiency (with a supporting table), compare past and present water quality (noting any efficiency trends), and outline process problems and their solutions.

The maintenance section should outline the maintenance projects completed during the year; describe preventive, predictive, and corrective maintenance activities; and list equipment repair and replacement costs. It also should describe the major projects and projected costs planned for the upcoming year.

The improvements section should describe capital additions to storage facilities, pumping stations, distribution system, and wastewater treatment plants. It also should list their costs and completion dates (for future reference).

Insurance Coverage. The insurance coverage report should include the types of policies, names of insurance companies, policy numbers, effective and expiration dates, and amounts of coverage. A wastewater utility's insurance coverage should be based on replacement costs and updated annually. Coverage based on property-value appraisals should be updated when appropriate.

Utility staff should hire a responsible insurance broker to recommend coverage. Some larger agencies may be self-insured.

Annual Budget. The annual budget may be included in the annual report or maintained as a separate report. It should list the previous year's budget, the current year's budget and actual expenditures and receipts, and the upcoming year's budget.

Annual Audit Report. Most utilities are legally required to be annually audited by a certified public accountant. Even if audits are not required, annual audits are a sound business practice. After examining a sample of receipts and expenditures, the accountant should be able to certify that the utility has been managed according to acceptable accounting practices. The utility should keep copies of the audit reports for as long as it exists.

Personnel Training Records. Every employee should have a training record. The U.S. Occupational Safety and Health Administration and other regulators require evidence of minimum training. The record should contain the employee's name, job description, work experience, education, and training needs. Comparing job descriptions with employees' knowledge and skills may reveal training needs. Also, maintenance work could be planned based on staff skills (often via a CMMS linked to employee training and certification records).

There are many types of training, all of which should be recorded in the participants' records. On-the-job training, for example, involves pairing an inexperienced worker with an experienced one until the inexperienced worker has learned enough to work independently. The training time and skills achieved should be recorded. Also, an in-plant library of technical materials and manuals could be made available to personnel for self-study.

In-house training sessions can be useful for learning safety procedures, process changes, and first aid, as well as preparing for licensing exams. Workshops, short courses, and seminars address a wide variety of O&M topics, and participants who satisfactorily complete such training typically receive certificates noting the topic and number of hours involved. Copies of these certificates should be included in the training records.

Training is not just for new employees; experienced staff may need training to upgrade skills and learn how to use new materials and equipment efficiently. Also, given today's concerns about terrorism and security, all staff should be trained on the following:

- The characteristics and uses of potential weapons,
- Vulnerability assessments of local water and wastewater utilities,

- Emergency response plans,
- Responding to and recovering from incidents, and
- Interacting with the media and residents during and after an act of terrorism.

For more information on the contents of a personnel or human resources management system, see Chapter 3.

ACCOUNTING RECORDS

Bill Payment. A requisition system can make bill paying simpler and more prompt. A purchasing system or CMMS can automatically create and convert requisitions to purchase orders (POs). Purchase orders are sent electronically or mailed to vendors and suppliers. Then, when products and/or services are received, invoices are received, and the appropriate personnel should approve and sign them. Each requisition, PO, invoice, and bill should be assigned a code number so all financial information can be categorized and tracked appropriately (Table 6.2).

Requisition systems can be a useful management tool at all wastewater utilities. They can help staff maintain financial records more easily. Staff also can use the system to compare options and control collection, treatment, and administrative costs. Requisition system data also can serve as a basis for developing future budgets.

Financial Reports. The reporting frequency typically coincides with the timing of the operating or permit holder, from the perspective of the regulators.

Periodically comparing expenditures and receipts with budgets enables staff to adjust their plans as necessary to avoid problems at the end of the fiscal year (Table 6.3). This process can be automated so weekly, monthly, or quarterly financial status reports will be readily available. Then, staff can compare their budgets and expenses in each category. Staff also can compare budgeted and actual revenues, as well as revenues and expenditures. The automated process also can be designed to project the full year's expenses based on receipts logged to date, so staff can note trends and prevent budgetary overruns.

An established, regular financial reporting system will make annual-budget and rate-increase approvals less controversial because staff will be more familiar with the plant's finances and prepared to act responsibly.

EMERGENCY RESPONSE RECORDS. Treatment plant staff should document emergencies and their responses to them because this information can be used to update the emergency response plan and track problem areas for future construction projects. Whenever a significant emergency threatens or occurs, staff should compile an emer-

TABLE 6.2 Example of expenditure categories.

Code	Function
Operations and maintenance—wastewater treatment plant	
101	Labor cost—regular operating personnel.
102	Labor cost—part-time personnel.
103	Electrical power purchased.
104	Fuel.
105	Process chemicals (lime, ferric chloride, aluminum sulfate, polymer, and chlorine).
106	Equipment and supplies.
107	Equipment and maintenance.
108	Buildings and grounds maintenance (cleaning and grounds care supplies).
109	Emergency repairs (by outside repair service).
110	Sludge dewatering and disposal.
111	Telephone, telemarketing, and metering.
112	Miscellaneous.
113	Capital improvement.
Operations and maintenance—wastewater collection system	
201	Labor cost—regular operating personnel.
202	Labor cost—part-time personnel.
203	Electrical power.
204	Fuel.
207	Equipment maintenance.
208	Buildings and grounds maintenance.
209	Emergency repairs (by outside repair service).
210	Meter calibration repair and replacement.
211	Line flushing and cleaning.
212	Telephone.
213	Miscellaneous.
214	Capital improvements.
Administrative and clerical	
301	Labor cost
302	Billing service.
303	Legal fees.
304	Audit fees.
305	Engineering fees.
306	Insurance.
307	Social security.
308	Meter reading.
309	Miscellaneous.

TABLE 6.3 Sample format for comparing revenues and expenditures to budgeted amounts.

Receipt or expenditure code number	Current budgeted amount	Expended or received this month	Expended or received year-to-date	Percent expended or received year-to-date

gency conditions report detailing the event. If the plant is flooded, for example, the report should note the following:

- When plant staff were notified of impending flooding,
- When flood water entered the site,
- Where water first entered the plant,
- The highest water level on-site (measured in relation to the plant's physical structures),
- The equipment or structures damaged by the flood,
- Reports of the receiving stream's maximum flood stage,
- The protective actions that staff undertook,
- Other organizations or agencies contacted and actions taken,
- How long and how much the water quality was affected,
- Descriptions of the repairs and replacements required to restore the plant to pre-flood conditions,
- Any job-related staff injuries,
- Any contractors, repair services, or equipment vendors involved in the repairs and replacements (including the names of their representatives),
- The costs of repairs and replacements,
- Actions taken to prevent the recurrence of flooding, and
- Photographs or videos of the flood and resulting damage.

Much of this information also would be included in the utility's annual operating report and may be necessary if insurance claims must be submitted [especially if submitting to the Federal Emergency Management Agency (FEMA)]. For more informa-

tion on FEMA's reporting requirements—which have been extensively revised—see the agency's Web site (www.fema.gov). For more guidance on disaster management, see *Natural Disaster Management for Wastewater Treatment Facilities* (WEF, 1999). This manual explains what to expect during a disaster (e.g., floods, earthquakes, and hurricanes) and focuses on disaster-recovery planning and management.

RECORD PRESERVATION. Typically, paper correspondence and reports should be stored in folders in filing cabinets. Equipment records should be stored and kept at least as long as the equipment itself is in service. (It is better to keep records too long than dispose of them too soon.)

Digital records (those stored on computers) should be backed up routinely, and copies of the backups should be maintained off-site. A critical computer system may be

TABLE 6.4 Distribution of records.

	Treatment plant	Operator's vehicle	Engineer	Federal	State	Trustee
Collection system drawings	■	■	■	■		
Treatment plant drawings	■		■	■	■	
Operations and maintenance manual	■		■	■	■	
Manufacturer's literature	■		■	■	■	
Weekly operating reports	■		■		■	
Annual operating reports	■		■			
Expenditure reports (requisition)	■					■
Monthly reports	■		■	■		
Insurance certificates	■					
Correspondence with regulatory agencies	■		■			
Audit	■		■			
Personnel records	■					

backed up hourly or more frequently and have a fully redundant system available in a secondary, remote location when the primary system is unavailable.

To prevent records from being destroyed in a flood, fire, or other disaster, they should be copied and distributed among multiple sites (Table 6.4). Some large utilities are going a step further and having their employees access records remotely via mobile data terminals or wireless notebook computers.

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INTRODUCTION

With each renewal of a plant's discharge permit, operations are required to meet additional and more stringent requirements for the quality of a plant's effluent. As a result, plant operations now control a growing number of more complicated processes. Often, plant staff levels are not increased commensurately with the increased numbers and complexities of the processes. However, if the processes are to operate efficiently and meet specific standards, proper monitoring and control are essential.

Traditionally, many types of analyses (e.g., chlorine residual, dissolved oxygen, pH, turbidity, and nutrient concentrations) have been performed in the laboratory on grab or composite samples. However, today, instrumentation allows continuous, online monitoring of these parameters. Real-time automatic monitoring and control of costly resources can routinely achieve significant savings in energy and chemical consumption without sacrificing effluent quality.

INSTRUMENTATION

Instrumentation in wastewater treatment plants includes a wide array of pneumatic, hydraulic, mechanical, and electrical or electronic equipment, ranging from simple gauges, flow meters, and control panel indicators to sophisticated plant-wide control systems with multiple computers, video displays, and printers. Instrumentation can do the following:

- Provide a real-time window on process operations by pinpointing transient conditions and allowing correlation of interprocess operations,
- Improve facility maintenance and equipment availability,
- Carry out automatic shutdown to reduce equipment damage resulting from mechanical failures by documenting and quantifying run status,
- Simplify implementation of preventive maintenance programs, and
- Facilitate information management systems.

Many process measurements may not be important enough to economically justify online instruments. The individual parameters to be measured online will vary from plant to plant and even within the same plant. Justification of an online instrument or control system includes identifying and quantifying both tangible and intangible benefits and liabilities. Tangible benefits include direct savings of funds by decreasing resource consumption or staffing levels and avoiding discharge permit violations and subsequent fines. Although sometimes considered an intangible benefit, instrumentation can significantly improve personnel protection from hazards found in treatment plants and collection systems. The cost of appropriate safety instrumentation pales compared with the cost of a human life or limb, or a lawsuit.

Intangible benefits are those for which a funding level is difficult to quantify. They include detailed process performance accountability, reduction of operator busywork, and peace of mind. Each plant's management staff and governing bodies most often determine the importance of intangible benefits.

Benefits are balanced by liabilities. Liabilities associated with instrumentation and control systems include significant capital expenditures and ongoing maintenance requirements. Sophisticated instruments and control systems require new staff skills and may warrant significant changes in a facility's organizational structure. Poorly designed or applied instrumentation and control systems can cost much more than the most idealistically projected benefits. Too much instrumentation or automation can be just as bad as (or worse than) having none.

SENSORS. A sensor is a device that measures a process variable (e.g., flow) and converts the information about the variable into a form operators can use. The conversion may result in a signal that permits economical transmission of the measurement signal to another device remote from the sensor. Here, the term *transmitter* is more appropriately used. Although the terms *sensor*, *instrument*, *transducer*, *converter*, and *transmitter* have broad and often overlapping meanings, the correct terminology depends on the function of the specific device, installation, or system.

Sensors that are in direct physical contact with the treatment process flow streams or the process equipment are *input devices*. They do not control equipment; they make up the input basis for control. Properly functioning sensors make process monitoring and control possible. The sensor, the eyes and ears of the system, is the most important device in the successful application of instrumentation systems. If properly installed and diligently maintained, sensors benefit plant operations.

Sensors monitor three categories of parameters: status, physical, and analytical. Typical status sensors include valve or gate status (opened or closed), equipment oper-

ating status (on or off), and remote switch position (automatic or manual). Status sensors are also used to generate alarms to notify operators of process upsets or dangerous conditions. They can interlock process equipment to shut down automatically, thus avoiding or limiting damage to essential or expensive equipment.

Physical parameters include flow, level, pressure, position, temperature, speed, and vibration. Typically the more significant factors in process and equipment control, physical parameters are used to monitor equipment performance, establish treatment requirements, generate historical data, and, when combined with analytical data, calculate process efficiencies.

Analytical parameters include pH, residual chlorine, turbidity (suspended solids), sludge density, ammonia, dissolved oxygen, nitrous oxides, and hydrocarbons. These parameters are used as input for automatic control functions or regulatory monitoring reports. Typically, analytical sensors are more expensive and complicated than those associated with status and physical parameters. Because the laboratory routinely tests for many of these parameters on grab and composite samples, the plant laboratory is closely involved with ensuring that these online measurements are correctly maintained and calibrated.

FINAL CONTROL ELEMENTS. The final control element is an electric, electronic, pneumatic, or hydraulic device or equipment adjusted to achieve a desired process variable measurement. A sensor provides input for the control; the final control element accepts outputs made to implement a control action. In wastewater treatment plants, the final control element is typically a valve, gate, or pump. Included with each final control element are secondary conversion devices that accept control-signal transmissions and convert them to a mechanical or physical action. The converters include valve actuators, positioners, and a variety of variable-speed, pump-control equipment (e.g., magnetic clutches, motorized pulleys, and variable frequency drives). If properly applied, installed, and diligently maintained, the final control elements and their supporting control and conversion equipment yield successful process control.

CONTROL PANEL INSTRUMENTATION. Control panel instrumentation includes a broad array of devices that provide operators with process information and points of control. Examples of control panel instrumentation are panel meters, indicators, alarm annunciators, status indicator lamps, recorders, controllers, pushbuttons, and selector switches. Sensors, final control elements, and control panel instrumentation allow operators to inspect and control a process from one convenient location. The

devices mounted in a control panel that operators do not directly see include electromechanical relays, signal-transmission conditioners and converters, and power supplies.

MICROPROCESSORS AND COMPUTERS. Microprocessors and computers are now commonly used in many applications, including individual instruments and entire digital-based control systems. Housed in small spaces, microprocessors can perform extremely complex functions at high speeds with low power consumption. For example, before microprocessors, the calculation required to convert the measured level in a flume to a flow signal required a hardwired electrical circuit that consumed much of the space in a flow meter cabinet. Today's microprocessors occupy less space, are more reliable, and permit calculations to be changed or reprogrammed easily, thereby allowing flexibility in use.

Industrial applications of programmable logic controllers (PLCs) have replaced the large banks of electromechanical control relays that used to be required for equipment control (Figure 7.1). The PLC, adapted to the industrial environment, allows plant personnel to easily change the logic used for equipment control.

Perhaps the most significant example of the utility of the microprocessor is the use of the personal computer (PC). These microprocessors are inexpensive, stand-alone computer systems that help a plant operator or manager enter, store, retrieve, and manipulate enormous amounts of plant data quickly and easily. Before PCs, even simple calculations and recordkeeping consumed hundreds of working hours annually. Now, PCs perform these activities quickly and accurately. In addition, available software packages make computer power affordable for even the smallest facility.

CONTROL SYSTEMS. Because of the nature and variety of wastewater treatment facilities, the processes are typically spread over a large area. Instrumentation and automation can centralize data reporting and control commands. Centralization saves operators time, because they no longer need to go to the piece of equipment to perform routine monitoring or control. However, centralization does not replace the need for operators to periodically inspect a piece of equipment. No control system can replace that function.

Control systems consist of individual electrical, electronic, and pneumatic components connected in a network hierarchy. Redundant control equipment components may be warranted to ensure that failure of a single control component does not result in critical process failure, equipment damage, or hazards to personnel. No matter how extensive or sophisticated the control system, there must always be a provision for local manual control of the equipment.

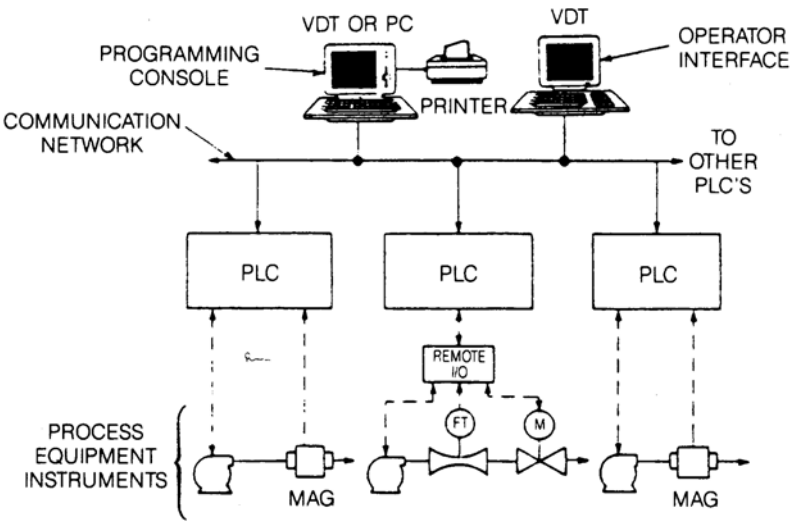


FIGURE 7.1 Distributed control system based on programmable logic controllers.

CONTROL SENSOR APPLICATION GUIDELINES

INSTALLATION. Operators should follow the manufacturer's recommendations when installing an instrument and should discuss any deviations or problems with the manufacturer. If the equipment is installed incorrectly, irreparable damage or malfunction may result. Careless installation will undermine even the most carefully selected and applied equipment. Successful installation incorporates the operator's knowledge and experience of the liquids and gases being measured and controlled. For example, all wastewater treatment plant operators are familiar with the tendency of wastewater and solids to plug small openings. Operators should consider this and other qualities of wastewater and solids when installing instruments. For inline installations, a means of bypass or a spool piece should be provided so the measuring element may be removed from service for replacement, maintenance, or calibration that must be done offsite.

ENVIRONMENT. Operators should minimize or eliminate dust, moisture, extreme temperature, and corrosive gases. Although the presence of low levels of corrosive gas (e.g., hydrogen sulfide) may not be detectable or considered hazardous to personnel, continued direct exposure of electronic parts to minute levels of corrosive gas will eventually result in damaged or inoperative equipment. To prevent the intrusion of moisture and gases, operators should seal all the instrumentation's electrical conduits

and covers. Multiple instrument arrays should be protected in cabinets by producing a slight positive pressure in the cabinet using clean, dry, compressed air with a dewpoint less than 4.4 ºC (40 ºF).

PLACEMENT. Placing the instrument at the proper location in a process is one of the more difficult problems in applying instruments in a wastewater treatment plant. With some instruments (e.g., flow meters), test data have scientifically documented improper placement. With other instruments (e.g., pH or dissolved oxygen meters), the best location is based on experience in similar applications or trial and error. With ultrasonic devices, care must be taken to install them where sidewalls or piping obstructions do not interfere with the instruments' measurements. Often, an instrument has been deemed defective or unreliable when, in fact, it was only placed improperly. Before abandoning an instrument, the manager should confirm that the sensor location is correct and, where possible, that alternatives have been tried. Manufacturers typically will provide considerable guidance, assistance, and suggestions for sensor placement.

MEASUREMENT RANGE. The expected measurement range of an instrument is based on current, rather than future, requirements. Range selection is based on the instrument turndown (i.e., the maximum expected measurement divided by the minimum expected measurement). When ultimate design values are used to determine the instrument range, the maximum expected measurement is large, resulting in an excessively large range. Over-ranging a device leads to instrument insensitivity and inaccuracy, because resulting measurements use only the lower end of the instrument's capacity.

ACCURACY AND REPEATABILITY. *Accuracy* expresses how close an instrument is to the true value of the variable being measured. *Instrument error* is the difference between the instrument reading and the true value. Because accuracy is specified in many ways, the operator should verify the accuracy criteria being used in each specific case. The most common specification of instrument accuracy is as a percentage of either the span of the instrument or the actual reading (Figure 7.2). For example, if a magnetic flow meter has a span of 0 to 5451 m^3/d (0 to 1000 gpm) and a specified accuracy of 1% of span, the reading would be expected to be within 55 m^3/d (10 gpm) of the actual flow. If the same instrument is specified as a percentage of the actual reading, the expected variation from the true flow will change, depending on the actual reading. At 545 m^3/d (100 gpm), the reading would be expected to be within 5 m^3/d (1 gpm). At 4910 m^3/d (900 gpm), the reading would be expected to be within 49 m^3/d (9 gpm).

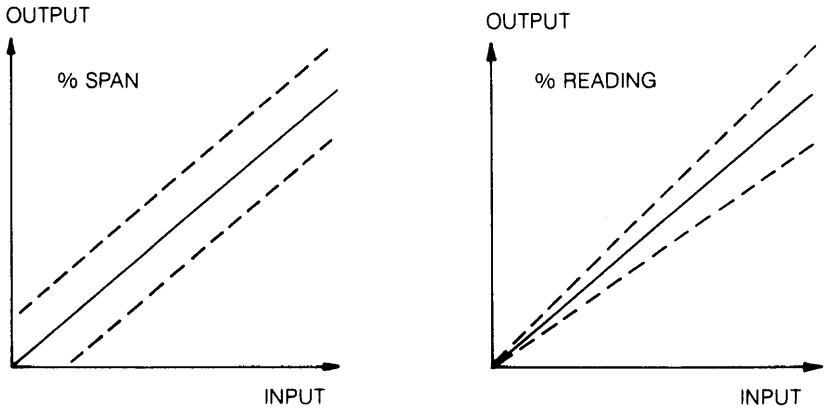


FIGURE 7.2 Accuracy: the solid line represents true values; the reading is within the band bordered by the dashed lines.

Repeatability is the closeness of agreement among a number of consecutive output measurements for the same input value under identical operating conditions and approaching from the same direction, for full-range traverses. If an instrument is repeatable and operators know the inherent errors, this type of input for control is often useful.

Other important instrument characteristics that are examined to learn if the instrument meets the needs of the application include hysteresis, sensitivity, linearity, dead-band, drift, and response time.

FLOW MEASUREMENT

Flow is one of the most important wastewater parameters to be measured. The many types of flow-measuring devices have three basic criteria that determine their performance: area, velocity, and device characteristics. The two basic types of flow measurement are open-channel and closed-pipe. For good measuring-device performance, both types require approach conditions free of obstructions and abrupt changes in size and direction. Obstructions and abrupt changes produce velocity-profile distortions that lead to inaccuracies.

OPEN-CHANNEL FLOW MEASUREMENT. A weir or flume measures the liquid flowing in open channels or partially filled pipes under atmospheric pressure (Figures 7.3 and 7.4). This device causes the flow to take on certain characteristics (e.g.,

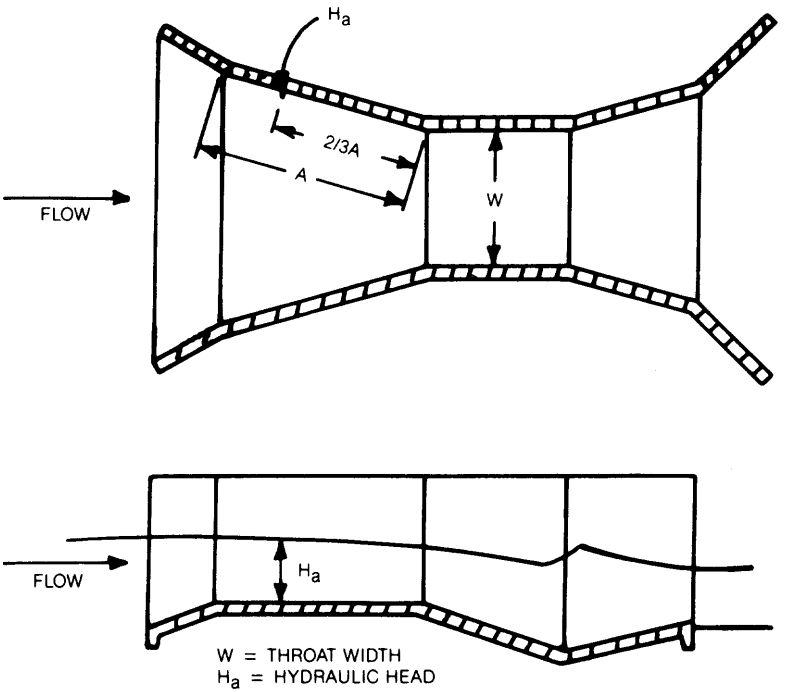


FIGURE 7.3 Parshall flume (Skrentner, 1989).

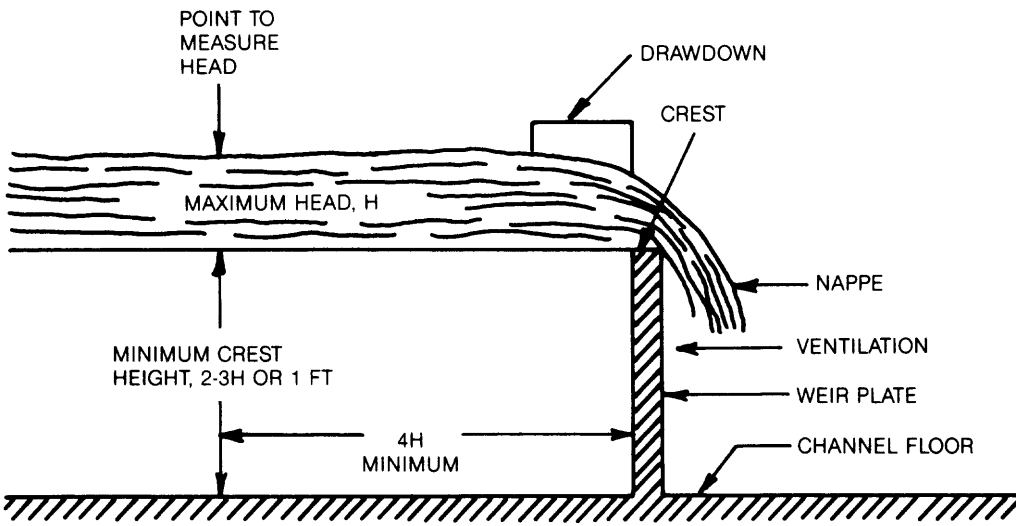


FIGURE 7.4 Typical weir: generated elevation (ft × 0.3048 = m).

shape and size), depending on the device used. Changes in flowrate produce a measurable change in the liquid level near or at the device. This level is related to flowrate via an appropriate mathematical formula. The specific device determines the location and accuracy of level measurements and is extremely important for accurate performance. Many texts deal extensively with open-channel flow metering. For more information, see the *Open Channel Flow Measurement Handbook* (Isco, Inc., 1989).

CLOSED-PIPE FLOW MEASUREMENT. When the pipe runs full in closed-pipe flow measurement, the cross-sectional area can be accurately determined. However, measuring velocity is more difficult, because friction from the pipe wall, fluid viscosity, and other factors affect the flow velocity. There are five classes of closed-pipe flow meters typically used in wastewater treatment: differential head, mechanical, magnetic, ultrasonic, and mass flow.

Differential-Head Flow Meters. Differential-head flow meters include orifice plates, venturi tubes (Figure 7.5), nozzles, pitot tubes, and variable-area rotameters. When properly selected and applied, they measure clean liquids (e.g., potable water and filtered water) and relatively clean gases (e.g., low-moisture digester gas and compressed air).

Differential-head flow meters use an in-pipe constriction that produces a temporary and measurable pressure drop across it. This pressure drop is related mathematically by the principles of mass and energy conservation to the velocity and flowrate of the fluid being metered. The meter's range is typically limited to a 4:1 ratio of maximum to minimum flow. For proper operation, differential-head meters require clear pipe taps both upstream and downstream of the constriction. Routine maintenance includes clearing these taps by blowing them out and removing any accumulated moisture in gas applications.

Mechanical Flow Meters. The propeller meter, the most common mechanical flow meter, functions on the principle that liquid impinging on a propeller causes rotation at a speed proportional to the flowrate (Figure 7.6). The propeller is linked mechanically to an indicator and often to a totalizer or transmitter. Proper operation requires low suspended solids and debris.

Magnetic Flow Meters. Magnetic flow meters are used extensively in applications ranging from filtered effluent to thickened or digested solids (Figure 7.7). They function via electromagnetic induction, in which the induced voltage generated by a conductor moving through a magnetic field is linearly proportional to the conductor's velocity. As the liquid (the conductor) moves through the meter (generating the magnetic

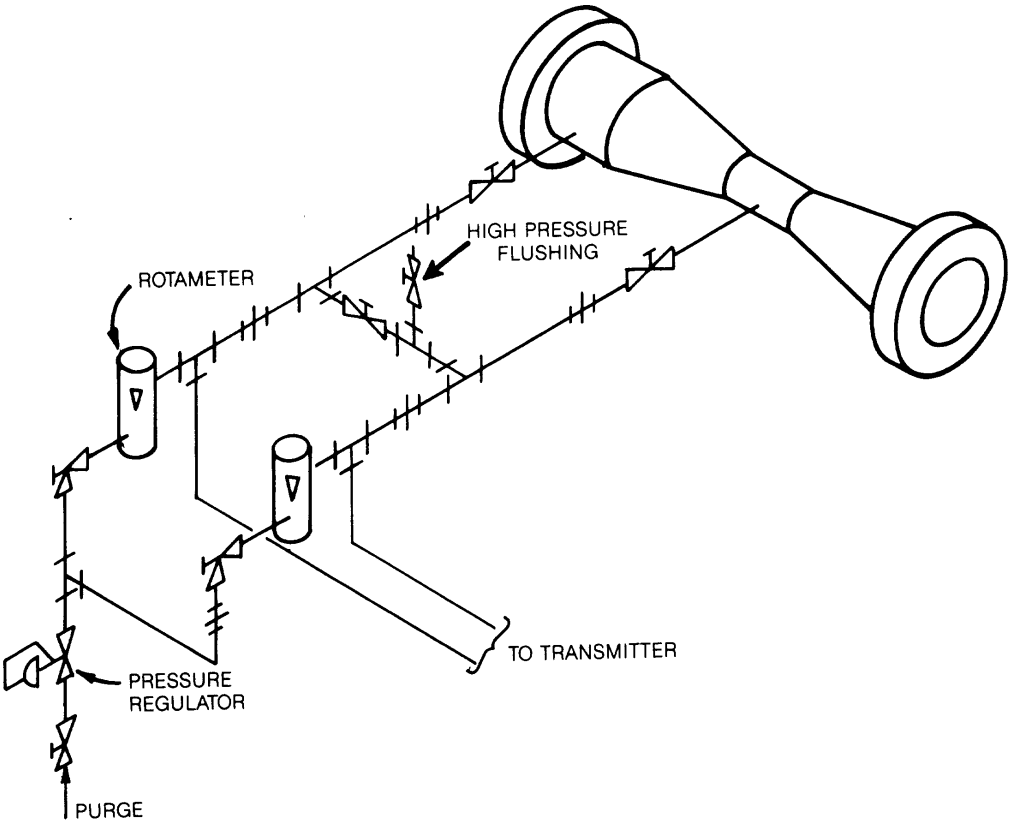


FIGURE 7.5 Typical Venturi meter with liquid purge (Skrentner, 1989).

field), the voltage produced is measured and converted to a velocity and, thus, a flowrate. Magnetic meters require a full pipe for proper operation. Proper grounding is important for certain brands. In applications where greasing of electrodes is likely, additional equipment for degreasing the electrode may be required. Magnetic flow meters provide no obstructions and are manufactured with abrasion- and corrosion-resistant liners, which is why they are frequently used in solids metering. Their major disadvantage is their relatively high price.

Ultrasonic Flow Meters. Ultrasonic flow meters are based on the measurement of ultrasonic wave-transit time or frequency shift caused by the flowing fluid. An instrument that measures wave-transit time is called a time-of-flight or counterpropagation ultrasonic flow meter (Figures 7.8 and 7.9). Ultrasonic waves of known frequency and

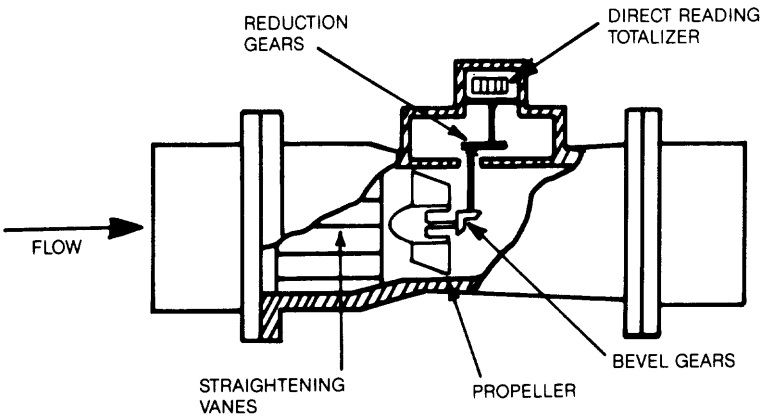


FIGURE 7.6 Propeller flow meter.

duration are beamed across the pipe at known angles. The waves are sensed either directly by an opposing receiver or indirectly as reflected waves. The changes in wave transit time or frequency caused by the flowing liquid are linearly proportional to the liquid velocity. This velocity is converted from flow and output to a display by the conversion electronics. The presence or absence of air bubbles and density of solids in the

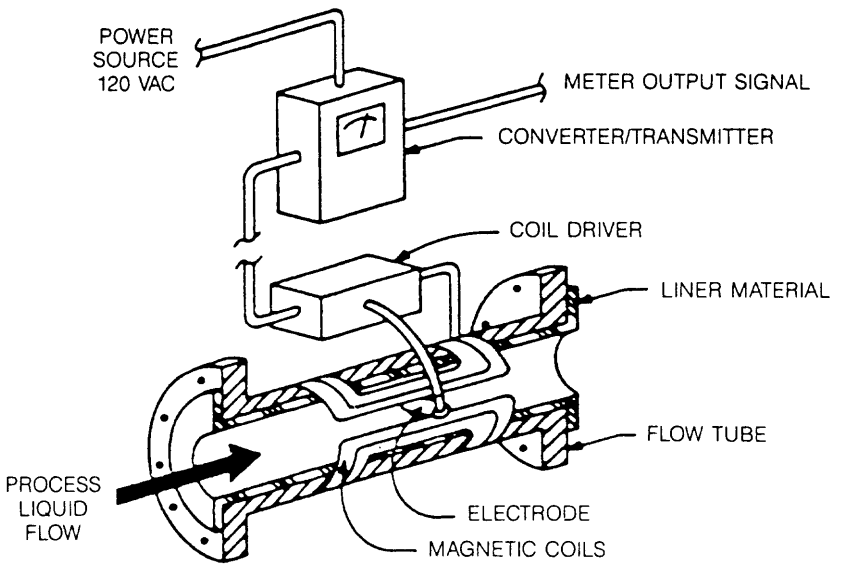


FIGURE 7.7 Magnetic flow meter.

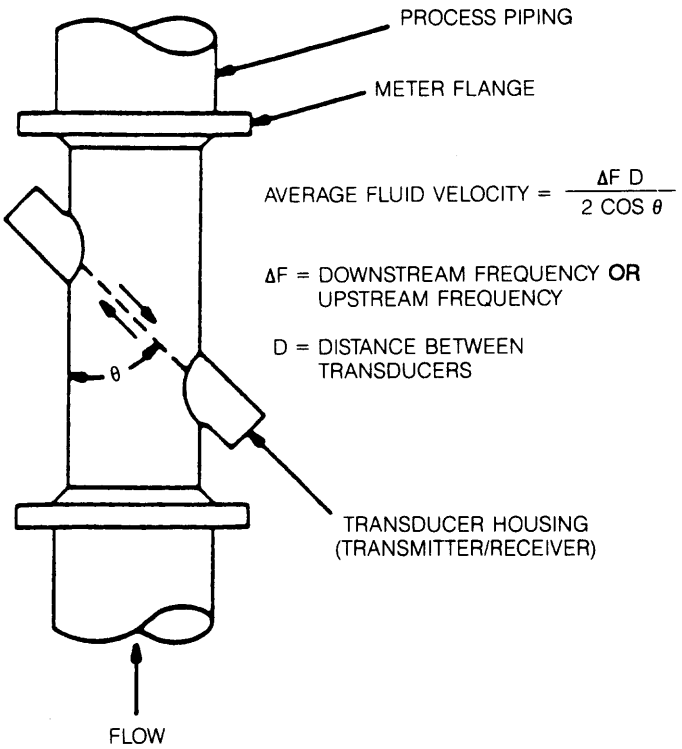


FIGURE 7.8 Time-of-flight ultrasonic flow meter.

fluid being metered affect the meters. Operators should follow the manufacturer's specifications and carefully match the meters to the application.

Mass Flow Meters. Mass flow meters measure the mass of material delivered in a unit of time. They use the density of the flowing fluid or gas and either the Coriolis effect or thermal dispersion to translate the measurement to mass flow.

In the Coriolis flow meter, either straight or bent tube(s) may be used. As the fluid flows through the tube, translational and rotational Coriolis forces simultaneously cause angular deformation or movement of the tubes. The amplitude of the deformation is measured; it depends directly on the velocity and density of the moving mass (mass flow). Another meter uses an oscillation instead of a constant angular velocity. Two parallel tubes are oscillated in anti-phase, much like a tuning fork. When a fluid flows through the tubes, a phase shift is generated. As fluid flow varies, electrody-

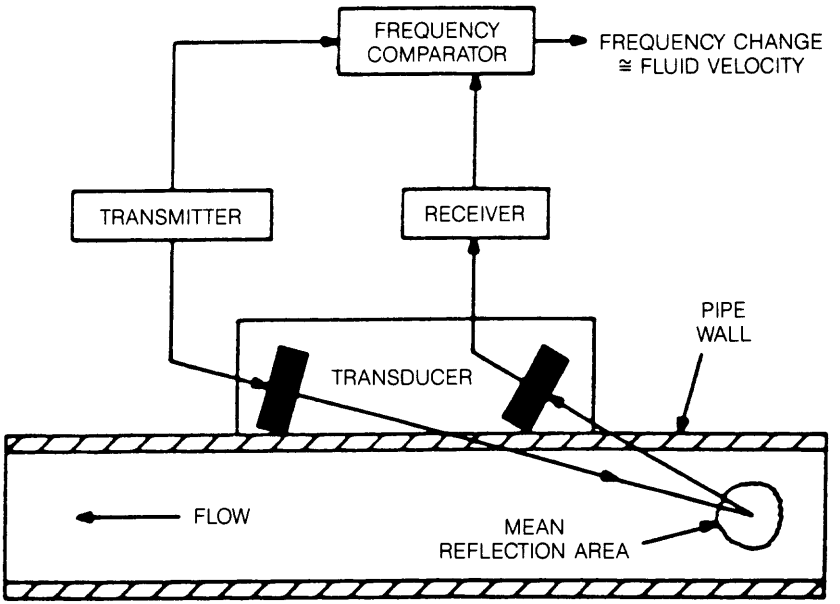


FIGURE 7.9 Reflecting ultrasonic flow meter.

namic sensors at the inlet and outlet measure the phase shift, which is directly proportional to mass flow.

Thermal-dispersion mass meters use heat transfer to determine the mass of material moved per unit of time. It measures the rise in temperature of a fluid after a known amount of heat has been added. From the thermodynamic characteristics of the flowing media, the volumetric and mass flow can be determined.

These meters are subject to fouling and should not be used on fluids with any appreciable suspended solids. They have been used to measure polymer, air, and digester-gas flows.

PRESSURE MEASUREMENT

Pressure is a parameter used extensively in wastewater treatment plants. Pressure measurements are used directly for the following:

- Monitoring most types of pumping equipment,
- Regulating pressure in various types of pressurized processes, and
- Maintaining proper pressures in lubrication and seal systems.

Some types of devices for measuring the full range of pressures include purely mechanical devices with local indicators (e.g., Bourdon tube gauges and spiral, helical, and bellows gauges) (Figure 7.10). Pneumatic or electronic pressure transmitters measure pressure and transmit the measurement to a remote location. Differential-pressure transmitters are also widely used for level- and flow-measurement applications. When properly selected and applied, all of these devices have proved reliable.

MECHANICAL PRESSURE GAUGES. Mechanical gauges work on the principle of physical displacement caused by changes in pressure (Figure 7.11). A link to an

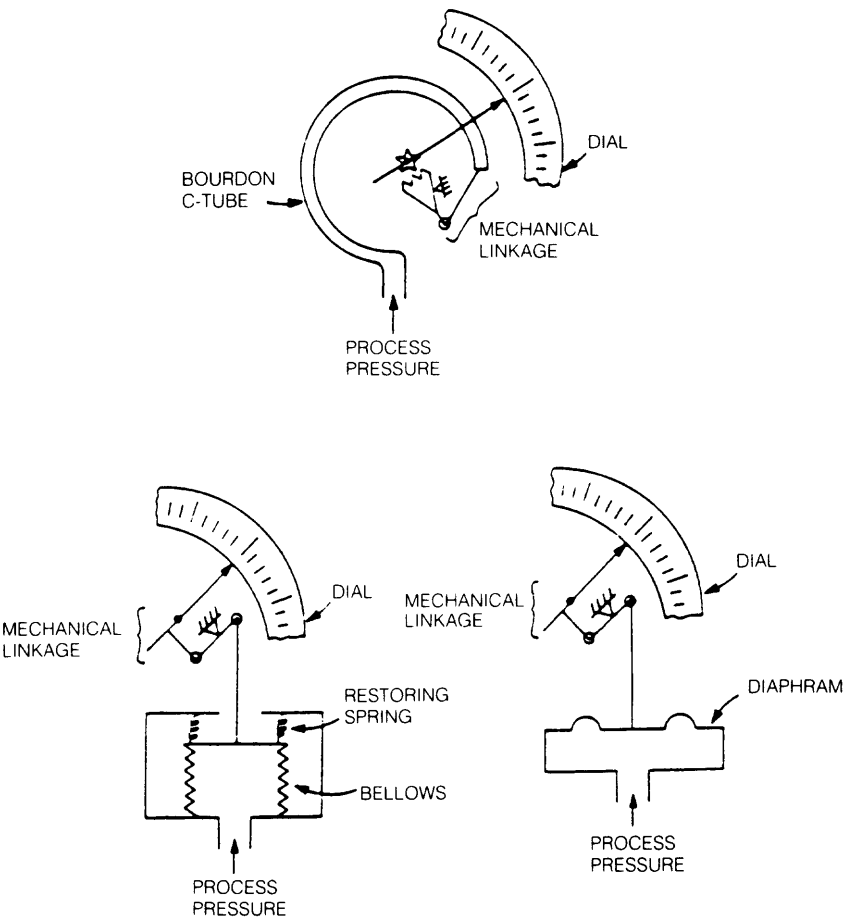


FIGURE 7.10 Mechanical pressure elements.

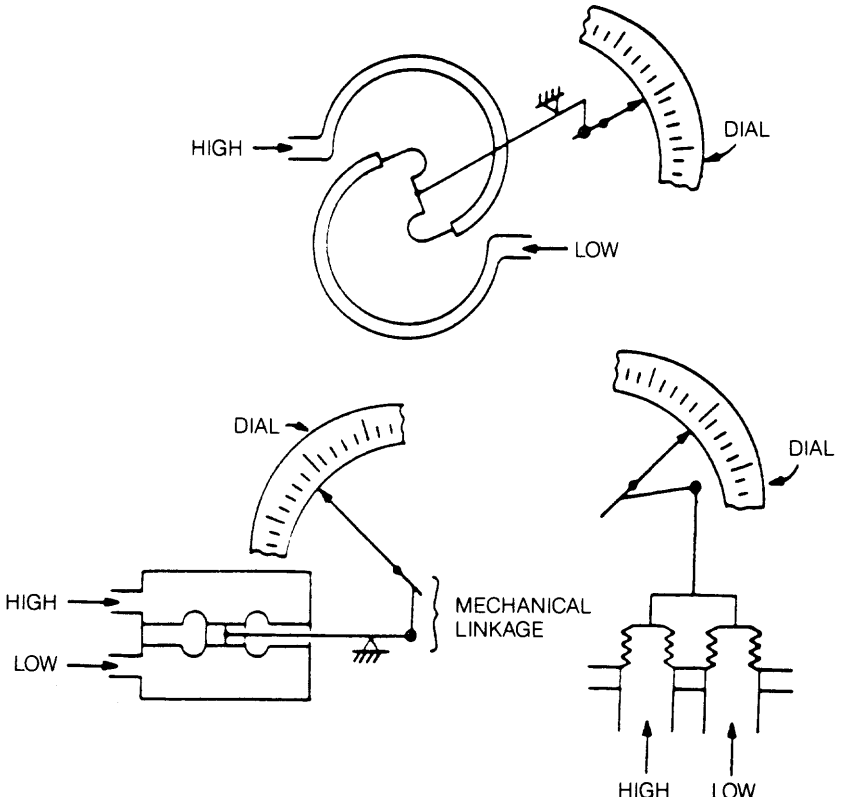


FIGURE 7.11 Mechanical differential-pressure elements.

indicator or pointer on a scale shows operators the pressure measurement. A wide array of pressure ranges is available for mechanical pressure gauges. For proper operation, the process tap for installation of the pressure gauge is made so the tap will not plug with solids or debris. Operators should isolate the gauges from highly pulsating pressures that will severely vibrate the instrument's delicate mechanical linkages. For acceptable accuracy, gauges should be selected to operate at the midpoint of the specified measurement range. If high accuracy is critical, gauges not in active use should be removed.

PNEUMATIC PRESSURE TRANSMITTERS. Pneumatic pressure transmitters using a compressed-air transmission system allow transmission of sensed pressure to a remote location. These transmitters use the principle of balancing pressures across a metal diaphragm using the process fluid on the "wet" side and instrument-supplied air

(regulated by a nozzle–baffle system) on the "dry" side. Any tendency of the diaphragm to move because of changes in process pressure causes a restriction of the nozzle-flapper system, which increases air pressure to bring the system into balance. Operators should apply these devices carefully in much the same way as mechanical pressure gauges to protect them against plugging and excessive vibration. They need to be calibrated periodically to maintain the relationship established between the process pressure and the change induced in the instrument-supplied pressure.

ELECTRONIC PRESSURE TRANSMITTERS. An electronic component attached to a mechanical pressure device (typically a diaphragm) generates an electrical signal proportional to the applied pressure. A change in the device changes the electrical property of the electronic component (capacitor or strain gauge). These devices are becoming widely used for remote pressure transmission with electronic display and control systems. They need to be calibrated periodically to maintain the relationship between the actual process pressure and the magnitude of the electronic transmission signal.

DIFFERENTIAL-PRESSURE TRANSMITTERS. Differential-pressure transmitters use one of the pressure-measurement devices discussed previously, along with a special housing or fittings. The housing or fittings provide two pressure connections that balance the pressure. Differential-pressure transmitters are used for level measurement on pressurized tanks and with differential-head flow measurement devices on pressurized pipes.

LEVEL MEASUREMENT

Level measurement is primarily used to control pumps to maintain levels in wet wells, tanks, and grit chambers. Level measurement is also used with other devices (e.g., flumes or weirs) for open-channel flow measurement. The three main methods of determining level are physical measurement of the liquid surface from above, measurement of head pressure from below, and electrical methods.

FLOATS AND ULTRASONIC DEVICES. A float or ultrasonic device measures a liquid level from above. Floats, one of the oldest and simplest methods of level measurement, are used extensively in wet wells or sludge vaults that require a discrete high- or low-level indication. They are also used for local indication of level in tanks and open channels. The primary maintenance concern of a float system is accumulation of solids, debris, or ice on the float or in the stilling well, when used (Figures 7.12 and 7.13).

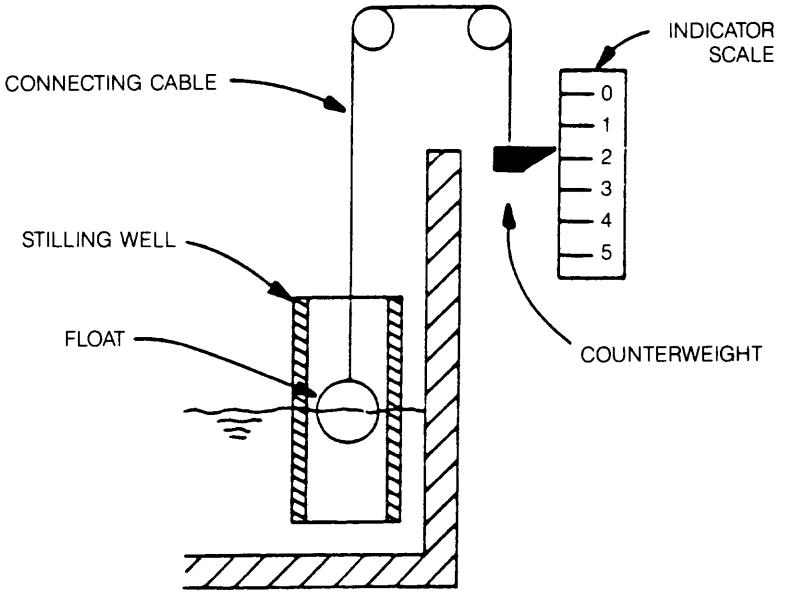


FIGURE 7.12 Counterweighted float-level indicator.

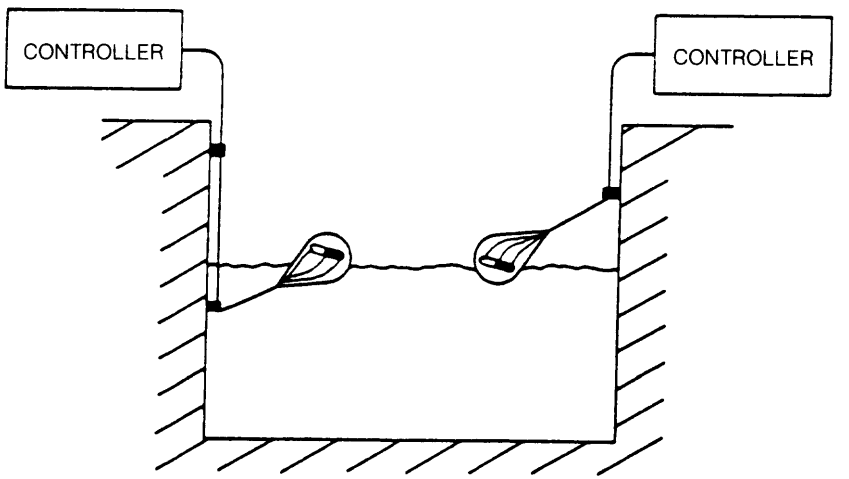


FIGURE 7.13 Float switches.

Ultrasonic level measuring devices installed above the liquid surface measure the level by generating a pulse of ultrasonic waves that bounce off the liquid surface. The instrument detects the echo, calculates the echo's travel time, and converts it to a level measurement (Figure 7.14). Changes in air temperature, surface foams, and fog can adversely affect ultrasonic level measurements. Operators should shield the sensitive electronic components from moisture and corrosive gases.

HEAD-PRESSURE LEVEL MEASUREMENT. Bubbler tubes and diaphragm bulbs measure the liquid level's head pressure and are often used in open-channel or nonpressurized tank applications (Figure 7.15).

Bubbler Tube System. The bubbler tube system uses a small, regulated airflow that constantly bubbles into the liquid. Because the airflow is small, the system produces a backpressure equal to the static head of the liquid. A conventional pressure gauge or transmitter measures this backpressure as the height of an equivalent water column. Corrections are required when the liquid's specific gravity differs significantly from

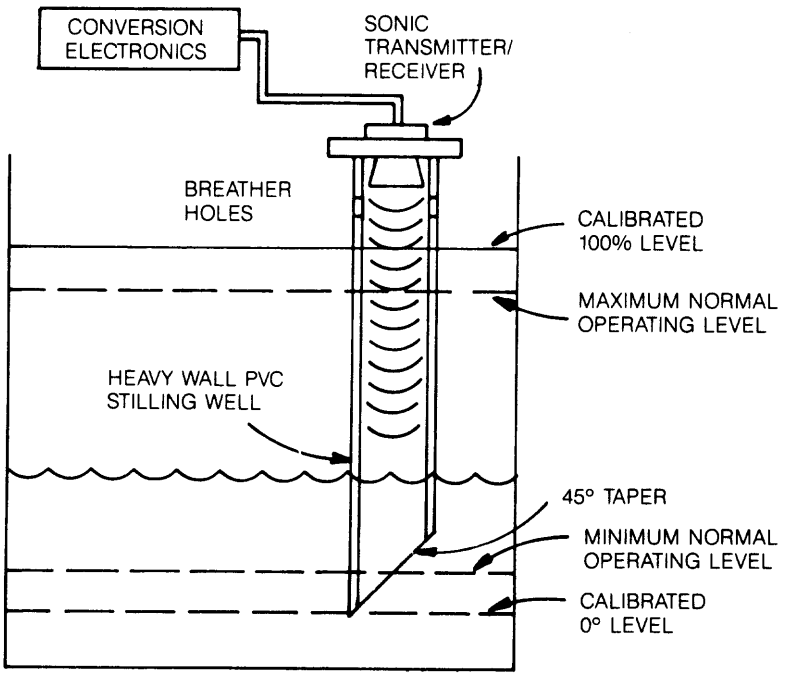


FIGURE 7.14 Acoustic level-sensor installation.

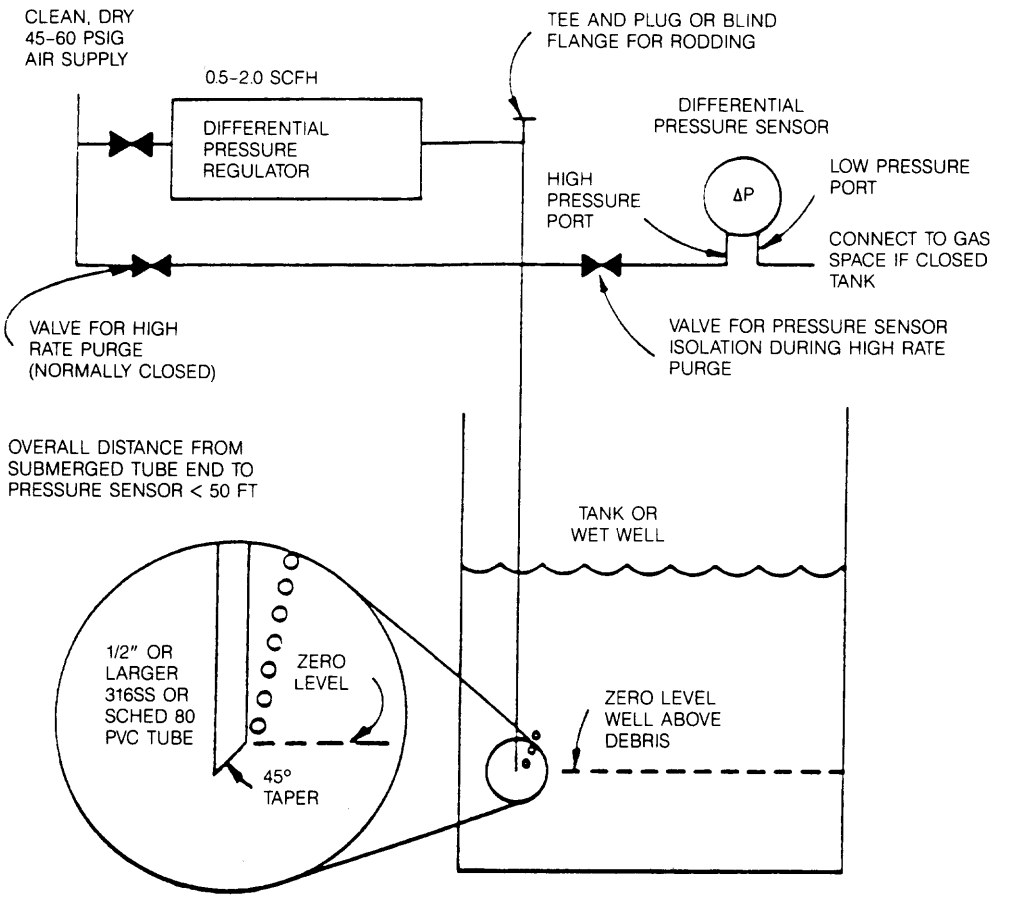


FIGURE 7.15 Schematic of bubbler-level system (ft × 0.3048 = m and in. × 25.4 = mm).

water. Because air is constantly bubbling out of the bubbler tube, the system is typically self-purging. Valving may be arranged to isolate the pressure-measuring device while providing high purge flow through the tube for preventive-maintenance blowdown if fouling occurs. Stilling wells are often used to protect the bubbler tube from turbulence and damage. To protect the pneumatic instruments and regulators, operators should clean the air supply of excessive moisture and oils.

Diaphragm Bulb System. The diaphragm bulb system operates on the principle that air sealed between the dry side of the diaphragm (in the capillary tube) and the receiver compresses or expands with the movement of the diaphragm. A change in the

static head of the liquid being measured moves the diaphragm, so the pressure of the trapped air is the same as the head pressure. Temperature changes because of sunlight or building heat, particularly along the capillary tube, can cause measurement errors as a result of expansion of the trapped air. To reduce the effect of temperature, the capillary can be filled with a fluid unaffected by operating temperature; however, this often affects the measurement response time.

ELECTRICAL METHODS. Electrical methods of level measurement consist primarily of conductance and capacitance probes (Figure 7.16). Conductivity probes are discrete devices used much like floats (e.g., turning pumps on and off and alarming).

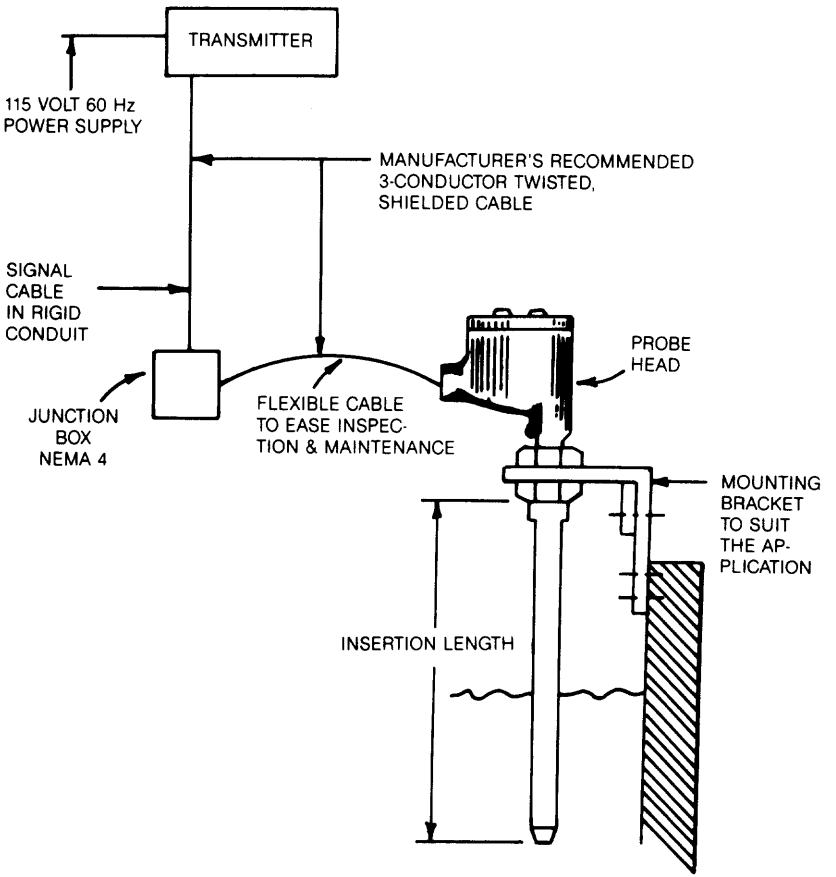


FIGURE 7.16 Typical capacitance probe installation (Skrentner, 1989).

Conductivity probes use the liquid to complete a circuit between two probes or between two sections of one probe. The devices should be used in relatively clean liquids because buildup on the probe can either complete the circuit or act as an insulator.

A capacitor consists of two electrically conductive plates separated by nonconductive material. In wastewater treatment applications, a capacitance probe acts as one conductive plate and the nonconductive material. The liquid acts as the other conductive plate. As the liquid level changes, the system's capacitance changes proportionally. The instrument measures this capacitance and displays the level. Problems occur if the probe accumulates solids, but many manufacturers have designed the instrumentation to compensate.

TEMPERATURE MEASUREMENT

Even though most of the major wastewater treatment processes are not temperature-controlled, many temperature measurements are required. Obvious applications for temperature measurement are anaerobic digesters, chlorine evaporators, incinerators, and equipment protection. Less obvious are temperature controls for analyzers and flow meters. Temperature-measurement devices include liquid thermometers, bimetal thermometers, pressure on liquid or gas expansion bulbs, thermistors, resistance temperature detectors (RTDs), infrared detectors, and crystal window tapes. The RTD is typically used on lower, ambient-range temperatures, while thermocouples provide better reliability in higher ranges. Also, gas- and liquid-filled temperature sensors and thermistors are frequently used for equipment-protection and cooling systems. For continued accurate service, operators should periodically calibrate the instruments using a standard temperature-measurement device with high accuracy.

THERMAL BULB. The most commonly used thermal bulb is gas-filled and operates on the physical law that the absolute pressure of a confined gas is proportional to the absolute temperature (Figure 7.17). Installed in a thermal well for protection and ease of inspection and calibration, the thermal bulb is available in several temperature ranges and accuracies. They are typically used for local control and indication only.

THERMOCOUPLE. The thermocouple operates on the principle that current flows in a circuit made of two different metals when the two electrical junctions between the metals are at different temperatures (Figure 7.18). The various combinations of metals used are tabulated in most engineering handbooks, and the selection of metals is based on the maximum temperature to be measured. Thermocouples measure as high as 980 °C (approximately 1800 °F), with an accuracy of 1% of full scale.

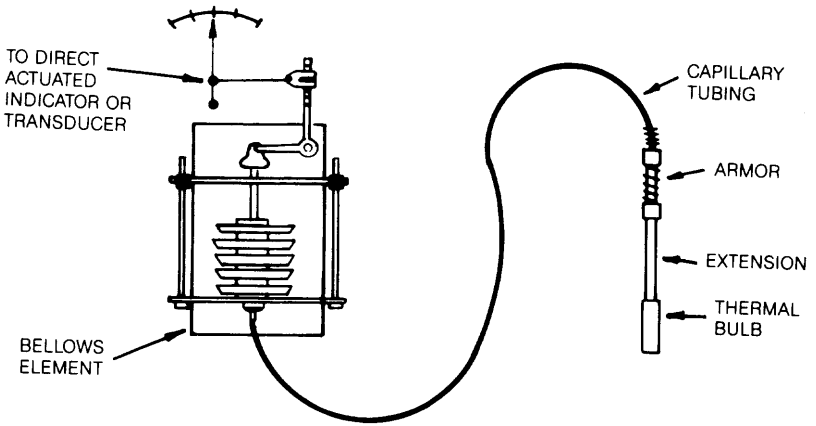


FIGURE 7.17 Thermal bulb system.

RESISTANCE TEMPERATURE DETECTORS. A resistance temperature detector has a temperature-sensitive element in which electrical resistance increases repeatedly and predictably with increasing temperature. The sensing element is typically made of small-diameter platinum, nickel, or copper wire wound on a special bobbin or otherwise supported in a virtually strain-free configuration. The detector is typically selected for high accuracy and stability. A common RTD application is the measurement of bearing and winding temperatures in electrical machinery.

THERMISTORS. A thermistor (the name comes from "thermally sensitive resistor") is a solid-state semiconductor whose resistance varies inversely as a function of

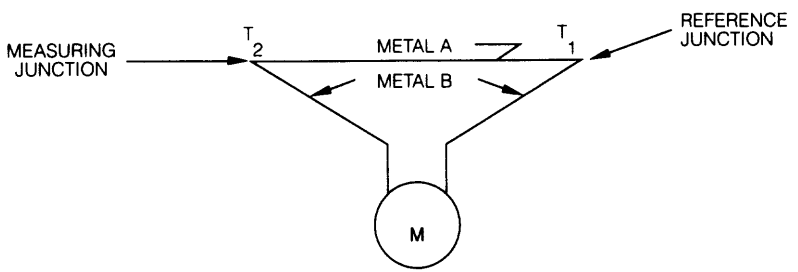


FIGURE 7.18 Typical thermocouple circuit.

temperature. Some thermistors are available with a sharp change in slope at some characteristic temperature. In some situations, a thermistor can replace an RTD as a temperature sensor. One advantage of the thermistor over the conventional wire RTD is that the thermistor has a greater resistance change for a given temperature change. A disadvantage is that the accuracy available, although good, is inferior to that of the conventional RTD.

TEMPERATURE SENSOR INSTALLATION. The temperature sensor's lifespan depends on its installation. Thermo-wells, made of metal or ceramic materials and threaded into the wall of a pipe or tank, shield the temperature sensors from the process and enable them to be removed without disturbing the process. In wastewater treatment applications, particularly where solids are involved, operators should not obstruct the full flow of fluid in the pipe. Of particular concern is the collection of debris (strings, plastics, and large chunks) on the thermo-well. Typically, if the thermo-well protrudes less than 25% of the pipe diameter and is at an elbow or T, the flow will wash away the debris.

WEIGHT MEASUREMENT

Weight measurement, an important part of operations, provides accurate data about chemical use or solids concentration before reduction or disposal. Weight measurements account for the dewatering and hauling costs. Several proven mechanical and electronic methods for measuring weight are weigh beam, hydraulic load cell, and strain gauge.

WEIGH BEAM. The standard weigh beam, the simplest mechanical method, involves a basic lever mechanism with a fulcrum between the two forces (Figure 7.19). For the beam indicator to match up with its reference, the load multiplied by its distance to the fulcrum must equal the counterbalance weights multiplied by their distance to the fulcrum. Scales of this type range from fractions of a kilogram (pound) to megagrams (tons) and may have accuracy of 0.1% of the actual weight.

HYDRAULIC LOAD CELL. This is a closed system in which the hydraulic oil in the cell is loaded by external force and transmits a corresponding pressure via a diaphragm to a pressure gauge (Figure 7.20). Multiple load cells may be used and the sum of their forces applied to a conventional scale beam. Hydraulic load cells are most effective on high-capacity applications and have an accuracy of 1% of full-scale.

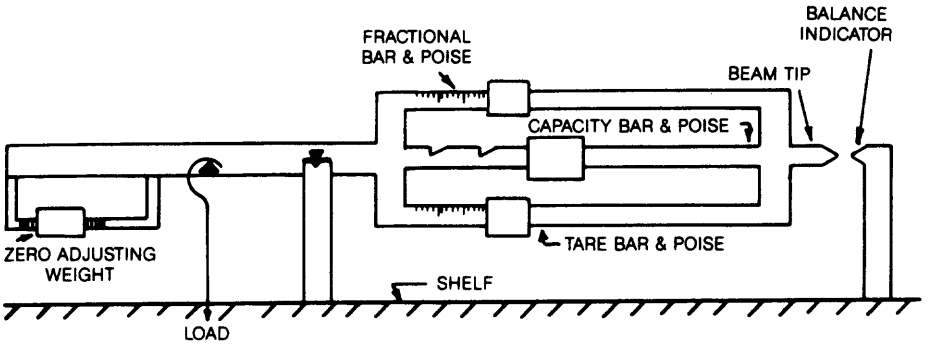


FIGURE 7.19 Weigh beam with sliding poises.

STRAIN GAUGE. A strain gauge is an electronic method of weighing. The load button transfers its load force to a preselected steel load column to which the strain gauges are attached. The strain or deflection of the steel column alters the gauges' resistance. Multiple units may be tied together electronically and produce standard output signals via electronic amplifiers. The accuracy of this system is typically 1% of full-scale.

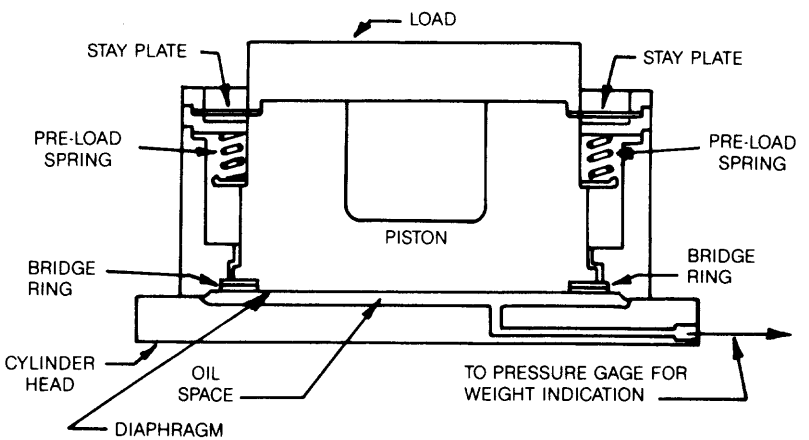


FIGURE 7.20 Hydraulic load cell.

SPEED MEASUREMENT

Speed measurement is used as a report-back signal or local indication for various types of mechanical equipment (e.g., variable speed drives on pumps, blowers, and some mechanical mixers). Speed-measurement methods include direct mechanical connection to a rotating shaft or gear and noncontact approaches that use magnetic or optical approaches.

TACHOMETER GENERATORS. The tachometer generator consists of a stator and a rotor. The stator (nonmoving member) typically consists of laminated steel plates with inward projections for the pickup coils. The rotor (rotating member) is a permanent magnet mounted to the shaft. The shaft is coupled to the member whose speed is to be measured. The output is read on an indicator, or via conversion devices, amplified into one of several standard output signals. Tachometers have an accuracy of 1% of full-scale.

NONCONTACT FREQUENCY GENERATORS. Noncontact frequency generators use a shaft-mounted gear and a noncontact electronic or optical pickup mounted close to the gear. The pickup detects the gaps between the tear teeth and the frequency with which they pass by the pickup. This frequency is then converted to a useful display given in revolutions per minute or percent of speed. The advantages of this type of speed sensor include accuracy and lack of moving parts.

PROXIMITY SENSORS

Proximity sensors—inductive, capacitive, or optical—measure equipment speed, alignment or position, and indexing without touching the equipment.

MAGNETIC PROXIMITY SENSORS. The three basic elements of proximity sensors are a sensing oscillator, a solid-state amplifier, and a switching device. Proximity sensing is achieved when a metallic object (target) enters the sensing field. The presence or absence of a metal target is sensed by a change in the magnetic field. This, in turn, changes the internal impedance of the oscillator, which provides a signal output. The output activates a solid-state amplifier and switching device.

CAPACITIVE PROXIMITY SENSORS. Capacitive proximity sensors, which sense the difference in capacitance, can sense nonmetallic materials (e.g., water or gasoline). The sensors are used as liquid-level sensors. Sensing is done directly through nonmetallic tank wells, ports, or metal tank walls, or else from inside a capped nonmetallic pipe submerged in the tank.

OPTICAL PROXIMITY SENSORS. Optical proximity sensors use a visible or infrared light beam to sense the presence or absence of an equipment component or process fluid. In wastewater treatment plant applications, optical sensing is used to sense the position of a valve or level in a storage bin.

PHYSICAL–CHEMICAL ANALYZERS

Physical and chemical analyzers measure the physical and chemical properties of process streams (e.g., plant influent, effluent, process sludges, centrate, process gases, and chemicals). Given the increasing regulatory requirements for excellence in overall treatment efficiencies, inline physical–chemical analyzers are playing an ever-increasing role in plant operations. Some physical–chemical analyzers are specific (i.e., they measure one chemical ion), while others measure a group of chemicals, a type of substance, or an effect:

- Specific chemical ions—dissolved oxygen, pH, ammonia, and oxidation–reduction potential (ORP);
- Group of chemicals—total chlorine residual and nitrogen oxides (commonly known as NO_X);
- Type of substance—total suspended solids and suspended solids; and
- Effect—biochemical and chemical oxygen demand.

ION-SELECTIVE ELECTRODES. A wide variety of ion-selection electrodes, some of which are specific-ion probes, are currently marketed. These electrodes have good monitoring capabilities. The most widely used electrodes measure ammonia, cyanide, dissolved oxygen, chloride, calcium, pH, fluoride, and sulfide. Typically, they are accurate in the laboratory but require careful and periodic maintenance in field applications. However, the reliability of many of these instruments has improved considerably in recent years. Some of the more noteworthy probes used for online monitoring or control in the wastewater treatment industry are described in the following paragraphs.

DISSOLVED OXYGEN. Aerobic microbial life processes need dissolved oxygen. Monitoring dissolved oxygen is a prime requirement in the activated sludge process (Figure 7.21). For optimum treatment, a certain level of oxygen must be maintained in the aeration tanks, particularly if nitrification is required. Controlling the quantity of air supplied to the activated sludge process can result in significant cost savings. Temperature, pressure, and dissolved solids all affect how much oxygen can be dissolved

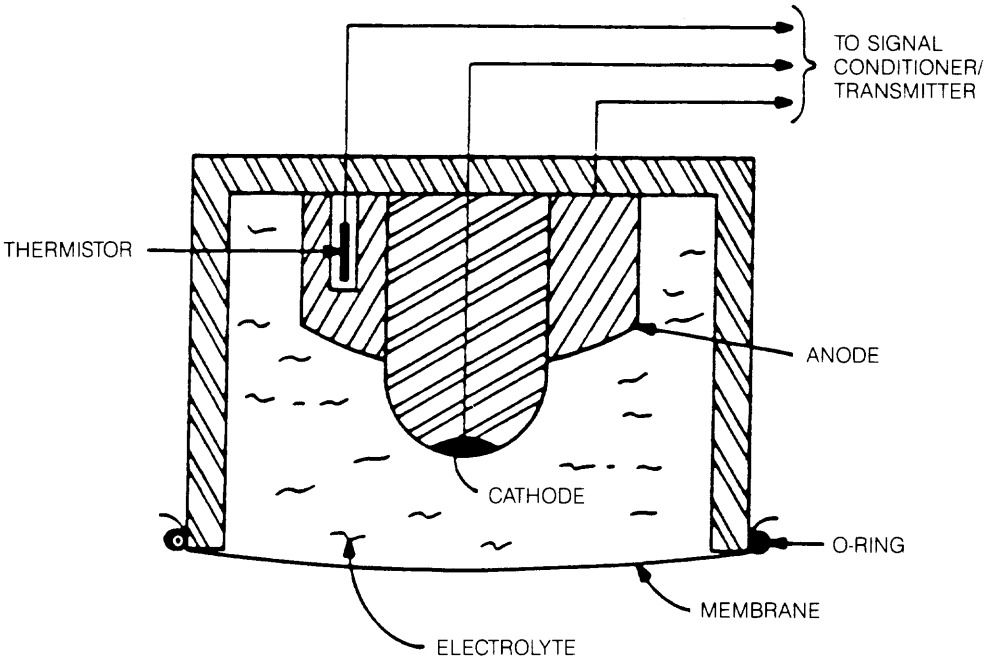


FIGURE 7.21 Membrane dissolved-oxygen probe.

in a solution. Most dissolved oxygen meters automatically compensate for temperature and pressure.

Volumetric (potentiometric) methods of oxygen measurement depend on the electrolytic reduction of molecular oxygen at a negatively charged electrode (cathode) to generate an electric current directly proportional to the oxygen content. The two volumetric electrode systems in popular use are the active and the passive systems.

Active System. The active system's electrodes measure the oxygen concentration by reducing molecular oxygen at the cathode. The electrons needed to reduce molecular oxygen are supplied by the active cell that uses dissimilar metals and an electrolyte. Its ability to generate voltage can be compared with the lead–acid storage battery in an automobile.

Passive System. The passive system's electrode operates on the same principle as the active cell, which is reduction of oxygen at a polarized cathode. The active cell's source of electrons is the cell itself, from the anode to the cathode. The passive cell's source of electrons is an external power source (e.g., a battery). The voltage is applied across the

anode and cathode, and any oxygen passing through the permeable membrane is consumed (reduced) at the cathode, causing current to flow. The magnitude of the current produced is proportional to the amount of oxygen in the sample and is, therefore, a measure of the oxygen present.

It is possible to measure the dissolved oxygen in a solution containing ionic and organic contaminants because the sensing element is separated from the test solution by a selectively permeable membrane. This ability to measure oxygen without interference from other material allows for measurement of oxygen *in situ*. Weekly calibration checks are typically required, and most require periodic wiping of the membrane to remove accumulations.

Manufacturers have realized the importance for easily removable probes and now supply excellent mounting hardware.

pH. The pH is a measurement of the acidity of a process liquid. Continuous measurements of the pH of incoming wastewater are frequently used, particularly in plants where drastic changes in pH (as a result of industrial discharges) cause treatment problems.

The glass electrode, which is sensitive to hydrogen ion activity, measures the pH of an aqueous solution (Figure 7.22). The electrode produces a voltage related to hydrogen ion activity and to pH. The pH is determined by measuring the voltage against a reference electrode. While it is generally assumed that no other ions seriously affect the pH electrode in an aqueous system, sodium ions can have an effect. Temperature corrections are also necessary but are typically done automatically by the meter.

AMMONIA. Ammonia is a chemical compound that undergoes oxidation and reduction to various forms of nitrogen compounds. To reduce the oxygen uptake in a receiving stream, many plants are required to oxidize ammonia. Many wastewater treatment plants have discharge limits expressed in terms of ammonia-nitrogen (NH_3-N). Alternatively, the amount of nitrate and nitrite (oxidized ammonia) can be used to determine if there is adequate dissolved oxygen in an aeration basin or if there are proper conditions in an aerobic digester. Ammonia analyzers use the selective ion probe approach to determine the amount of ammonia present. Operators should calibrate the ammonia analyzers periodically and maintain them to standard solution concentrations. Sampling systems can provide representative samples and filter sample streams to improve accuracy.

OXIDATION–REDUCTION POTENTIAL. Oxidation–reduction potential is a measure of the easily oxidizable or reducible substances in a wastewater sample. An operator can control the process better by knowing if there is a large quantity of reduc-

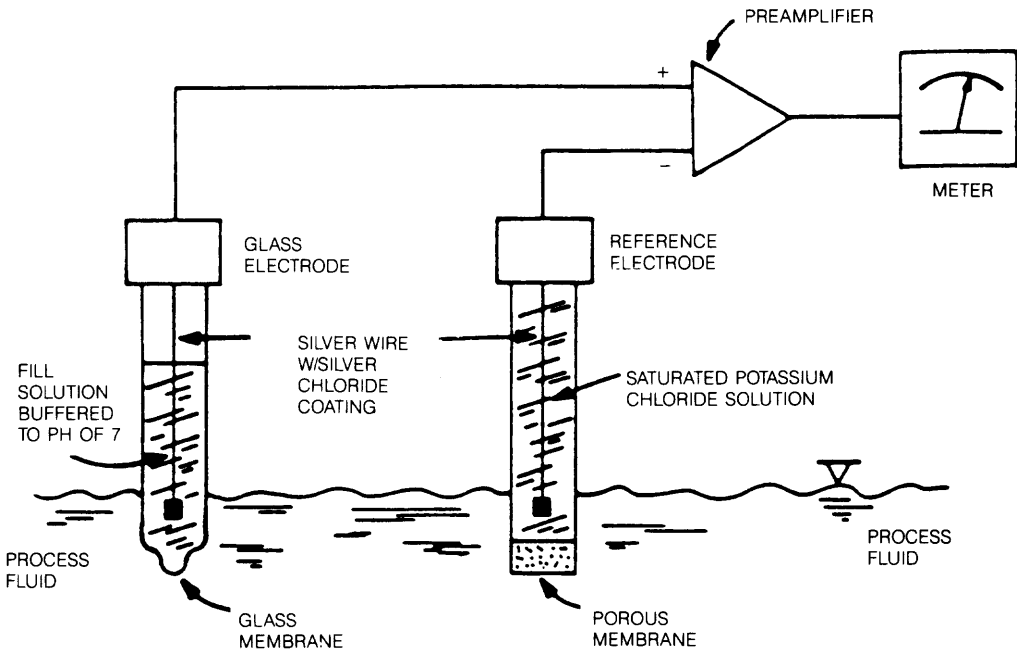


FIGURE 7.22 Typical pH sensor.

ing substances (e.g., sulfide and sulfite) that may have an immediate, high oxygen demand and may result in an inadequate supply of oxygen for the microorganisms in the secondary process. Although not specific, the ORP measurement is instantaneous (an electrode is used) and can be used to help maintain dissolved oxygen in the aeration tank. Another application is to evaluate the progress of digestion and process stability in the anaerobic digesters.

CHLORINE RESIDUAL. The continuous measurement of residual chlorine is important in final effluent disinfection. In addition, some areas of the United States require dechlorination to reduce the toxic effects of chorine residual on aquatic life. Dechlorination requires the use of chlorine residual analyzers to prove that virtually no chlorine remains. Clorination controls become much more important when dechlorination is required. Logically, the more constant the chlorine residual after chlorination, the easier dechlorination is.

The most commonly used chlorine analyzers are designed to measure chlorine amperometrically (Figure 7.23). The analyzer has a flow-through cellblock that contains the platinum measuring electrode and the copper reference electrode. As the sample

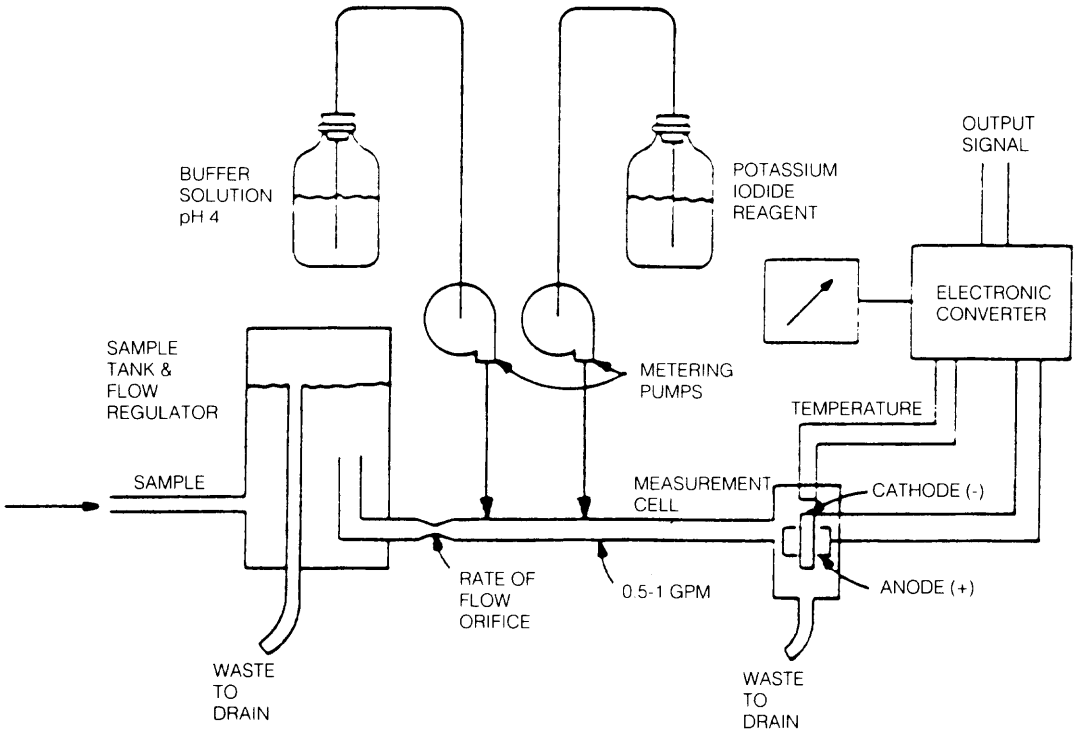


FIGURE 7.23 Amperometric total chlorine residual analyzer (gpm $\times$ 5.451 = m^3/d).

flows past the electrodes, a direct current is generated that is proportional to the chlorine residual in the sample. Other units use optical methods, in which a color is developed and then analyzed via light absorption. Manual amperometric titration is widely used as a standard to calibrate the analyzers.

There are several forms of chlorine. Typically, either free or total chlorine residuals are of interest (Chapter 26). Analyzers for a variety of these groups are available.

Chlorine residual meters require periodic maintenance and calibration. Annual maintenance and supplies needed to maintain the instrument may exceed its capital cost. However, in a large plant, improved stability and reduced chemical cost can easily outweigh the capital cost of the instruments.

NITRATE AND NITRITE. Nitrate is typically used to monitor and control biological nutrient removal (BNR) plants. Although present in BNR plants, nitrite quickly oxidizes to nitrate or reduces to nitrogen. Probes are available for its measurement, but it

is of less interest than nitrate. Online nitrate instruments are used in BNR plants to control anoxic-zone recycle rates and intermittent operation of aeration systems, as well as monitor effluent.

Nitrate and nitrite ions absorb UV light up to 240 nm. In online measurement, a beam of UV light is directed through the sample, and the amount that passes through to the detector is measured. The amount absorbed is converted to a nitrate measurement. The instruments are provided with a means to compensate for any turbidity interference.

Because the value of nitrite is typically insignificant, the value is widely accepted as NO_3 for plant control purposes.

Nitrate can also be monitored using the specific-ion approach, but it suffers from interferences and is rarely applied to wastewater.

SOLIDS CONCENTRATION

Generally, the complexity of wastewater solids prevents any attempt to measure a particular type of solid. In the laboratory, these solids include suspended, dissolved, and settleable solids. At times, the term *density* has been mistakenly used as an equivalent to solids concentration. Density describes the weight of fluid rather than weight of solid per unit volume. Most sludges are denser than pure water. The largest causes for variations in the density of many sludges are temperature, the amount of entrained gases, or the amount of low specific-gravity particles in the water. An example of a low-density sludge with a high solids concentration is a rising or floating sludge in a clarifier. To avoid confusion, operators should use the terms *solids* or *solids concentration*, not density.

Because a continuous online analyzer cannot dry the sample, all solids concentration meters use indirect methods (e.g., optical, ultrasonic, and nuclear). Indirect methods correlate the solids concentration with a measurable factor. The limitation of not relating perfectly to the quantity of suspended matter does not seriously affect the analyzers' ability to produce a repeatable signal of great value in process control.

NEPHELOMETERS. When a light beam is directed into a liquid containing suspended particulates, the suspended particulates scatter some of the light. The nephelometer helps observers measure the amount of light that the particulate matter scatters (Figure 7.24). The amount of scattered light relates approximately to the amount of particulate matter, particle size, and surface optical properties. The nephelometer is a photoelectric device that uses an incandescent light source (lamp), which produces light in wavelengths from blue to red. The light is directed to a liquid and, if the liquid contains particles, some of the light strikes the particles and scatters. By placing a photocell

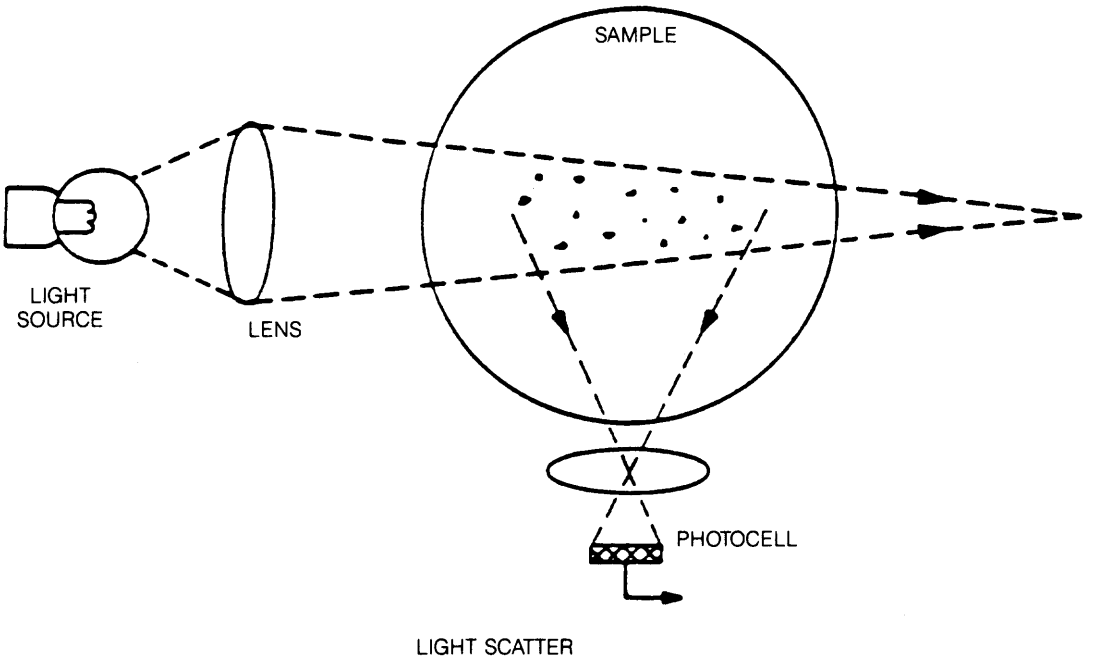


FIGURE 7.24 Nephelometer.

or light detector at an angle to the light beam rather than directly in front of it, the detector receives only light scattered by the suspended particulate matter. Most nephelometers have the photo detector placed at a 90-degree angle to the incandescent light source.

TURBIDIMETERS. In process control, one way of determining the solids concentration is to relate the solids concentration to the turbidity caused by the presence of suspended matter. Turbidity is the optical property of a water sample that causes light to be scattered and absorbed rather than transmitted in straight lines through the sample (Figure 7.25). Typically, a beam from a standard light source is directed through a clear glass window into the fluid stream to be measured. A percentage of this light is reflected (backscattered) by the suspended matter in the liquid, and a percentage is absorbed. A photosensitive detector uses an attenuation beam of reflected light as a measure of the solids concentration. Some turbidity meters use a second (reference) detector to compensate for the changes in temperature or light source.

To reduce the interferences caused by accumulated dirt, slime, or bubbles in the sampling chamber, one manufacturer has developed a method in which a reciprocat-

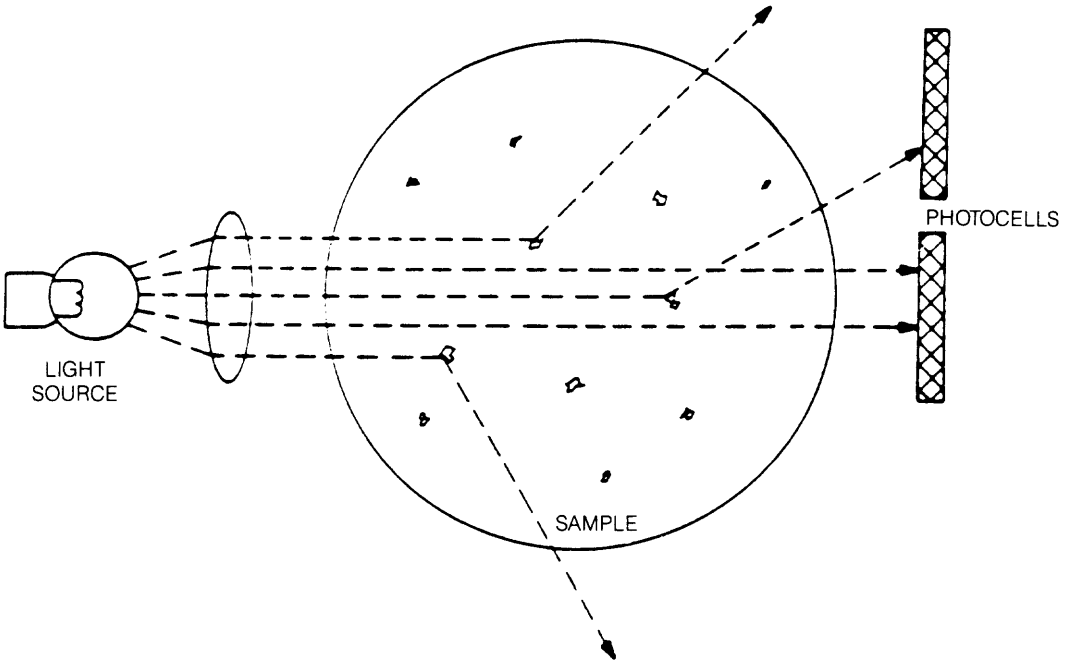


FIGURE 7.25 Turbidimeter.

ing motor-driven piston draws and expels the sample every few seconds while wiping the optical surface of the sampling tube on each cycle. Other manufacturers use either special optical surfaces or the scouring action of the process flow to keep the optical surfaces clean. Certain sensors use surface scatter to keep both the light source and the detector away from the fouling sludge.

ULTRASONIC SOLIDS METERS. The operating principles of ultrasonic solids meters are based on the attenuation of mechanical vibrations because of solids. Attenuation meters consist of transmitting and receiving transducers. The transmitter generates vibration signals that travel through the liquid, which are attenuated (dampened) by scattering caused by the suspended matter. The receiving transducer picks up the attenuated signal. The reduction of signal strength relates to the solids concentration. The speed of sound through sludge is used to measure the solids concentration. This change in speed is quite small but can be measured with extreme accuracy. The meters may need to be corrected to compensate for the effects of temperature and pressure on sound velocity.

NUCLEAR-DENSITY METERS. Gamma radiation (nuclear-density) detectors depend on a source of radioactive material that emits energy in the gamma region and a detector for this energy (Figure 7.26). The radioactive source is placed on one side of a pipe and the detector on the opposite side. Both water and solids act as gamma-radiation absorbers. For thicker sludges, the solids concentration may vary proportionally with the density of the sludge, thus allowing the use of a density meter as a solids meter. The benefits of nuclear-density meters include the following:

- Reasonable sensitivity,
- No moving parts, and
- Reduced maintenance because they do not touch the material.

On the other hand, the difficulties of nuclear-density meters include the following:

- The reading is not accurate if the pipe is not full of sludge or the material stratifies;
- Periodic calibration or compensation is required if the sludge's temperature changes, because temperature affects density;
- Entrained air renders the method useless for many applications;
- The density of greases and oils differs from that of sludge; and
- A U.S. Nuclear Regulatory Commission (Washington, D.C.) license is required to use, calibrate, and dispose of the radioactive materials.

SLUDGE BLANKET SENSORS. Many solids-concentration measurement techniques are used to detect sludge blankets. The instruments can be fixed at a certain depth to show the presence or absence of a sludge blanket. The instruments can also be movable, allowing the actual blanket interface to be located. Automatic detection of changes in blanket level is used to increase process-control stability.

SIGNAL-TRANSMISSION TECHNIQUES

For maximum use and effectiveness, signals generated by various sensors and instruments are transmitted from the sensor to a receiver at another location. Often, the sensor output is transmitted to a control panel or computer system, which allows operators to inspect many process variables simultaneously.

The three components of a signal-transmission system are the transmitter, receiver, and transmission medium (the connection between the transmitter and receiver). The transmitter converts a mechanical or electrical signal from the sensor into a form that

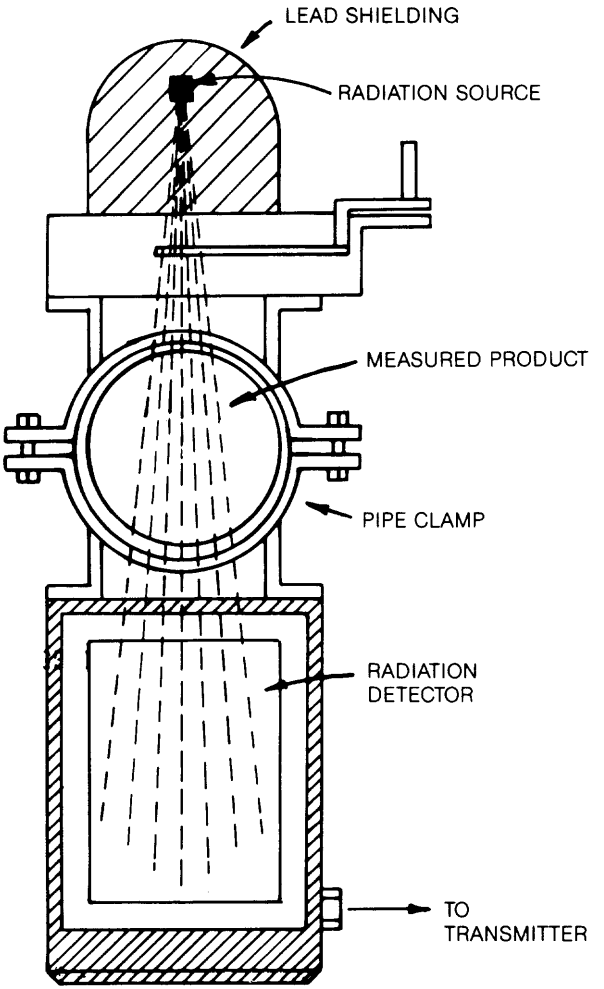


FIGURE 7.26 Nuclear solids analyzer (Skrentner, 1989).

the transmission medium can use. The transmission medium contains the signal and transfers it to the receiver. The receiver subsequently converts it into a form that the receiving system can use.

ANALOG SIGNAL TRANSMISSION. Analog signal-transmission systems continuously and proportionally convert a continuous sensor output to another form. For example, an analog pneumatic transmission system converts the sensor output

from a mechanical displacement to a proportional pressure, typically 20 to 100 kPa (3 to 15 psig). The key characteristic of analog systems is that the transmission signal is continuous and proportional to the sensor output.

Pre-electronic analog transmission systems included pneumatic (compressed air) and hydraulic (compressed fluid) systems. In each case, a mechanical sensor displacement is converted and conveyed by the system without the use of electricity. These systems used to be the workhorse transmission systems in wastewater and industrial treatment plants. Their advantages include intrinsic safety (no sparking potential in hazardous areas) and ease of understanding by mechanical maintenance personnel. However, response time is sluggish in these systems, particularly where long transmission distances are involved.

Electronic analog transmission systems use relatively low voltage and current electricity. They offer the instantaneous response and low-cost characteristics of electricity. Standard electronic transmission systems use 4 to 20 mA-DC or 1 to 5 V-DC signals. As with pneumatic and hydraulic systems, they provide a continuous signal proportional to the sensor output. Electronic signal wiring should be shielded to protect it from high voltages and the other electronic noise encountered in an industrial environment. While they are more responsive and less expensive to install, electronic systems require the skills of an electronics technician for adequate maintenance.

DIGITAL SIGNAL TRANSMISSION. Like computers, digital signal transmitters use the binary number system, which expresses all decimal numbers as a combination of zeros and ones. Electrically, this is manifested as either the presence or absence of electrical voltage. To transmit an analog signal via a digital system, an analog-to digital converter is used. This device accepts the sensor's analog signal and electronically converts it to an appropriate series of zeros and ones. The receiver may use a digital-to-analog converter if the digital signal is not used directly.

The advantages of a digital signal-transmission system are that large amounts of data may be inexpensively and accurately transmitted at high speeds. Digital transmission systems use either an electronic transmission technique or, through further conversion, optical techniques involving optical fibers instead of wires.

SIGNAL-TRANSMISSION NETWORKS. Many sensor and control signals can be combined to form an electronic or fiber-optic transmission network. Various electronic components and computers linked to the network consolidate large amounts of plant data to be used at various locations in the facility. Networks can drastically reduce the total number of wires required to transmit data from the field sensors to an operator station. The many networks vary according to the type of medium and the

network components required. With the advent of digital sensors, it is now possible to connect a series of field instruments or final control elements into networks (Fieldbus).

TELEMETRY. Both analog and digital signal-transmission techniques link remote facilities (e.g., lift stations) with a central monitoring point (Figure 7.27). These specialized systems, often called *telemetry systems*, use radio, telephone, microwaves, or lasers as communication media to transmit information over long distances or difficult terrain. When combined with computers, telemetry systems easily consolidate the monitoring and control of many remote facilities. Because telemetry systems are purely electronic, they require the skills of an electronics technician for adequate preventive maintenance.

CONTROL CONCEPTS

Control of a process variable would not be required if processes were always steady-state (i.e., operated without change). However, process conditions in a treatment plant are always changing based on the flow and strength of the wastewater being treated. These changes create deviations from ideal process adjustments or setpoints, resulting in process inefficiencies, including over- and under-treatment of wastewater and the

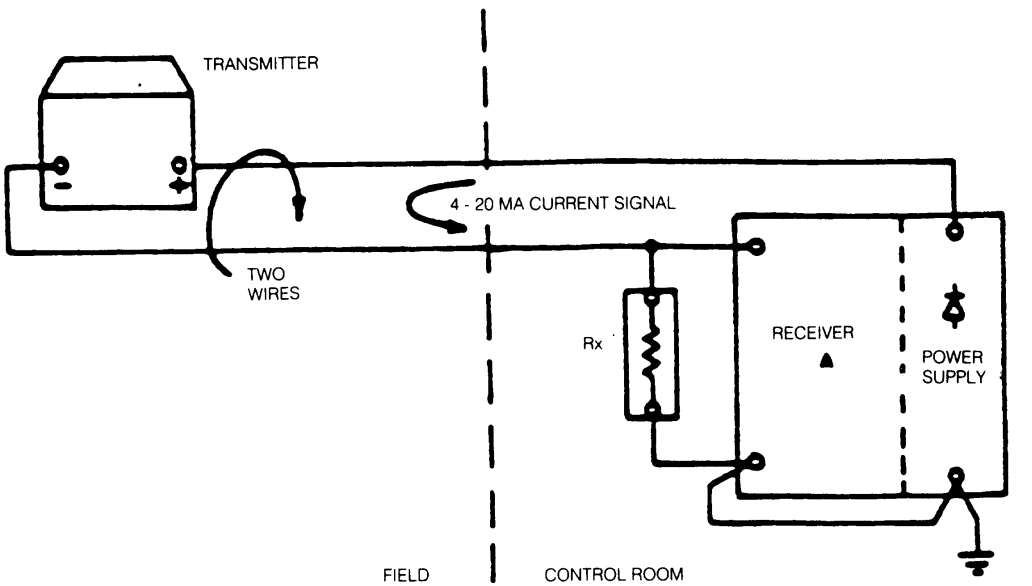


FIGURE 7.27 Typical electronic analog signal-transmission system.

removed solids. Control of a process variable (e.g., flow or level) is accomplished by moving valves or changing pump speed, commonly called the *manipulated variable*.

MANUAL CONTROL. An operator performs manual control. For example, if an operator observes a rising level in a wet well and slightly increases the speed of a pump to match the flow into the well, the new level will be maintained. To take the level back to its original point, the operator will have to increase the pump speed to lower the level sufficiently and then slow it again to match the inlet flow. With experience, the operator may guess the speed necessary to maintain the wet well at an acceptable level, but as the flow changes, the level will again deviate from the optimum level. This kind of control is also called *open-loop control* because there is no direct connection between the desired value of the process variable (setpoint), the instantaneous value of the process variable, and the action of the controlled variable, unless the plant operator constantly observes and changes the manipulated variable.

FEEDBACK CONTROL. In the above example, if the operator is continuously monitoring the level, the operator is providing the feedback. However, doing so is not an efficient use of resources. Feedback control is the easiest way to automate the control of a process. A feedback controller (Figure 7.28) receives sensor output on either the process variable or the desired result and compares it with an operator-entered set-

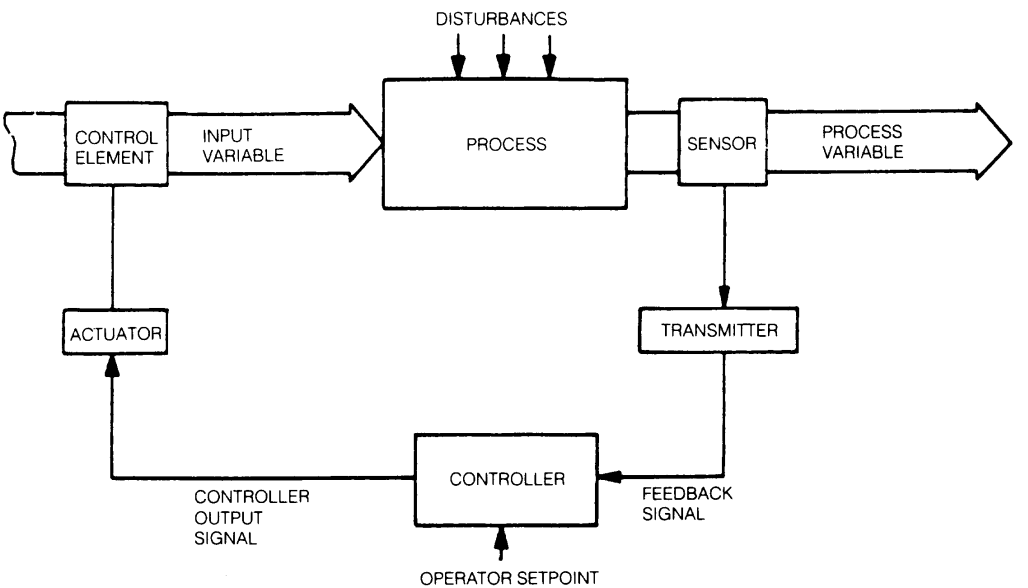


FIGURE 7.28 Feedback control.

point. The controller automatically calculates the difference (error) and determines an appropriate control action for the input variable. Because the feedback controller is always on duty, the level in the wet well can be maintained close to the optimum required (the operator's setpoint).

Feedback control accounts for all existing possible errors, process disturbances, and process inputs. The individual errors and disturbances need not be specifically quantified, because the feedback mechanism gives the controller a cumulative effect.

One disadvantage of feedback control is the time lag between a process adjustment and the evidence of that adjustment. The time lag is typically not a problem when controlling the flow or level in relatively small vessels. However, if the time lag is 30 minutes or longer, feedback control alone may be inadequate.

FEEDFORWARD CONTROL. Feedforward control uses information about the inputs to a process to prevent process errors (Figure 7.29). A good example of feedforward control is ratio control. In a chlorination system, the rate of chorine application is based on the amount of plant flow entering the chlorination facility. An automatic ratio-control system allows the operator to establish a mass-to-flow chlorine-dose setpoint. Then, as the plant flow increases or decreases, the chlorine application rate adapts automatically and proportionally.

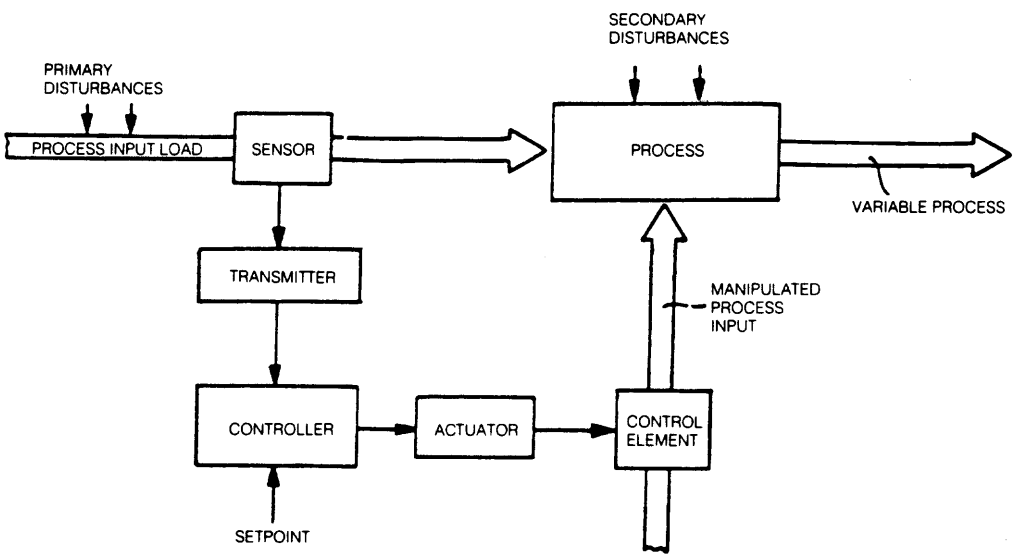


FIGURE 7.29 Feedforward control.

COMPOUND CONTROL. Combining feedback and feedforward controls provides the ultimate in automatic control for certain processes. As in the chlorination example, the operator determines a ratio of chlorine to be applied as the plant inflow changes. The feedforward controller faithfully meters the chlorine according to this requirement. However, the ultimate process goal is maintaining a residual level of chorine. Suspended solids, pH, and other process characteristics not detected by the feedforward control equipment will produce considerable variation in the chlorine residual, despite the constant adjustment provided by the chlorine-application ratio.

In a compound control loop for chlorination, feedback control adjusts the ratio setpoint of the feedforward control loop. A chlorine residual analyzer continuously monitors the chlorine residual in chlorination effluent. As the process variable deviates from the desired setpoint, a new setpoint is sent to the ratio controller, which readjusts the ratio of chlorine to plant inflow accordingly.

ADVANCED CONTROL. Computers, microprocessors, and other programmable devices allow unique control concepts to be applied to a specific process or group of processes (e.g., the concept of sequential control or logic statements that compare process conditions with preprogrammed conditions allowing specific outputs to the process equipment). The control system outputs precisely imitate an operator's actions in response to the process changes. Pure feedback or feedforward controls may be only partially adequate for the control situation encountered. Advanced control is typically best applied where multiple, parallel treatment units are used or where changing process conditions cannot be anticipated by the change in one process input or output.

Advanced control programs take into account dozens of process sensors while manipulating selected pieces of equipment to achieve the desired process control. Advanced mathematical calculations, models, or condition matrices are used to maintain correct setpoints or properly correct for extreme process conditions. Besides variable-speed pump or valve adjustment, equipment may be started or stopped. These programs are often generated by trial-and-error techniques until the best match is found. The feedback and feedforward control concepts are often used as portions of the overall control logic.

AUTOMATIC CONTROLLERS

Automatic controllers are prepackaged devices that not only accept input signals from sensors and operators but also output calculated control signals to a final control element to maintain an operator-entered or otherwise calculated setpoint. The controllers

in use today are primarily electronic in principle, although pneumatic and mechanical controllers are still used successfully, depending on the application. The following modes of control are available and applied based on control requirements.

ON–OFF CONTROL. On–off (differential) control is the most widely used automatic control in industrial and domestic control applications. On–off control is used when extremely tight control of a specified setpoint is not required (Figure 7.30). The process variable is controlled based on a specific band of values rather than just one value. By nature, on–off control is discontinuous.

A common domestic example of on–off control is a thermostat. A common wastewater treatment example of on–off control is that used in a small single-pump lift station. Two floats (sensors) indicate the high and low levels desired in the wet well. When the high float is tripped, the pump starts and runs until the low float is tripped, shutting off the pump. Thus, the liquid level in the wet well is maintained between the levels of the floats (the acceptable band of operation).

PROPORTIONAL CONTROL. Proportional control is often used when continuous control is required and a wide operating band for the process variable is not acceptable. Proportional control is based on a linear mathematical relationship in which the controller output is equal to the error between the setpoint and actual value of the process variable multiplied by a constant adjustable factor known as *gain* (Figure 7.31).

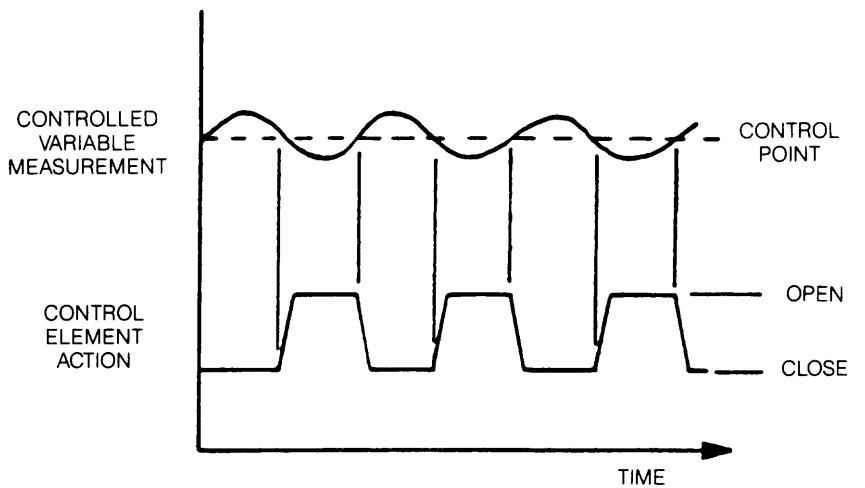


FIGURE 7.30 On–off control.

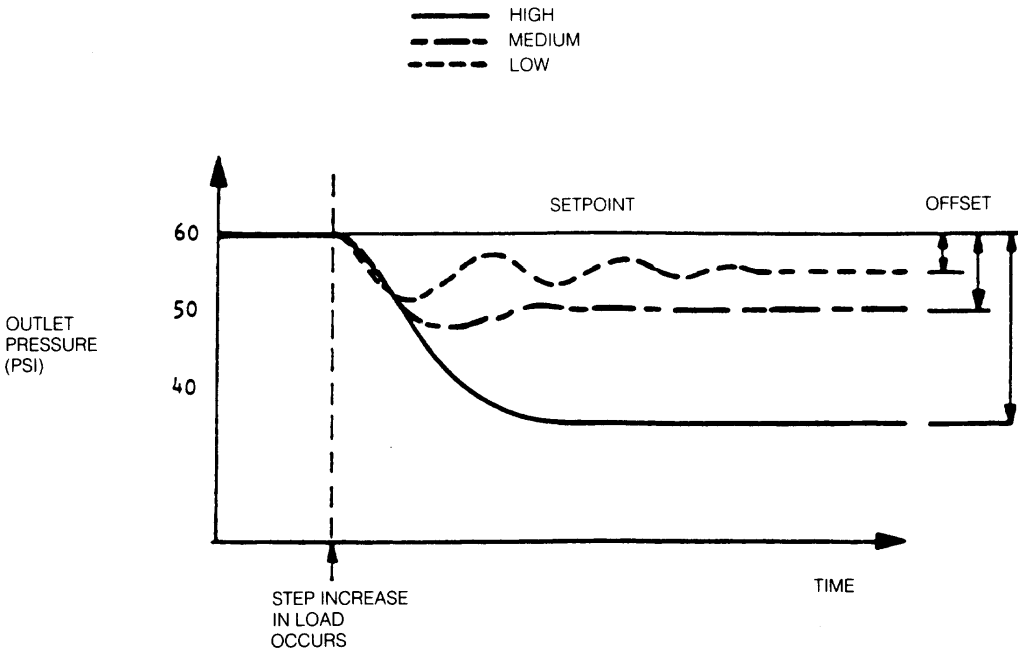


FIGURE 7.31 Proportional-mode control response: pressure-control example (psi × 6.895 = kPa).

As the error increases, the controller output increases proportionally to compensate. The higher the gain, the larger the output increases for each unit change in the error.

Proportional control has one major disadvantage. At steady state, the controller exhibits an offset between the ultimate desired setpoint and that achieved with the controller. Often, this offset is considered insignificant, so proportional control is more than adequate.

RESET CONTROL ACTION. In cases where the inherent offset of proportional control is unacceptable, reset control action may be required. Reset control action uses a mathematical integration of the error signal, allowing the controller output to change at a rate matching the change of the error signal over time. This action, in combination with proportional control, corrects for the offset condition inherent with proportional control alone. This type of controller is often referred to as having proportional–integral action (Figure 7.32). The disadvantage of this controller is that it is inherently less sta-

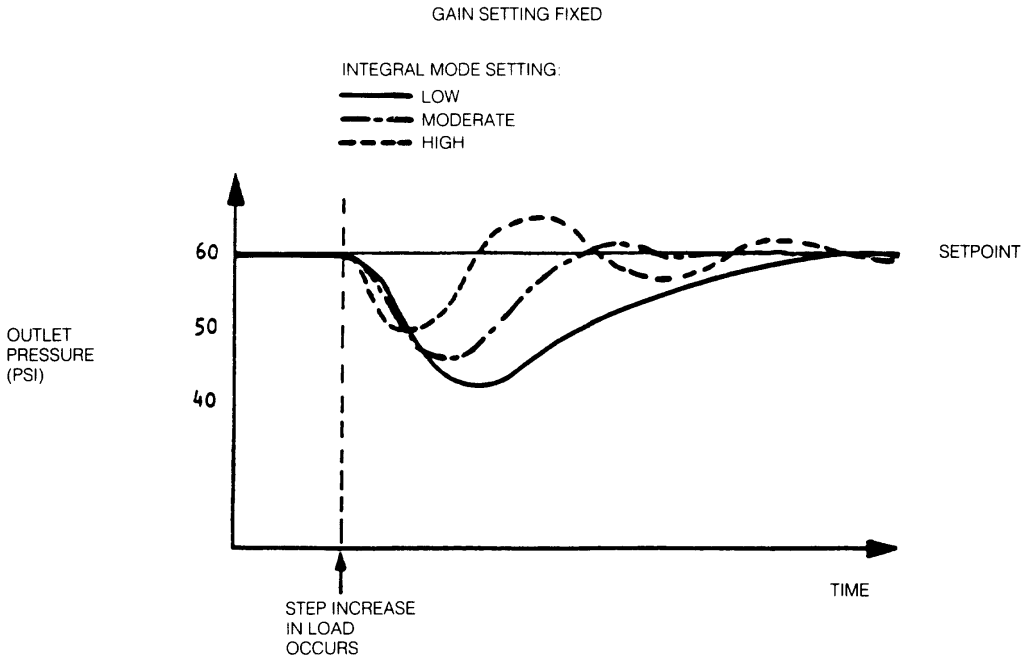


FIGURE 7.32 Proportional plus integral mode control response: pressure-control example (psi × 6.895 = kPa).

ble than a proportional-only controller and so may be difficult to tune during initial application.

THREE-MODE CONTROL. A three-mode controller (commonly known as a *proportional–integral–derivative controller*) is the most sophisticated standard controller available for feedback control loops (Figure 7.33).

This controller uses the features of the proportional–integral controller and adds a third action (derivative control) for even more responsive control. Derivative action provides a mechanism for adding lead action to the control loop, compensating for time lags in the control loop. It cannot be used alone because a large continuous, unchanging error would result in no controller response. Derivative controller applications are rare in wastewater treatment control applications. This type of controller is covered here because controllers may often be found installed with all three modes available for use. Operators should be aware that all three modes are not required for adequate control.

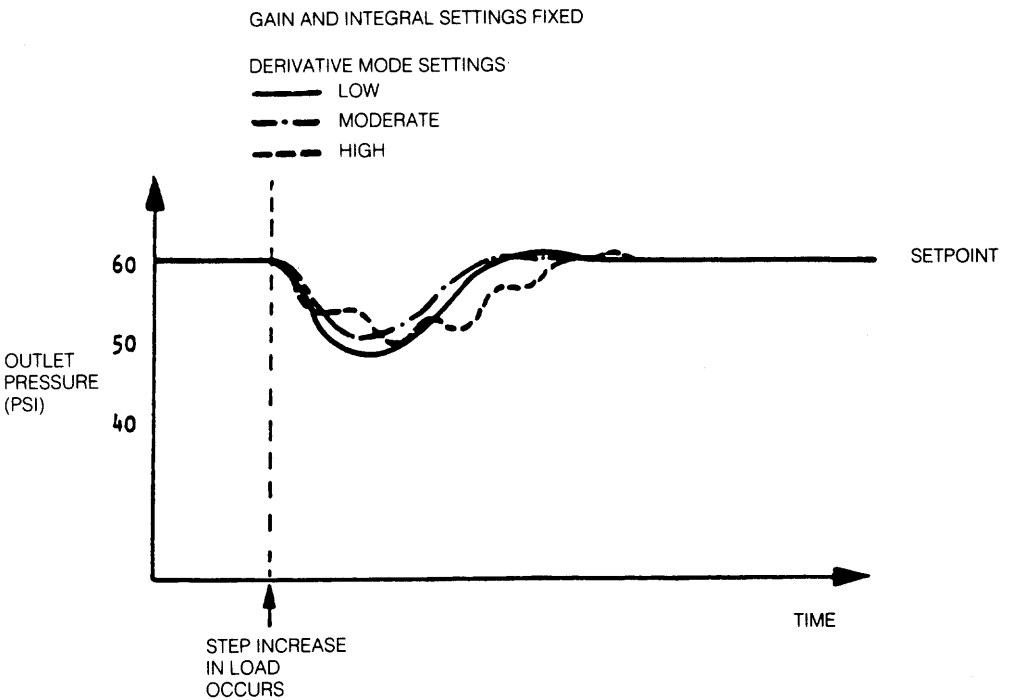


FIGURE 7.33 Proportional plus integral plus derivative control response: pressure-control example (psi × 6.895 = kPa).

PERSONNEL PROTECTION INSTRUMENTATION

Specialized gas-detection instrumentation is an essential component of a modern personnel protection program. Instrumentation systems sample ambient-air conditions in a plant building or manhole and provide early warning of hazardous conditions. These systems may also automatically activate ventilation equipment and other alarm systems. Hazardous atmospheric conditions typically found in wastewater collection and treatment facilities include oxygen deficiency; explosive gases; and toxic gases (e.g., hydrogen sulfide, chlorine, sulfur dioxide, and carbon monoxide). *Safety and Health in Wastewater Systems* (Water Environment Federation, 1994) provides more information on personnel protection programs.

Personnel-protection instrumentation systems are packaged for both portable and stationary applications. Portable applications include confined-space entry (manholes and wet wells) for inspections and maintenance. Stationary applications include equipment structures below grade (e.g., lift stations or pipe galleries) or any enclosed area

where gases may escape from wastewater or sludges in a routine way (e.g., a screening room, grit chamber, or dewatering areas). Managers of any wastewater treatment or collection operation, no matter how small, should consider purchasing a minimum complement of hazardous-condition instrumentation, because this equipment is reasonably priced and reliable.

PORTABLE EQUIPMENT. Portable, battery-powered alarm systems that detect multiple gases are essential equipment for any personnel entering a confined space, even if it pretested as safe. Worn by personnel, the units will sound an alarm at preset gas levels. Health and safety organizations and federal, state, and local regulations establish the alarm limits. Essential features of portable multigas testing equipment include the following:

- Visible and audible alarms for each gas according to real-time exposure limits, 15-minute short-term exposure limits, and 8-hour time-weighted-average limits;
- A display for the actual numerical concentration of each gas;
- An operating battery life of at least 10 hours, with audible low-battery charge alarm;
- Certification as intrinsically safe in hazardous environments;
- Ability to function over a range of temperatures, from below freezing to approximately 49 °C (120 °F);
- Accessories for calibration and remote sampling; and
- Documentation that clearly describes operation, calibration techniques, and equipment and provides a list of gases that could interfere with a particular sensor.

Operators should use a portable gas measurement system that meets the established plant standard safety procedures.

Operators should keep written records of routine calibration, repairs, sensor replacement, and all alarm incidents. Sensor life varies depending on the environment where it is stored and used. Operators should replace sensors routinely, based on the factory-recommended schedule or on the sensor failure history, whichever is more frequent.

STATIONARY EQUIPMENT. Stationary systems include gas sensors and conversion electronics permanently mounted in a given location. Chemical storage and feed areas, pumping stations, the digester-gas compression room, and other areas often use stationary systems connected to plant alarm systems that trigger the operation of ventilation equipment. Because sensor installation is permanent, proper placement is essential to allow accurate sampling of the atmosphere in an area. For gases heavier

than air, sensors should be no more than 0.3 m (1 ft) above the floor. Pockets of toxic gas may collect near the floor, even on a floor that is above grade. If auxiliary equipment (e.g., a sampling pump) is used with the system, its failure should be treated as a hazardous condition.

Because most of the areas where stationary systems are used are often moist with varying concentrations of corrosive gases, operators should protect the electronics and power-supply components by putting them in a clean environment or suitable enclosure. Many toxic gas hazards can occur during electrical power failure, so plant staff should consider providing a source of uninterruptible electrical power (e.g., a battery) for a stationary system. The essential features of a stationary system and a portable system are the same. As with portable gas-detection equipment, thorough records of calibration, repair, and alarm conditions are required.

OXYGEN DEFICIENCY. An oxygen-deficiency sensor measures and shows the percentage of oxygen in the air being sampled. It is important to test various levels of the airspace being sampled because gases lighter or heavier than air will form layers. The fact that oxygen is present at safe levels does not necessarily mean that the area is not potentially dangerous because other toxic gases may be present.

EXPLOSIVE GASES. Explosive gases are dangerous combinations of oxygen and hydrocarbon gases (e.g., methane, ethane and gasoline and paint solvent vapors). Tests for these gases must be conducted with extreme caution, avoiding sparks that could ignite an explosive gas mixture.

HYDROGEN SULFIDE. Hydrogen sulfide gas, commonly found in wastewater treatment and collection systems, is malodorous (smells like rotten eggs at lower concentrations). High concentrations of the gas quickly numb the sense of smell and may mislead an operator into thinking that conditions are safe. Besides being toxic and potentially fatal to personnel, hydrogen sulfide is corrosive.

FACILITY PERSONNEL PROTECTION AND SECURITY

Facility-wide instrumentation systems are often provided to protect the facility's personnel, structures, and equipment. These systems may include fire detection, card access, page party, and closed-circuit television. The fire detection system is used to warn personnel of a fire for evacuation purposes, notify the local fire response agencies, and to locate the fire. Card access systems are used to permit site access, to limit access within plant areas, for personnel recordkeeping, and for security emergency response. The

closed-circuit television can be used to monitor public areas surrounding the plant and help protect against unauthorized access to areas within the plant. A page-party system is used to alert personnel during an emergency, provide communication between personnel on the plant site, and help locate personnel by voice announcement and response.

FIRE DETECTION SYSTEM. Fire detection system standards for wastewater treatment facilities have been established by the National Fire Protection Association (Quincy, Massachusetts) and are often augmented by state and local building codes to define minimum requirements for alarm systems and fire-suppression systems. Typical suppression systems include water sprinklers or sprays, foam, halon, carbon dioxide, dry chemicals, and preaction sprinkler systems. A fire-detection system supervises and monitors these systems and monitors for fire or smoke via photoelectric, ionization, and temperature detectors. In sprinkled areas, the system would also monitor the manual pull stations.

The fire-detection system, via audible and visual indication devices, provides early warning to building occupants so a safe and orderly evacuation can be made. Local fire panels annunciate the detector's location so fire respondents can quickly address the problem. The panel can also be interfaced with heating, ventilation, and air conditioning systems to help evacuate smoke, elevators to limit access and return to the proper floor, page-party systems to provide personnel evacuation instructions, closed-circuit television systems to monitor the affected area, and the telephone system to contact the local municipal fire station for appropriate response.

On large digital systems, local panels are connected via data highways and monitored via cathode ray tube screens. Each device can be monitored for current status, and alarm limits can be modified for differing area working conditions (reducing false alarms). Operating and alarm history records are maintained in the system database.

Fire-detection systems must be tested quarterly to ensure that the monitoring devices are properly cleaned and calibrated and that the system performs as required.

CARD-ACCESS SECURITY SYSTEM. Card-access systems are used to limit access to an area and can be provided as standalone devices interfacing electrically to a magnetic door latch (or gate motor) to permit entry and an infrared detector (or pressure-sensing device) to permit egress. With more sophisticated card readers or scanners, these devices can be connected to a computerized system, which can be programmed to permit facility access or restrict access to certain areas within the plant. Individual access can be programmed and limited by time of the day or day of the week. Schedules can be set up to cover work shift assignments and more. Information stored on the system can be used to identify personnel access and maintain time and attendance records.

INTRUSION DETECTION. Like the card-access system, intrusion detectors are used to monitor unstaffed areas of the facility. Depending on the area to be protected, limit switches, conductive tape, and magnetic intrusion detectors can be mounted on doors, hatches, or windows, with passive infrared motion detectors installed to cover specified areas. Remote pumping stations often use this hardware to notify plant personnel via radio or telephone telemetry that the station is being accessed. To provide facility perimeter detection, taut wire systems within security fencing and bistatic and monostatic microwave systems can be used. The latter devices require an overlapping layout to prevent blind spots.

CLOSED-CIRCUIT TELEVISION SYSTEM. A closed-circuit television system uses a camera and cathode ray tube to monitor an area. These devices are hardwired or networked back to a local control or security office to provide visual input to the operator of existing field conditions. Cameras can be provided with sun screens; lenses for low-light operation; pan, tilt, and zoom capabilities to observe a wider area or get a close-up view; heaters for winter applications; and wipers to combat rain or snow. Controls can be implemented with the card-access system or intrusion-detection devices to focus on a certain area if unauthorized access is attempted or access is permitted after normal working hours. The cameras can be connected to video recorders so a record of previous activity is maintained. These same functions can be interfaced with the fire alarm system to provide a video record of the event.

PAGE-PARTY SYSTEM. The page-party function supports two types of voice communication: paging, which allows announcements to be made; and party lines, which allow "telephone" communications between persons connected to the same party line. A page-party system may use integrated page-party stations providing both types of voice communication in a single enclosure and using separate wiring to connect the integrated page-party stations together. A page-party system may also be an independent paging system using amplifiers, wiring, and speakers to provide paging and separate handsets to provide point-to-point voice communication. A hybrid solution using both types of page-party systems may also be used to provide the page-party function. The benefit of an integrated page-party system is simple and efficient communication in both the process and administrative areas of the plant.

Each page-party station, including the handset, speaker, and speaker amplifier, can be provided with internal monitoring and diagnostic capability. These functions can be centrally monitored for use and maintenance purposes. This capability has proven useful when personnel use the system in an unauthorized manner.

INSTRUMENT MAINTENANCE

RECORDKEEPING. There is no substitute for a good recordkeeping program. A record of instrument performance and repairs allow operations or maintenance personnel to properly evaluate an instrument's effectiveness and determine if the instrument meets the objectives used to justify its purchase and installation. As a minimum, the following basic information should be maintained for each instrument in the wastewater treatment plant:

- Plant equipment identification number,
- Manufacturer,
- Model number and serial number,
- Type,
- Dates placed into and removed from service,
- Reasons for removal,
- Location when installed,
- Calibration data and procedures,
- Hours required to perform maintenance,
- Cost of replacement parts, and
- Operations and maintenance manual references and their locations.

MAINTENANCE. Preventive maintenance requirements are best met by combining the recommendations of the equipment manufacturer with the experience and knowledge acquired over time by operations and maintenance personnel. Typically, preventive maintenance for instrumentation is divided into four areas: reasonability checks, cleaning, detailed inspection, and calibration.

A *reasonability check* is the act of observing the indication of the instrument with process changes and in comparison with other related instrumentation. For example, acceptable operation of an influent flow meter can be verified by observing its response to step-flow changes in the main flow to the plant as main lift pumps are cycled off and on. The same meter can be compared with the sum of multiple, parallel downstream meters. For a dissolved oxygen sensor, a second portable dissolved oxygen meter can be used to make a quick comparison. Reasonability checks are not a replacement for a detailed inspection and calibration. Instrumentation technicians can do reasonability checks, but they are mandatory for operations personnel.

Cleaning involves everything from wiping the cover of a recorder to removing inline pH or dissolved oxygen probes for removal of precipitates or solids deposits.

Detailed inspections may be part of the cleaning activity or can be scheduled on a calendar basis. To prevent instrument damage, a trained technician should inspect the instrument. To maintain consistency and ensure that the instrument is not damaged, specific cleaning procedures need to be followed. The specific environment in which the instrument is installed determines the frequency and methods of cleaning.

Calibration—the process of fixing, checking, or correcting the graduation of an instrument—is the comparison of the instrument's performance against some accepted standard followed by adjustment to match the standard. Excessive calibration may indicate that the instrument is failing. If an instrument appears to be malfunctioning, operators should first determine that it is not showing transient process conditions or other non-instrument-related conditions. Calibration adjustment should not be made casually to force an instrument to match what is perceived to be correct based on observed process performance, because that would defeat the purpose of instrumentation as a reliable tool for verifying process performance. Operators should replace parts when it is confirmed that a device has malfunctioned or when it is called for in preventive maintenance procedures. The plant should stock adequate spare parts, because delivery times can range up to several months, depending on the device. Certain parts are best replaced by the manufacturer, while others can be easily replaced by nearly anyone who can follow a written procedure. Electronic components must be handled carefully, because they are subject to severe damage from static electricity and even weak magnetic fields. Personnel who replace parts need proper training for the specific activity.

PERSONNEL TRAINING. Despite plant or staff size, each plant develops its specific instrumentation training program. At a minimum, operators must be trained in the principles of instrument operation that allow detection of malfunctions. Maintenance personnel should be trained to use the specialized equipment required for instrument maintenance. Training can include short courses, seminars, or formal classes conducted by instrument manufacturers or consultants. It may include the use of videotapes offered by professional organizations [e.g., the Instrumentation, Systems, and Automation Society (Research Triangle Park, North Carolina)]. Regardless of the training source, the format can include lectures and, more importantly, hands-on activities. Whenever possible, hands-on training in the plant should use the actual instruments to be maintained. Written documentation and audio–visual techniques should be used to record the training.

Annual allocations for personnel training should be included in the budget. Because advances in the field of instrumentation and control systems occur more rapidly than other areas of plant maintenance (e.g., repair of mechanical process equipment) instrument repair personnel need more frequent training to stay abreast of the industry.

MAINTENANCE CONTRACTS. An effective alternative to having a full-time maintenance technician on staff is to contract with the instrument or control-system supplier or a qualified third-party maintenance organization. This is particularly true for smaller treatment facilities. Larger facilities should carefully evaluate the relative benefits of this approach. A contract with a reputable maintenance organization typically provides access to a skilled technician and specialized test equipment. Various types of service packages are available, ranging from complete service (e.g., parts, routine service calls, and emergency repairs) to simple quarterly visits during normal working hours using parts supplied by the treatment plant.

The annual cost of maintenance contracts may be 10% of the equipment cost or more, depending on the response provisions. A negative aspect of maintenance contracts is the outside technician's relative unfamiliarity with the plant's equipment compared with that of employees. Additionally, the service organization may not appreciate the relative importance of one device over another. Thus, plant managers must provide direction and arrange priorities for the service people. To ensure that the work performed meets the contract terms, service personnel should be monitored.

Some wastewater treatment plants have created hybrid operator–instrument technician positions to allow the needed intimacy with the equipment without creating a full-time, dedicated position. This approach yields additional benefits because the operational knowledge allows the employee to fully understand the process function and importance of a particular device.

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INTRODUCTION

Pumping systems (which include pumps, motors, valves, and controls) are integral to wastewater treatment. Collection and treatment system operations depend on pumping systems to help transport wastewater and solids to the treatment plant and between various treatment processes. Pumping systems transfer fluid from one point to another or one elevation to another so it can then flow via gravity through the collection or treatment system to the next pumping system. [In this chapter, *fluid* is any material being pumped, *liquid* is any fluid that is predominantly water, and *solids* is a fluid with significant solids content. Raw wastewater, for example, is a liquid; it typically contains 200 to 300 mg/L of total suspended solids (0.02 to 0.03%)—too little to affect flow characteristics. Return activated sludge could be a liquid or solids; it typically contains 10 times more solids, which could affect flow characteristics. Thickened, dewatered sludge is a solids; it can contain more than 20% solids, which profoundly affects flow characteristics.]

Operators should be able to recognize pumping system components, know how they function, understand how basic hydraulic conditions affect performance, and

learn how to optimize pumping systems for long, productive service lives. They also should be familiar with wastewater-related hazards. For example, gritty and stringy solids can plug pumping systems or wear them out more rapidly. Both wastewater and solids contain high concentrations of pathogens known to cause illness in people. They also are susceptible to biological reactions that can increase pumping system pressures and generate poisonous gases that could both build up to dangerously high levels if not vented properly.

Pumping strategies (e.g., increasing off-peak pumping and maintaining high wet well levels) should be designed to lower energy costs and balance flow through treatment processes. However, these strategies will alter the design and operation of various process units and could create the following problems:

- Increasing evening flows through the treatment plant will increase chemical-addition and solids-pumping monitoring needs during off hours, when the requisite staff may not be present.
- Maintaining continuously higher wet well levels will lower velocities in the collection system, promoting deposition of solids.
- Detaining flow in the collection system can lead to more odors.
- Holding flow in the collection system will shrink the reserve capacity available for emergency or wet-weather conditions.

So, utility staff should thoroughly investigate potential consequences before implementing any pumping changes.

(For even more information, see the "Hydraulics Institute Standards", which provides detailed information on pump types, nomenclature, ratings, test standards, and applications, as well as instructions for installing, operating, and maintaining centrifugal, rotary, and reciprocating pumps.)

PUMP AND PUMPING FUNDAMENTALS

A pumping system typically includes a pump, suction and discharge reservoirs, interconnecting piping, and various appurtenances (e.g., valves, flow-monitoring devices, and controls). To deliver a given volume of fluid through the system, a pump must transfer enough energy to the fluid to overcome all system energy losses.

In the following subsections, various energy needs (headlosses) are identified and defined, and the energy (head) that the pump imparts to the fluid is described. Head is typically measured as meters of water (m H_2O) or feet of water (ft H_2O).

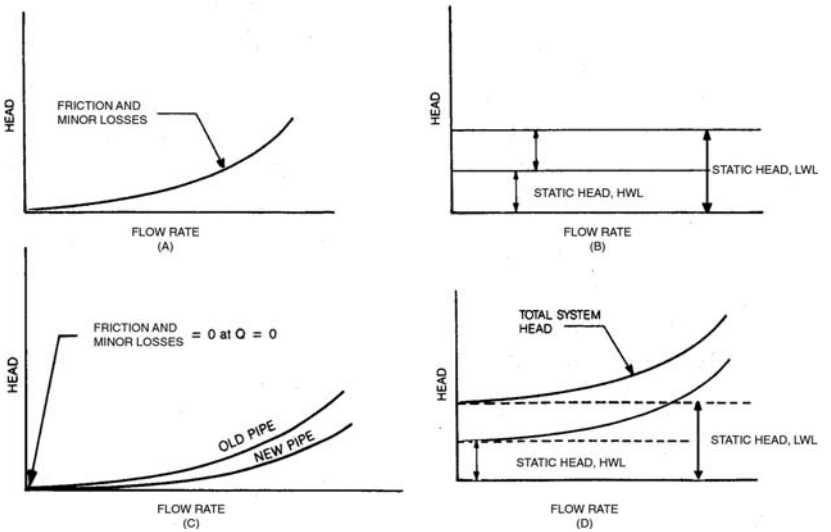


FIGURE 8.1 Pump system head curves: (A) friction head loss versus flow, (B) velocity head and static head versus flow, (C) friction loss curves, and (D) total system head versus flow.

SYSTEM HEAD. A pumping system requires a certain amount of energy to convey a given amount of flow at a specific rate. Its "system curve" is a graph charting the total energy requirement at various flow rates (Figure 8.1). The *total energy requirement* includes both the energy needed to overcome velocity losses as the fluid moves through the pumping system and that needed to overcome elevation changes from the pumping system's inlet to its outlet.

Static Head. *Static head* is the difference between the fluid's surface level (pressure head) at the pumping system's entrance (suction point) and that at its exit (discharge point) (Figure 8.1, Part B). In liquid pumping systems, the fluid level in the influent wet well varies, while that in the discharge tank is relatively constant. So, the static head is a larger value when the influent level is low and a smaller one when it is high. The static head can be zero or less than zero, depending on the downstream fluid surface elevation and pressure head.

Velocity Head. *Velocity head* is the distance required to accelerate the fluid from a standstill to a particular velocity. It depends on the desired fluid velocity and is calculated as follows:

$$\text{Velocity head} = v^2/2g$$

where

v = the fluid velocity in meters per second (m/s) or feet per second (ft/sec),
1 ft/sec = 0.3048 m/s, and
g = 9.80 m/s^2 (32.2 ft/sec^2).

Typically, the velocity head is added to a pumping system's headlosses.

Headlosses. A pumping system's headlosses include both friction and minor losses.

Friction Losses. Friction loss is the energy that flow loses because of frictional resistance in pipes. It can be calculated via various formulas (e.g., Darcy, Darcy–Weisbach, and Hazen–Williams). Over time, the friction head at a specified flow within a particular system may not equal the design head because

- The "as built" system differs from the design;
- The mechanical equipment's manufactured tolerances vary;
- A fluid's viscosity changes when its temperature changes [applies to fluids with a viscosity much greater than water (e.g., solids)];
- Solids have accumulated or air is entrained in the system, causing a partial restriction;
- The piping system is deteriorating.

These changes could either increase or decrease friction loss, so utility staff should calculate friction losses for both newer and older piping.

Minor Losses. Whenever a fluid changes direction and speed to travel through a pumping system's valves, bends, and other appurtenances, it loses energy. Such losses are called *minor losses* because each individual loss is not a large value. They are calculated as follows:

$$\text{Minor loss} = kv^2/2g$$

where k = an appurtenance-specific loss (Brater et al., 1996; Street et al., 1995).

While each individual loss is minor, the cumulative effect of these losses can be substantial. It can even exceed the pumping system's total friction losses.

Total Headlosses. A pumping system's *total headloss* is the sum of both friction losses and minor losses. It depends on the square of the flow rate (Figure 8.1, Part A). Typically, new piping has fewer headlosses than old piping (Figure 8.1, Part C).

Total System Head or Total Dynamic Head. Total system head, which is typically synonymous with total dynamic head at a given flow rate, is the sum of the static head, velocity head, minor losses (including entrance and exit losses), and total friction losses through all piping (Figure 8.1, Part D). It serves the following two purposes:

- Defines the total energy losses realized at a given flow rate through a pumping system, and
- Determines the total energy required to convey and lift fluid at a given rate through a pumping system.

Typically, the velocity head is ignored because it is inconsequential compared to total minor and friction losses. Total minor losses are estimated based on k factors, which are only accurate to within 10 or 20% (unless the pumping system has been calibrated to field measurements). Depending on the pumping system's configuration, the total system head could be zero at a given flow rate, but this is unusual.

Most pumping systems are not defined by one system head curve, but rather by a band of total system headlosses or head requirements lying between the maximum and minimum total system head curves. This band may or may not be significant, depending on the pumping system.

PUMP PERFORMANCE. Every pumping system needs a pump that can provide the necessary energy to overcome the total system head for a particular operating point. Pumps are defined by their performance curves, efficiency curves, and net positive suction head (NPSH) requirements. Manufacturers typically provide this information in one graph, which plots each characteristic for varying flow rates.

Pump Performance Curves. Pump performance curves (also called "pump curves") show how much energy (head) a pump will impart to the fluid. This typically is illustrated as one line per impeller diameter operating in similar casings at one constant speed (Figure 8.2a). It can also be shown as several curves illustrating multiple speeds for one impeller diameter and casing (Figure 8.2b) (Karassik, 1982).

Pump and Motor Power and Efficiency. *Power.* The power generated or used by a pump can be expressed in three forms:

- *Water power* (P_W), which is the energy needed to pump fluid from one location to another, as well as that fluid's energy on leaving the pump (it equals all of the energy losses in a pumping system).
- *Brake power* (P_B), which is the energy provided to the pump by the motor (it equals the power applied to the pump shaft) ($P_B > P_W$).

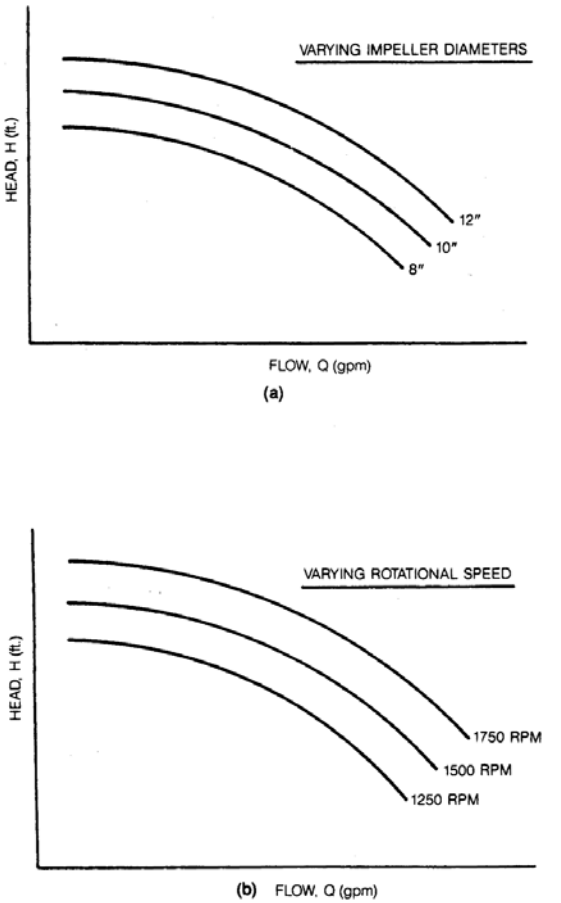


FIGURE 8.2 Centrifugal pump performance curves: (a) curves for varying impeller diameters at constant rotational speed and (b) curves for varying rotational speed with a constant impeller diameter (ft $\times$ 0.304 8 = m; gpm $\times$ 5.451 = m^3/d; and in. $\times$ 25.4 = mm).

- *Wire or motor power* (P_M), which is the electrical power required by the motor ($P_M > P_B$).

Efficiency. A pump's *efficiency* is the difference between brake power input and water power output. It is always less than 1.0. A motor's efficiency is the difference between motor power input and brake power output. The percent efficiency of a pump is:

$$100 \times P_W/P_B$$

and the percent efficiency of a motor is:

$$100 \times P_M / P_B$$

where 1 hp = 550 ft-lb/s of work, 33 000 ft-lb/min of work, or 0.7457 kW.

Pump efficiency curves illustrate how efficiently a pump impeller transfers energy into the fluid (Figure 8.3). Pump manufacturers provide graphs depicting pump efficiency versus flow rate for a given pump, typically on the same graph that shows the pump curve.

Pump Affinity Laws. *Affinity laws* are the relationships that determine pump performance based on rotational speed or impeller diameter. Utility personnel use them to determine how to alter a pumping system to meet a new design or operating condition. For example, if flows have increased, a pump's speed or impeller diameter could be increased to compensate. The affinity laws quantify the alteration required to meet a new condition.

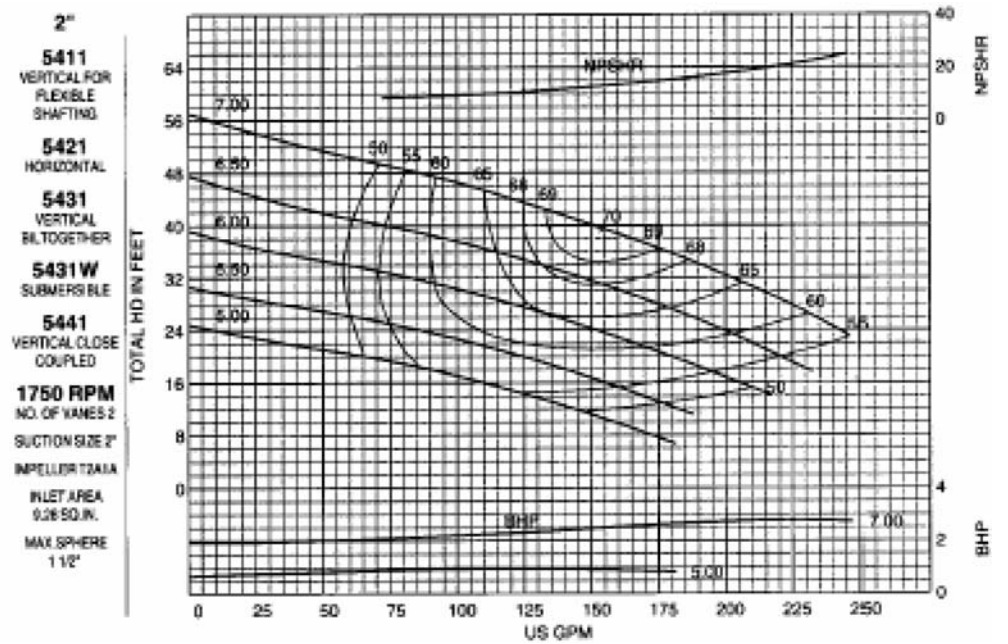


FIGURE 8.3 Example of pump efficiency curves and $NPSH_R$ curve (Courtesy of Fairbanks Morse).

Pump Rotational Speed. When a pump's rotational speed (ω) is changed, the following three relationships apply:

- The flow capacity (Q) varies directly with the speed:

$$Q_2/Q_1 = \omega_2/\omega_1.$$

- The head (H) varies with the square of the speed:

$$H_2/H_1 = (\omega_2/\omega_1)^2.$$

- The brake horsepower (P) varies with the cube of the speed:

$$P_2/P_1 = (\omega_2/\omega_1)^3.$$

Subscript 1 indicates known (existing) characteristics. Subscript 2 indicates the new characteristics.

Pump Impeller Diameter. When a pump impeller's diameter (D) changes, the following three relationships apply:

- The flow capacity (Q) varies directly with the cube of the diameter:

$$Q_2/Q_1 = (D_2/D_1)^3.$$

- The head (H) varies with the square of the diameter:

$$H_2/H_1 = (D_2/D_1)^2.$$

- The brake horsepower (P) varies with the quintic of the diameter:

$$P_2/P_1 = (D_2/D_1)^5.$$

Subscript 1 indicates known (existing) characteristics. Subscript 2 indicates the new characteristics.

Example. For a given pump, utility staff can develop a new pump curve by doing the following:

- Select a point on the existing pump curve and note its coordinate (Q_1, H_1).
- Choose a new operating speed.
- Calculate a point on the new pump curve using the first two affinity laws for speed; this establishes a new coordinate (Q_2, H_2), which lies on the new pump curve.

- Repeat this process with enough points to establish a smooth pump curve for the new operating speed.
- Determine whether the new pump curve can meet the changed conditions.
- Select a new operating speed and repeat this process, if needed.

Specific Speed. An impeller's *specific speed* is the number of revolutions per minute at which a geometrically similar impeller would rotate if it were sized to discharge against a head of 1 ft. It classifies pump impellers based on their geometric characteristics by correlating pump capacity, head, and speed at optimum efficiency. Specific speed is typically expressed as:

$$\omega_S = \frac{\omega\sqrt{Q}}{H^{0.75}}$$

where

ω_S = pump specific speed,
ω = rotational speed (rpm),
Q = flow rate at optimum efficiency (L/s or gpm), and
H = total head (m or ft).

Specific speed indicates an impeller's shape and characteristics because the ratios of major dimensions vary uniformly with specific speed (Figure 8.4). So, it helps designers predict the proportions required and helps application engineers check a pump's suction limitations.

Although pumps are traditionally divided into three classes (radial-flow, mixed-flow, and axial-flow), each has a wide range of specific speeds:

- In radial-flow pumps, fluid enters the hub, flows radially to the periphery, and discharges at about 90 degrees from its point of entry. Those with single-inlet impellers have a specific speed less than 4200; those with double-inlet impellers have a specific speed less than 6000.
- Mixed-flow pumps have a single-inlet impeller with the flow entering axially and discharging in both axial and radial directions (at about 45 degrees from the point of entry). Their specific speed ranges from 4200 to 9000.
- Axial-flow (propeller) pumps have a single-inlet impeller with the flow entering axially and discharging nearly axially (at nearly 180 degrees from the point of entry). Their specific speed is typically more than 9000.
- Pumps that fall between the radial- and mixed-flow types typically have a specific speed between 1500 and 4000.

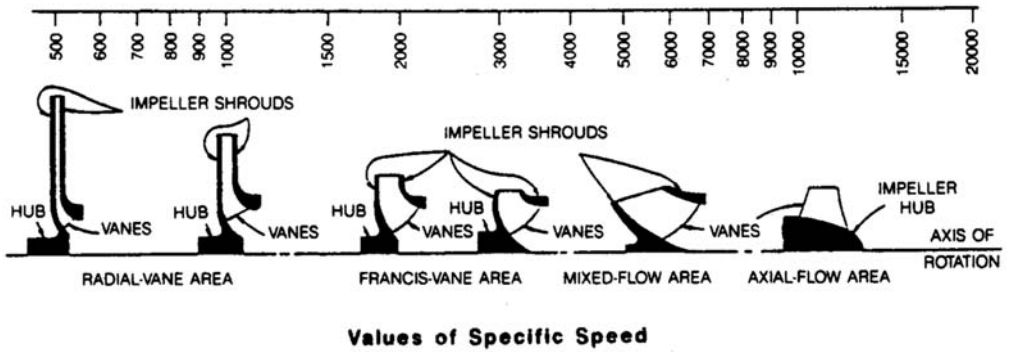


FIGURE 8.4 Standard, specific scale and impeller types.

The distinctions among pumps are not rigid; many are combinations of two types. Also, in the specific speed range of about 1000 to 6000, double-suction impellers are used as often as single-suction impellers.

System Operating Point. The *system operating point* is the intersection of a pump performance curve and a total system head curve at a particular speed (Figure 8.5). It indicates the flow rate at which a given pumping system will operate when using a specific pump. (If the pumping system is properly designed, this flow rate should exceed the design flow rate.) The goal of pump design and operations is for this operating point to equal or be very near the best efficiency point (BEP). The *best efficiency point* is the point on a pump curve where a pump would operate at maximum efficiency.

Net Positive Suction Head. The *net positive suction head* is the remaining energy (head) on the suction side of the pump. If headlosses in the suction piping are too large, then energy and pressure will drop. If the pressure becomes too low (reaches the vapor pressure of the fluid), the fluid will convert into the gas phase and form vapor cavities, a process defined as *cavitation* and referred to as *pump cavitation* in this case. Cavitation can be damaging to the pump when the vapor cavities collapse.

The minimum head required [required NPSH ($NPSH_R$)] is pump-specific. To determine whether a pump will operate properly, engineers compare the required NPSH to the available NPSH ($NPSH_A$), which depends on elevation and pumping-system characteristics (it is independent of the pump, however). Typically, NPSH and its associated calculations and analyses are a design issue, but if system changes are implemented, then NPSH should be checked.

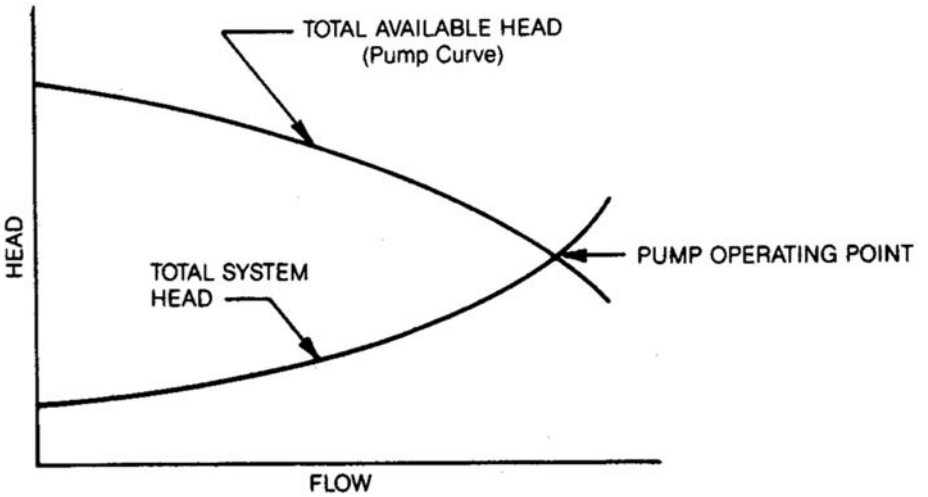


FIGURE 8.5 Centrifugal pumping system head curves.

Required Net Positive Suction Head. The *required NPSH* is the minimum head needed on the suction side of the pump to avoid cavitation as the fluid is conveyed through the pumping system. Pump manufacturers provide graphs depicting a pump's required NPSH versus flow rate, typically on the same graph that shows the pump curve (Figure 8.3).

Available Net Positive Suction Head. The available NPSH is calculated as follows:

$$NPSH_A = \frac{P_{\text{atm}} - P_{vp}}{\gamma} \pm Z_W - H_L$$

where

P_{atm} = the absolute atmospheric pressure exerted on the free fluid surface on the suction side of the pump, where the atmospheric pressure is based on absolute elevation (above sea level) of the free fluid surface;

P_{vp} = the fluid's vapor pressure, where the vapor pressure is based on the fluid's temperature at the pump suction;

Z_W = the vertical distance between the fluid surface and the pump centerline (it will be negative if the fluid surface is below the centerline, and positive if it is above the centerline); and

H_L = the sum of all headlosses in the suction piping (Figure 8.6).

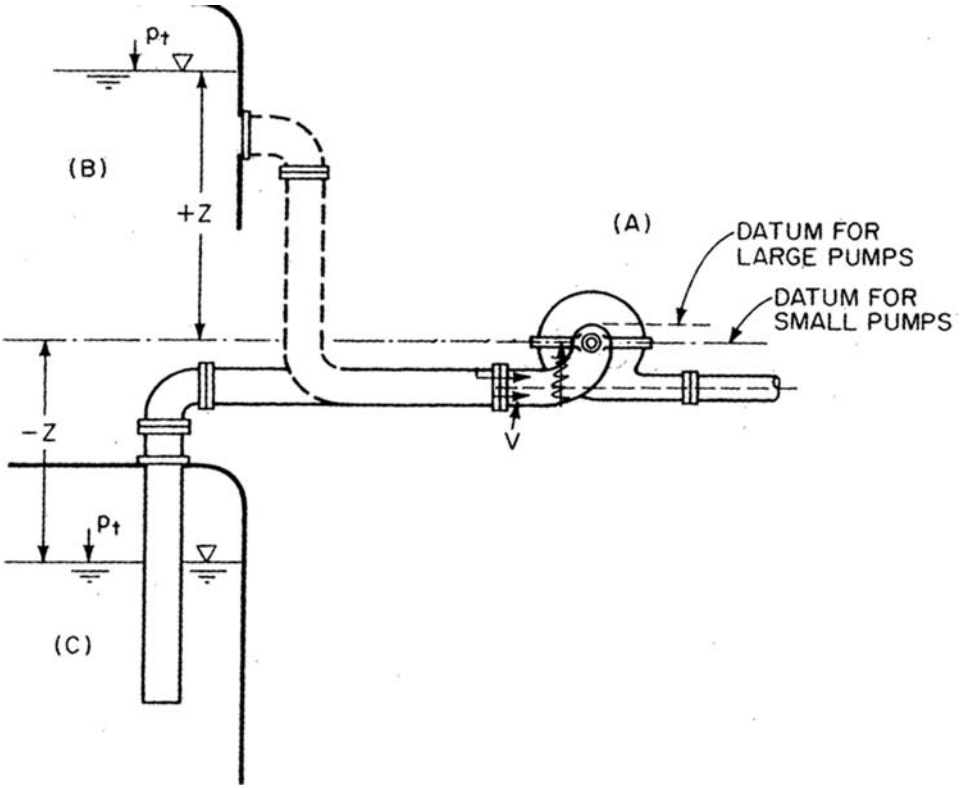


FIGURE 8.6 Definition sketch for computing NPSH. (Karrasik et al., 1976)

Net Positive Suction Head Evaluation. To avoid pump cavitation, the following must be true:

$$NPSH_A > NPSH_R$$

Determination of Pumping Energy Requirements and Costs. The following example illustrates pumping energy requirements and associated costs. Calculate the horsepower delivered by a pump, the size (wire hp) of the pump's electrical motor, the power consumption of the motor, and the annual cost of the required electrical energy, given the following data:

- Flow = 300 gpm,
- Total head = 175 ft,

- Pump efficiency = 85%,
- Motor efficiency = 90%,
- Pump run time = 12 hours/day and 4 days/week, and
- Energy cost = \$0.07/kWh.

Step 1. Calculate the pump's water power:

$$\begin{aligned} P_W &= \frac{Q \times 8.34 \text{ lb/gal} \times TDH}{33,000 \text{ ft - lb/min}} \\ &= \frac{300 \times 8.34 \times 175}{33,000} \\ &= 13.3 \text{ hp} \end{aligned}$$

Step 2. Calculate the motor's brake power:

$$\begin{aligned} P_B &= \frac{P_B}{\text{PumpEfficiency}(\%/100)} \\ &= \frac{13.3}{(85/100)} \\ &= 15.6 \text{ hp} \end{aligned}$$

Step 3. Calculate the motor's wire power:

$$\begin{aligned} P_M &= \frac{P_B}{\text{MotorEfficiency}(\%/100)} \\ &= \frac{15.6}{(90/100)} \\ &= 17.3 \text{ hp} \end{aligned}$$

Step 4. Calculate the motor's power consumption:

$$\begin{aligned} W_M &= P_M \times 746 \text{ W/hp} \\ &= 17.3 \times 746 \\ &= 12,900 \text{ W} \\ &= 12.9 \text{ kW} \end{aligned}$$

Step 5. Calculate the pump's annual electrical costs:

Annual energy cost	= Cost/kWh × annual running time (hours/year) × kW
Annual running time	= 12 (hours/day) × 4 (days/week) × 52 (weeks/year)
hours	= 12 × 4 × 52
	= 2,496 (hours/year)
Annual energy cost	= \$0.07 kWh × 2,496 hours/year × 12.9 kW
	= \$2,253.89

PUMP CLASSIFICATION. In this manual, pumps are classified based on how they add energy to the fluid being pumped (Figure 8.7). They are either kinetic or positive-displacement.

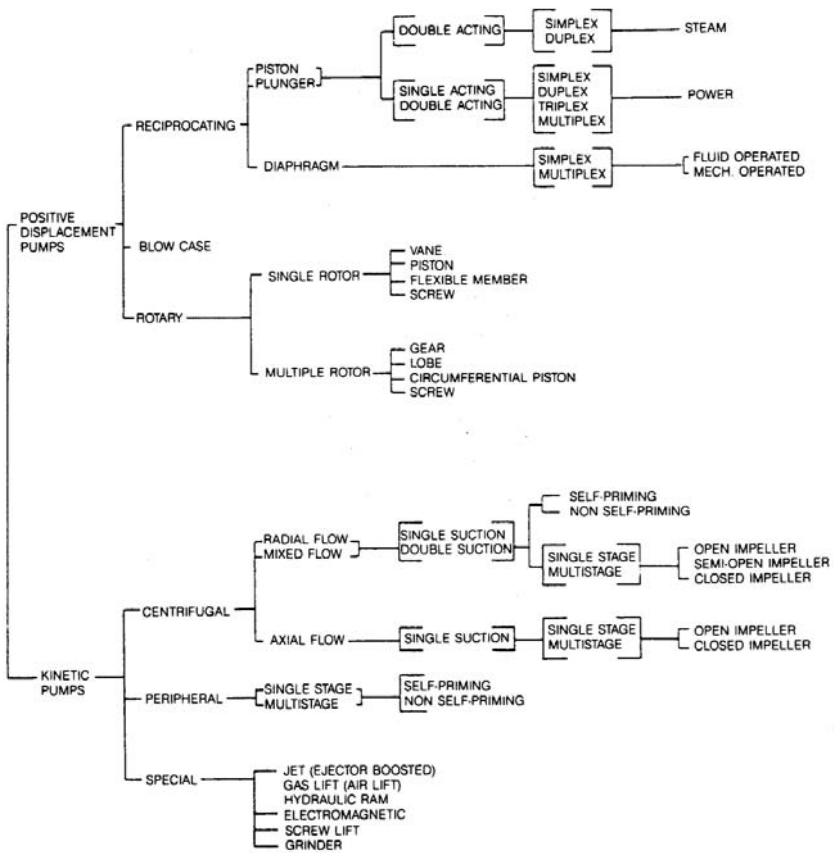


FIGURE 8.7 Classification of pumps.

Kinetic. Kinetic (dynamic) pumps continuously add energy to the fluid as it is conveyed through the pumping system. The most common is the centrifugal pump. Kinetic pumps are mainly used for liquids (e.g., raw or treated wastewater).

Positive-Displacement. Positive-displacement pumps periodically add energy to a defined volume of fluid via a movable boundary. They are primarily subcategorized as either reciprocating or rotary, depending on how the movable boundary travels. Positive-displacement pumps are primarily used for solids.

PUMP SEALS. Most pumps transfer mechanical energy to the fluid via a rotating mechanical component (e.g., a shaft) that is in contact with both the fluid and the motor while passing through the stationary pump housing. The places where this component enters and exits the pump housing must be sealed so the fluid being pumped does not leak from the housing. Seal friction and wear also must be minimized.

Three types of seals are used: packing, seal water, and mechanical seals. Proper operations and maintenance (O&M) ensures proper sealing and pump operation. Seal failure can lead to either excessive leakage or critical damage to a pump.

Packing. *Packing* is the term for a braided "rope" wedged tightly into the space between the moving and stationary components. Because the rope is made of carbon and other materials that do not adhere to the moving component, it reduces leakage while allowing the component to move relatively freely and not overheat. However, packing degrades over time and must be replaced.

Seal Water. Seal water is not a mechanical means to stop or reduce leakage. Instead, seal water is supplied under higher pressure than the pumped fluid and keeps the pumped fluid from leaking out of the pump between the moving and stationary components. The seal water then flows out of the pump and must be collected and conveyed to a drain. Seal water must be provided in a continuous stream (typically, a couple gallons per minute on average) whenever the pump is operating. Wastewater utilities typically use filtered or screened secondary effluent for this purpose.

The drawbacks of this option are the need for distribution, control, monitoring, and drainage systems for the seal water and the need to deal with a steady stream of seal water whenever operating, maintaining, or simply observing the pumps (i.e., it can be messy because the water dribbles down the pump and across the floor to the drain).

Mechanical Seals. A mechanical seal is a device affixed to both the rotating and stationary components to prevent fluid leakage while allowing the rotating component to

move freely (i.e., a more precise packing). All mechanical seals have three basic sets of parts (Figure 8.8):

- A set of primary seal faces: one rotary and one stationary (e.g., a seal ring and insert);
- A set of secondary seals called *shaft packings* and *insert mountings* (e.g., O-rings, wedges, and V-rings); and
- Hardware (e.g., gland rings, collars, compression rings, pins, springs, and bellows).

The two flat, lapped faces of the primary seal are perpendicular to the shaft and rub together, minimizing leakage. One is typically made of a non-galling material (e.g., carbon-graphite), while the other is a relatively hard material (e.g., silicon-carbide) so they will not adhere to each other. The softer face is typically smaller and is called the *wear nose*.

For example, an end face mechanical seal has four main sealing points: A, B, C, and D (Figure 8.9). The primary seal is at the seal face (A). The leakage path at B is blocked by an O-ring, V-ring, or wedge. The leakage paths at C and D are blocked by gaskets or O-rings.

The seal faces are lubricated via a boundary layer of gas or liquid between the faces. Design engineers must decide which lubricant will provide the desired leakage,

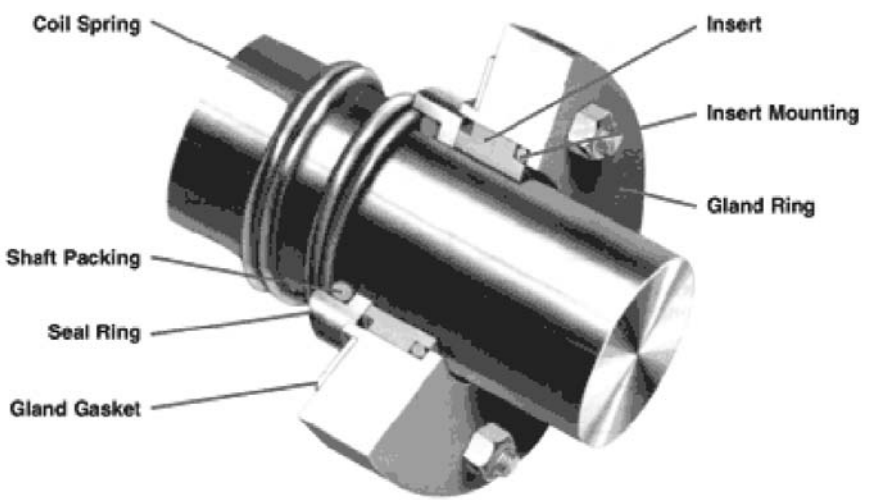


FIGURE 8.8 Mechanical seal section (Courtesy of Goulds Pumps).

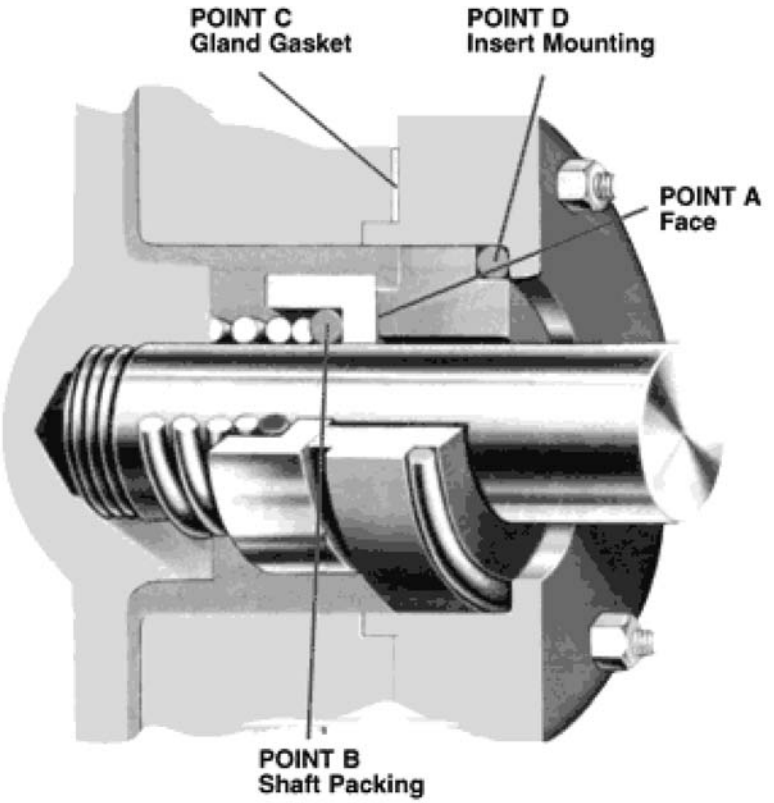


FIGURE 8.9 Four main sealing points of a mechanical seal (Courtesy of Goulds Pumps).

seal life, and energy consumption. Operators must provide this lubrication, monitor the seals, and rebuild them when needed.

Although mechanical seals are similar to packing, they provide tighter seals with less friction (thereby reducing a pump's power consumption). They also last longer, reducing maintenance costs. The drawbacks include greater initial costs than packing and greater overall costs than seal water.

GENERAL OPERATIONS AND MAINTENANCE REQUIREMENTS

All pumping systems need similar O&M activities to maximize their operating lives. In addition to the activities recommended below, utility staff should follow the manufac-

turer's O&M recommendations because of their equipment-specific expertise and warranty requirements.

Whenever mechanical problems occur, utility staff should review them to determine whether they are the result of normal operations, inadequate equipment, or an abnormal situation. If caused by one of the two latter conditions, process or equipment modifications may remedy or reduce the problem.

Operations. The following operations activities directly affect pump performance.

Appurtenances. Major pumping system appurtenances include the motor or drive system (which can be constant-speed, variable-speed, or variable-frequency); standby or redundant capacity; pipes and valves; and surge protection or mitigation. Monitors and controllers (e.g., time clocks and timing controls, pressure gauges, flow meters, solids analyzers, and level detectors) are also important.

Although appurtenances are typically chosen and laid out during design, these decisions can profoundly affect pump O&M. Improper appurtenances or inaccurate monitoring will reduce pump effectiveness, no matter how well-maintained or precise the appurtenance or monitoring system is. To ensure personnel safety and avoid major disruptions, operators need to know what the pumping system's appurtenances are and how they work. Taking a pump out of service for repair or replacement, for example, is a lot simpler when there are valves on both sides of the pump that can be closed to isolate it from other pumps and associated piping. Without them, removing a pump from service would require more extensive efforts (e.g., shutting down the entire pumping station).

When choosing appurtenances, design engineers must anticipate potential process and mechanical problems, as well as provide enough flexibility for the process to achieve the necessary operating range. Also, pumping systems typically must be able to accommodate ever-increasing flows (i.e., handle both smaller startup flows and larger design flows). In addition, they must be flexible enough to allow for bypassing, standby, or redundant pumping when needed.

Testing Procedures. Pumps can be either factory-tested or field-tested. Factory tests occur in a controlled environment with prescribed hydraulic, mechanical, and electrical equipment. They are typically performed in accordance with Hydraulic Institute (Parsippany, N.J.) guidelines to ensure that the pump will meet the specified performance conditions.

Field tests involve all pumping-system components (e.g., the pump, driver, electrical equipment, piping, and overall installation). Although precise data measurements can be more difficult to obtain because of installation limitations (e.g., buried piping

and tight site constraints), field tests evaluate the entire pump installation under actual service conditions. It is typical for pump efficiencies measured via field tests to be lower than those measured via factory tests.

Specific testing procedures depend on the pump involved, but typically a pump's capacity, total head, speed, and input horsepower are tested before the pump is put into service and periodically thereafter.

Startup. Before starting up a pump, operators should do the following:

1. Review the manufacturer's literature on all systems and subsystems before initial use.
2. Review all of the manufacturer's step-by-step procedures for starting up the equipment.
3. Inspect and clean all debris from the tanks, piping, and suction well.
4. Check all hand-operated valves for smooth operation, proper seating, and proper orientation.
5. Confirm that the inlet and discharge valves are open.
6. Ensure that all equipment is properly installed and lubricated, and if applicable, that lubricating fluid is in the pump.
7. Check that all the belts or couplings are aligned properly.
8. Ensure that all guards and other safety devices have been installed properly.
9. Check that the seal has lubrication or water at the proper pressure (this depends on the type of pump seal involved).
10. Confirm that all electrical connections are complete (incorrectly wired motors can run in reverse) and the required voltage is available.
11. Bump motor to see that it rotates freely.

Shutdown. To shut down a pump, operators should do the following:

1. Disconnect or turn off the power to the driver. Then, lock out the appropriate breaker and tag it "out of service" to prevent accidental or inadvertent operation.
2. Close the suction and discharge valves, and isolate any external service connections. In solids and other applications where pressure could build in the out-of-service pump, leave one valve cracked open or install an appropriately sized pressure-relief valve.
3. If the pump will be out of service for a long time (typically on the order of several months or more—please consult with the manufacturer to confirm the specific period because different types of pumps require different levels of care), refer to the O&M manual for long-term storage instructions.

Monitoring. Monitoring various pumping system components confirms that pumps are operating properly or indicates the need for maintenance. Below are typical monitoring devices and their uses:

- Pump-motor indicators note whether the motor is on (i.e., whether the pump's switch is set to "Auto" or "On").
- Flowmeters indicate the rate at which fluid is being conveyed through the pumping system.
- Pressure sensors note the pressure in the piping. Low pressure in the suction piping can indicate blockages or unexpectedly low fluid levels in the wet well. Low pressure in the discharge piping can indicate impending cavitation or total system head alterations because of line breaks, major leaks, or other piping malfunctions. High pressure in the discharge piping can indicate blockages. Pressure and flow rate combined indicate the pump's water power (i.e., how much the pump is working). Increasing water power can indicate blockages or restrictions (e.g., improperly opened valves) in the line.
- Voltage and amperage meters show how much electricity the equipment is drawing, so operators can optimize pump operations. Increasing energy draw can indicate a developing problem (e.g., if the motor needs more energy and the pump's water power is the same, then the system's efficiency is decreasing because of impeller wear, bearing wear, motor wear, etc.).
- Temperature sensors note the temperature of a component (e.g., bearings). An incremental change can point to a potential problem.
- Vibration sensors note how much the pump or piping is vibrating. Increasing vibration may be the result of internal problems (e.g., bearing failures or impeller damage) or deteriorating mountings or anchors. In large installations, critical equipment has online sensors that can monitor vibration in real time, signaling problems before failure and more serious damage occurs.

Wastewater and solids are inherently corrosive and can hinder the proper performance of instruments in contact with them. Monitoring devices installed in such harsh environments may need more maintenance, more frequent replacement, or protection from the fluid. A magnetic flowmeter, for example, may use externally mounted magnetic sensors to measure velocity or flow. If a sensor must be directly installed in the fluid, a diaphragm seal can be placed between it and the fluid.

Controls. Pumping-system controls include on–off switches that are activated by pressure sensors, temperature sensors, or the depth of fluid in the wet well (as measured by float switches, bubbler systems, pressure transducers, or ultrasonic devices). They also

include variable-speed or variable-frequency drives, which change speed to match inflow rates. In addition, solids pumps may be controlled via time clocks, secondary treatment process flow rates, etc.

Although the choice of controls is typically considered a design issue, controls can profoundly affect pump O&M. Knowing how the control system functions will help operators better maintain the utility's pumping systems. Suppose, for example, that a pumping station's pumps activate automatically based on wet-well fluid levels. If operators isolate one of the pumps for service, removal, or repair without modifying the controls first, the results could be disastrous. The solution may be simple (e.g., flip a local switch from "Auto" to "Off" and lock- and tag-out the pump at the breaker), but operators need to know what it is to ensure safe operations.

Sophisticated control systems monitor both the equipment and the treatment process itself, continually monitoring various pump or appurtenance conditions. Knowing this enables operators to note the current equipment and pumping system status and track changes that indicate potential failures or substandard operating conditions.

The current trend is to control pumps and processes via programmable logic controllers or supervisory control and data acquisition (SCADA) systems and integrate them into an overall control scheme (e.g., the Wonderware system). However, operators still need to know how to operate this equipment manually when the automated control system is offline or when unusual loadings or abnormal conditions occur.

Maintenance. The following maintenance activities may not directly affect pump performance, but they can affect pump longevity. For example, monitoring vibrations does not affect system operations because a vibrating pump can still deliver design-level flows. However, excessive vibration can lead to failure of the pump or related equipment.

Periodic cleaning and a simple "look–feel" inspection of each pump are prudent, systematic procedures for detecting early signs of trouble. They only require a few minutes and may save a lot of money and inconvenience.

When performing a typical "look–feel" inspection, utility staff should

- Observe the pumps, motors, and drives for unusual noise, vibration, heating, or leakage;
- Check the pump's discharge lines for leaks and confirm that the valves are in the proper positions;
- Check the pump seal water and adjust if necessary (if the pump has mechanical seals, a seal water system is unnecessary);
- Confirm that the control panel switches are in the proper positions;
- Monitor discharge flow rates and pump revolutions per minute; and
- Monitor pump suction and discharge pressures.

These activities can be automatically monitored and archived via the pump's control system, so operators must be familiar with the control system.

Wear. All rotating equipment will wear over time, but the amount and degree of wear depends on the abrasiveness of the fluid being pumped, the pump's run time, and the operating conditions. Operating pumps at faster than optimal speeds, for example, can increase wear no matter what fluid is being pumped.

Detecting early signs of wear enables operators to repair pumps at minimal cost and downtime. A gradual drop in flow or pressure, for example, indicates that the impeller or wear rings may be worn. Excessive leaking from the gland suggests that the seal or packing may be worn. Vibration, noise, or hot spots on the pump are signs that the bearings are worn.

Standard Maintenance. Pumps are maintenance-intensive—perhaps more so than any other equipment at a wastewater treatment plant. Solids pumping and grinding operations are particularly wearing, often causing pumping equipment to deteriorate rapidly and need replacements (of either parts or the entire system). So, manufacturers recommend specific maintenance procedures to maximize the useful life of pumping systems.

Preventive maintenance (e.g., lubrication, cleaning, and component inspections) can reduce the likelihood of major-equipment damage, failure, downtime, and replacement, thereby improving equipment reliability and lowering equipment costs. This is important for wastewater pumping systems, where redundancy may be required but downtime can be disastrous. Major pump overhauls should be included in the O&M budget and planned for times when the treatment plant or pumping system is not being used to its design capacity.

Preventive maintenance can be tracked manually or electronically. A simple card or paper filing system can record all the equipment's run-time intervals, maintenance history, problems, repair frequency, and the materials and costs involved. A computerized maintenance management system takes this a step farther; not only can it maintain equipment management histories, but it also can issue and monitor work orders, and enable utility staff to analyze all O&M data. Maintenance information is valuable for planning capital and O&M needs, estimating related budgets, and detecting and diagnosing problems early.

Equipment maintenance schedules must conform to manufacturers' O&M manuals to ensure that warranty requirements are met. These manuals can be kept in bound notebooks in the operators' office and other appropriate locations, but making the data even more accessible to field staff further facilitates maintenance activities by making them easier to accomplish. Some wastewater utilities are converting to electronic

documentation, which can be searched, referenced, and viewed from any computer connected to the database, and issuing staff personal data assistants (PDAs) that contain maintenance schedules and checklists.

Sometimes lubricant companies will review the plant's equipment and prepare a master lubrication schedule. Alternatively, utility staff can put together this schedule themselves based on reviews of all the equipment O&M manuals. The recommendations should be commensurate with the damage that could occur because of inadequate lubrication. For example, equipment that needs continuous or nearly continuous lubrication should have automated oilers or grease-fitting systems whose reservoirs permit routine inspections and refills.

Whenever applying lubricants, operators should first take unfiltered samples of existing lubricants and have them analyzed for pH, wear-related debris, water content, and viscosity. The results will show whether the bearings or seals are excessively worn and are allowing process fluid to pass through the seal. Lubricant analysis will detect bearing and seal wear up to 6 weeks before vibration analysis detects them. (Most lubrication companies will analyze lubricant samples for free, but if the utility's supplier cannot—or its analysis is self-serving—the plant should consider an independent lab.)

If a utility is following the manufacturer's guidelines and the equipment seems to need excessive maintenance, staff should consult the manufacturer. Most are willing to review their recommendations and make adjustments that will alleviate the problem. However, if the excessive maintenance is the result of improper or atypical use, then equipment or process modifications may be required.

Predictive Maintenance. Predictive maintenance involves monitoring operating conditions and tracking performance trends to detect when equipment is beginning to operate outside its long-term, normal range. Then, operators can maintain the equipment before it fails.

Typical predictive maintenance activities include vibration monitoring, infrared analysis, alignment checks, motor current analyses, ultrasonic testing, and oil analyses. Vibration monitoring is used to determine equipment deterioration. Vibration readings can be taken by a specialist or an operator (via an inexpensive vibration pen), depending on the utility's financial resources. Critical equipment should have monthly readings; noncritical equipment should have quarterly readings. (If vibrations are monitored automatically, the data should be reviewed monthly or quarterly, as appropriate.) The readings should be taken in the horizontal, vertical, and axial directions on the inner and outer bearings of the pump, motor, and couplings. Each site should be plotted separately to develop a trend line; the horizontal (X) axis notes the dates of each

reading, while the vertical (Y) axis lists vibration readings in centimeters per second (cm/sec) or inches per second (in/sec). The equipment should be closely monitored when vibration levels reach 0.3 in/sec. It should be shut down when vibration reaches 0.5 in/sec. After each overhaul, a complete vibration analysis should be done to establish a baseline for comparison.

Used to inspect equipment while it is operating, infrared analyzers note whether there are temperature variations in pumping-system components (e.g., bearings). They can indicate potential problems before failure occurs.

If the pump, coupling, and driver are misaligned, the pumping system will vibrate more and bearing life will shorten. Equipment alignment may gradually change under normal operating conditions, so it should be checked periodically (according to manufacturer recommendations). Alignment tools are available to check the alignment of integral pump components.

Motor current analyses are performed to check on the current draw of an electrical motor. If a motor is not operating correctly, it will not draw the correct current and can overheat or burn out.

Ultrasonic testing can be used to track and monitor bearing wear by observing changes in a pump's ultrasonic signature and can be used to expose electrical tracking and corona effects.

Oil analyses can be performed, as noted above with respect to lubrication, to check if seals are beginning to fail.

Spare Parts. Even with a well-planned and -executed O&M program, all equipment eventually wears and then fails. Treatment plants typically are designed with some redundancy, but once a backup system is activated, there is no backup for it. So, an inventory of critical spare parts must be maintained onsite.

Operators should begin by determining what spare parts are needed for each pumping-system component. This information is available in the manufacturer-provided O&M manuals. When calculating how many of each part to keep onsite, operators should consider the pumping system's critical needs, its redundancy, the part's failure rate, and its availability.

An area should be set aside for an orderly inventory of spare parts. They should be stored in a clean, dry area away from vibration and in accordance with manufacturer instructions. They also should be inspected for corrosion every 6 months. Whenever a spare part is removed, a replacement should be automatically reordered to keep the inventory up-to-date. Otherwise, the spare parts program will be ineffective.

Some spare parts may need to be kept at the pumping system site if it is critical, operating conditions are severe, and repairs can be performed in the field.

When specifying or purchasing a pump, utilities should ask the manufacturer to provide a suggested spare parts list that includes an estimate of lead time between ordering and delivery. If the pump is critical, it and its spare parts should be purchased simultaneously to avoid unexpected downtime. Utilities also should ensure that the manufacturer keeps detailed records (by serial number) of all their pumps.

Troubleshooting. In addition to monitoring leaks, excessive noise, vibration, and high temperatures, operators can track pump hydraulics to find signs of impending trouble. Hydraulics monitoring can be the best and simplest trouble alert because a correctly functioning pump should be capable of pumping its design flow rate, while a pump that is failing to provide its design flowrate obviously has a problem. This approach can provide a first clue to the advent of a problem; however, it cannot diagnose the cause. (Although the pumping system is chosen during plant design, operators need to know how to capitalize on using hydraulic monitoring to alert them to trouble.) Other simple tools for troubleshooting pumps include:

- Pressure gauges, which indicate whether $NPSH_A$ is adequate and the pump is operating in an acceptable range on the pump curve (the gauges should be installed as close to the suction and discharge ends of the pump as possible);
- Flow meters, which help further determine the pump's operating point;
- Voltage and amperage meters, which determine if the incoming power is sufficient or if the motor has problems; and
- Tachometers, which check the speed of dry-pit pumps.

For pump-specific troubleshooting guidance, see the manufacturer's O&M manual.

LIQUIDS PUMPING

Most wastewater and some solids are pumped via kinetic pumps. In wastewater applications, centrifugal pumps are primarily used.

TYPES OF KINETIC PUMPS. There are three types of kinetic pumps: centrifugal, peripheral or regenerative turbine, and special (Figure 8.7).

Centrifugal. A centrifugal pump has one moving part: an impeller rotating within a casing (Figure 8.10). The impeller is mounted on a shaft that is supported by bearings and connected to a drive. Leakage along the shaft is limited by seals.

Peripheral or Regenerative Turbine. The peripheral or regenerative turbine pump is a low-flow, high-head pump using peripheral or side channel vanes on a rotating

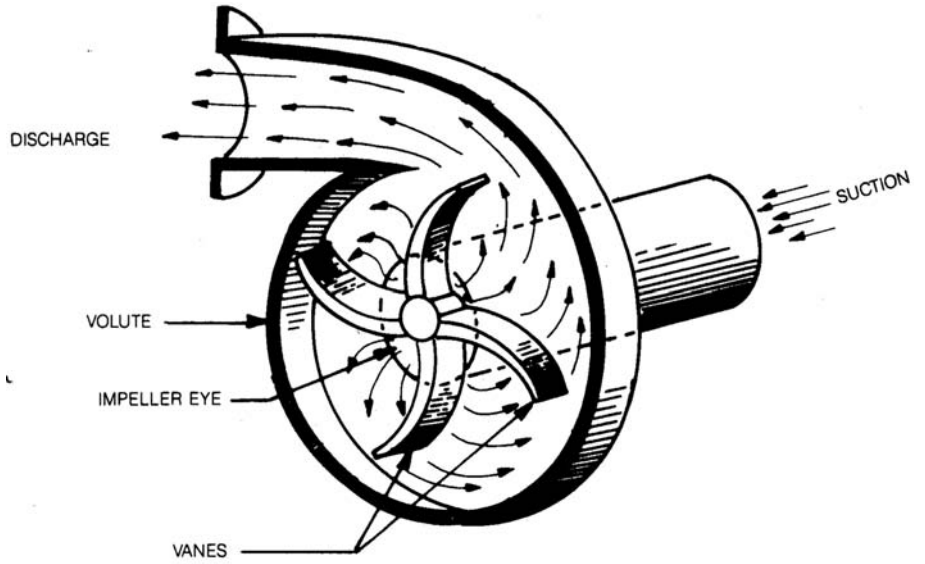


FIGURE 8.10 Diagram of centrifugal pump.

impeller to impart energy to the pumped fluid. It differs from a centrifugal pump, because fluid enters near the impeller outside diameter and exits the pump discharge near the same radius. Pressure is generated in the pump because the fluid is accelerated tangentially in the direction of rotation and radially outward into the casing channel because of centrifugal force. As the fluid hits the casing wall it is redirected back onto an adjacent blade where more energy is imparted.

The regenerative turbine pump can achieve more head at a given impeller diameter than any centrifugal pump. Unfortunately to achieve this high head, the pump has very tight clearances between the impeller vanes and the casing walls, so pumping solids is impractical.

Special. Special pumps include propellers, screw lifts, and grinders.

Propeller. Propeller pumps are similar to centrifugal pumps, except the impeller resembles a common boat propeller. They can efficiently lift up to 5000 L/s (50 000 gpm) of fluid at up to 10 m (30 ft) of head. Flow is conveyed through the pump axially (Figure 8.11).

Screw-Lift. A screw-lift pump consists of a spiral screw—a tube with spiral flights set in an inclined trough or enclosed tube—and an upper bearing, a lower bearing, and a drive arrangement. Used in many applications (e.g., raw wastewater, return activated

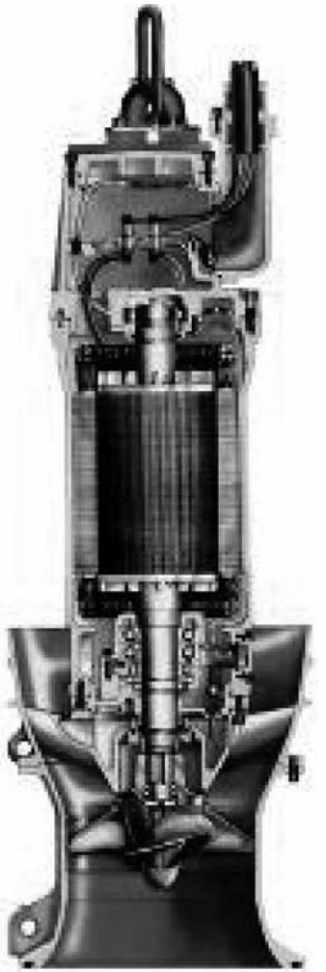


FIGURE 8.11 Propeller pump section (Courtesy of ITT Industries, Flygt).

sludge, and stormwater), screw-lift pumps efficiently lift large volumes of fluid at low heads, automatically adjusting their pumping rate and power consumption to match the inflow depth while operating at a constant speed. They operate economically down to 30% of maximum design capacity. They need little maintenance and no prescreening, but require a lot of space and can aerate the pumped fluid.

Grinder. Grinder pumps typically are centrifugal pumps with a mechanical grinder placed across the suction side of the pump. The grinding mechanism chews incoming solids into finer solids, so the impeller only has to handle the finer solids.

CATEGORIZATION. Liquid pumps typically are categorized based on impeller type, suction, location, and orientation.

Impellers. A kinetic pump imparts energy to fluids via a rotating element (called an *impeller*) that is shaped to force the fluid along or through the pump and increase its pressure. The fluid can be forced outward perpendicular from the impeller's axis (*radial flow*), along the impeller's axis (*axial flow*), or in both directions (*mixed flow*).

Radial- and mixed-flow pumps typically are called *centrifugal pumps* because the impeller develops its head via the centrifugal force imparted to the fluid. Flow enters the eye of the impeller and exits perpendicular to the shaft at high velocity. In the process, most of the fluid's velocity head is converted to pressure head by the pump's casing or volute. Mixed-flow impellers develop head mostly via centrifugal force and partly via the axial thrust imparted to the wastewater.

Induced vortex pumps have impellers recessed in the volute chamber (Figure 8.12). The impellers induce a vortex to pull the fluid through the pump with minimal impeller contact (Krebs, 1990).

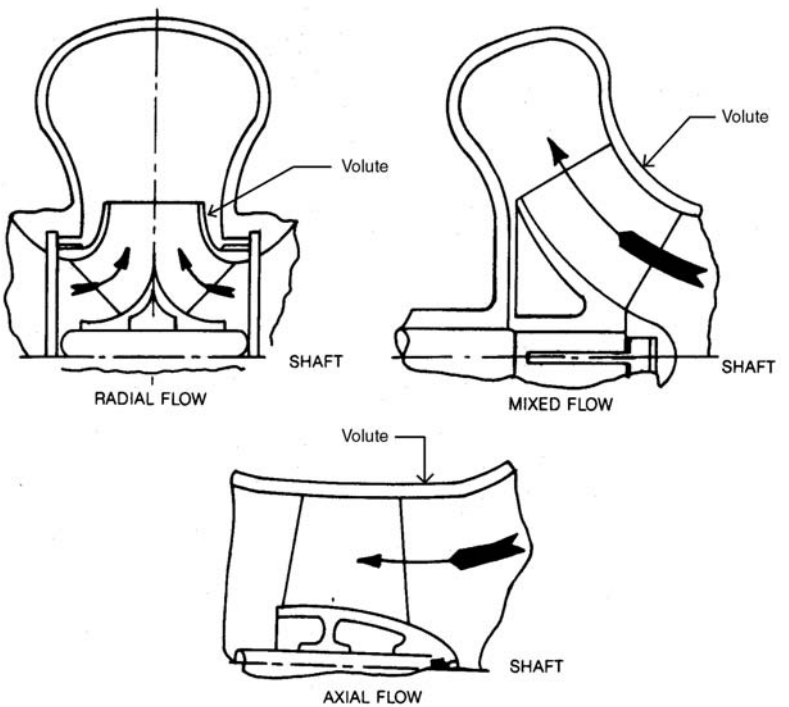


FIGURE 8.12 Impeller types based on flow pattern.

The choice of pump depends on the hydraulic conditions involved. Radial-flow pumps are best for high heads, axial-flow pumps are best for low heads, and mixed-flow pumps are best for moderate heads. Mixed-flow impellers also are used when the flow is relatively high but the head is relatively low.

Open and Semi-open Impellers. Open and semi-open impellers are typically used to pump raw wastewater and sludge with a high solids content or large solids particles. They operate under high volume and low pressure. Their solids-pumping capabilities depend on the gap between the impeller and the suction side of the volute case. This gap can vary from 0.38 mm (0.015 in.) to several inches.

Open impellers have no front or back shroud; they are typically used to pump wastewater containing large solids. (A shroud looks like a duck's foot webbing.) The impeller in Figure 8.13 rotates counterclockwise.

Semi-open impellers have a back shroud and several vanes (Figure 8.14). They are typically used to pump return activated sludge or raw wastewater containing medium-size solids (Karassik et al., 1976).

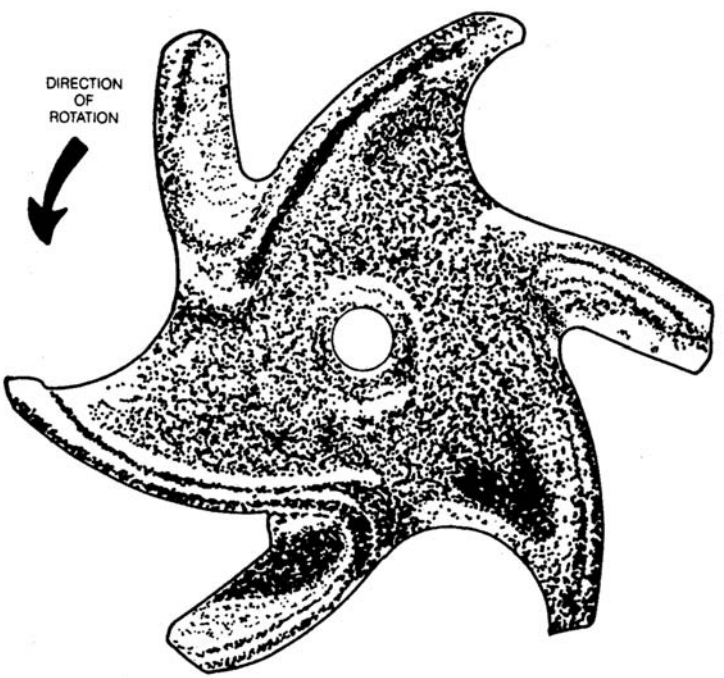


FIGURE 8.13 Open impeller.

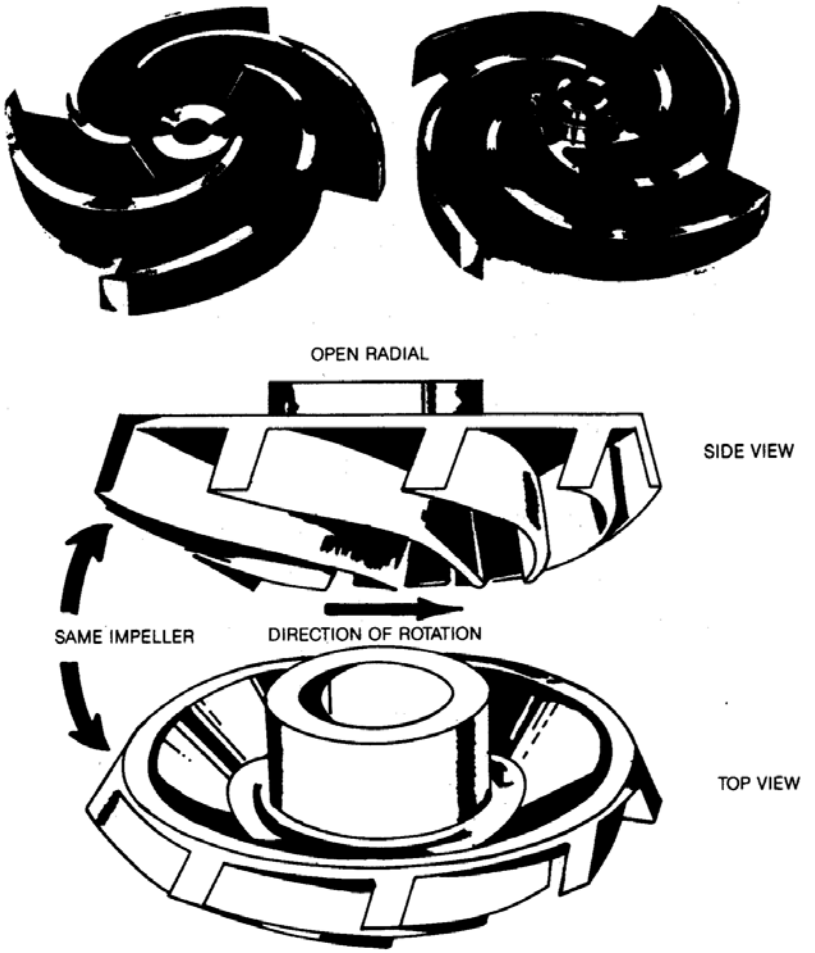


FIGURE 8.14 Semi-open impeller.

Closed Impellers. Enclosed, nonclog impellers with two vanes handle 80% of wastewater with low solids concentrations [e.g., raw and settled wastewater, return sludge (from all secondary processes), waste sludge, filter feed, and plant effluent]. Fully closed impellers, which rotate counterclockwise, transfer energy most efficiently (Figure 8.15). The largest solids particle that can be passed by a closed impeller depends on the distance between shrouds.

Propeller. The axial-flow (propeller) impeller develops its head via the axial thrust imparted to the fluid by the propeller blades. It is used at low heads and operates at rela-

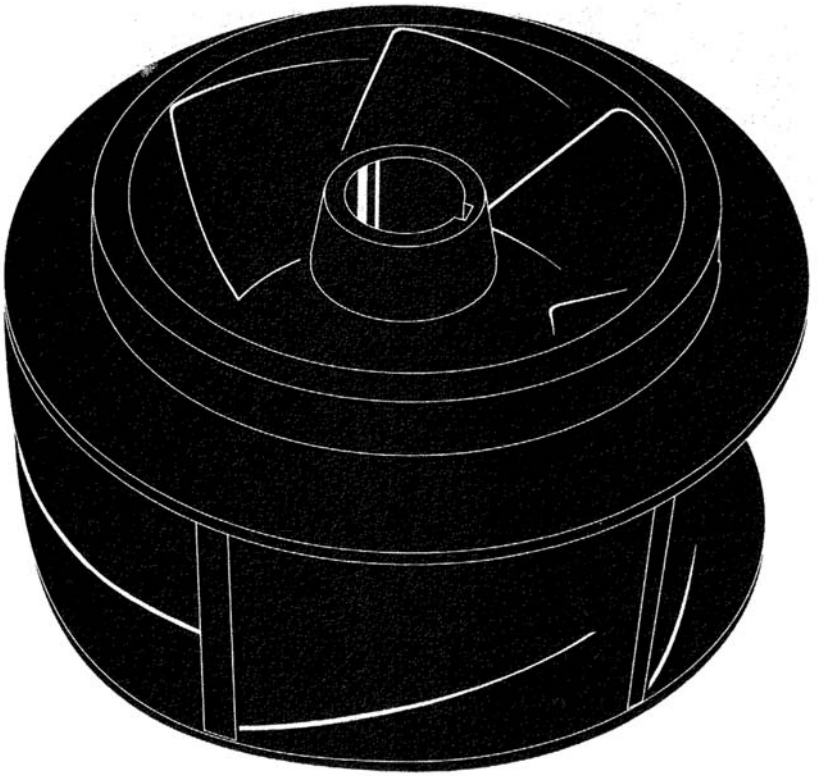


FIGURE 8.15 Closed-radial impeller.

tively low revolutions per minute. Some have large capacities but must operate with positive suction pressures.

Grinders. Although a grinder is not an impeller, it is intimately associated with impellers. Grinders can be fitted across the suction end of centrifugal or positive-displacement pumps. In centrifugal pumps, the grinding mechanism and pump impeller are typically connected to a common shaft.

Suction. Pumps may be designed as single-suction (end-suction) or double-suction units. Generally, all of the impellers above are available for any type of kinetic pump suction. An axial-flow pump requires a single-suction setup and an open or closed impeller; it cannot support double-suction setups or semi-open impellers (Figure 8.7). Radial- and mixed-flow pumps, on the other hand, can support both types of suction and all styles of impellers.

Single-Suction. Single-suction pumps typically handle raw wastewater or other solids-bearing liquids. In these pumps, fluid only enters one side of the impeller, which is designed with relatively large clearances, fewer blades, and no shroud connecting the blades. Such open-impeller (nonclog) pumps handle solids of various sizes (ask the manufacturer to specify the maximum solids size that can safely pass through a particular pump). However, strings and rags may entangle the impeller blades and clog the pump, so they and excessively large solids must be removed from the liquid before it is pumped.

*Double-Suction***.** In a double-suction pump, internal passages split the influent equally between the two sides of the impeller. Such pumps, which have small internal clearances, typically are designed to handle clear liquids (e.g., relatively "clean" plant water for seal water, washdown water, and fire hydrants, or to boost potable water).

Location. Pumps can be installed inside or outside the fluid being pumped.

In Fluid. Pumps installed within the fluid are called *submerged pumps* or *vertical wet-well pumps*. They can be mounted horizontally or vertically. The impeller is submerged or nearly submerged in the fluid, and no additional piping is required to convey the fluid to the impeller.

Outside of Fluid. Pumps installed outside the fluid are called *dry-pit pumps*; they can be mounted horizontally or vertically in a dry well. Fluid is piped to the suction of these pumps.

Orientation. Pumps may be oriented (mounted) vertically or horizontally.

Vertical. Vertical wet-pit pumps are mounted vertically with the impeller submerged in the fluid and its driver above both the suction and any "high" fluid level. On the discharge side of the impeller, the *bowl*—gradually expanding passages with guide vanes (baffles)—converts velocity head to pressure (Figure 8.16). Vertical wet-pit pumps with radial flow or low–speed, mixed-flow impellers are called *turbine pumps*. Because turbine pumps convert energy via a bowl rather than a volute, they can be constructed with small diameters (similar to those in water-supply wells). Turbine pumps are readily adaptable because more bowls and impellers can be attached to the turbine shaft.

Horizontal. Horizontal pumps are typically installed in dry pits with the motor next to the pump. They are typically centrifugal pumps (e.g., standard, non-clog, recessed impeller, and closed coupled horizontal).

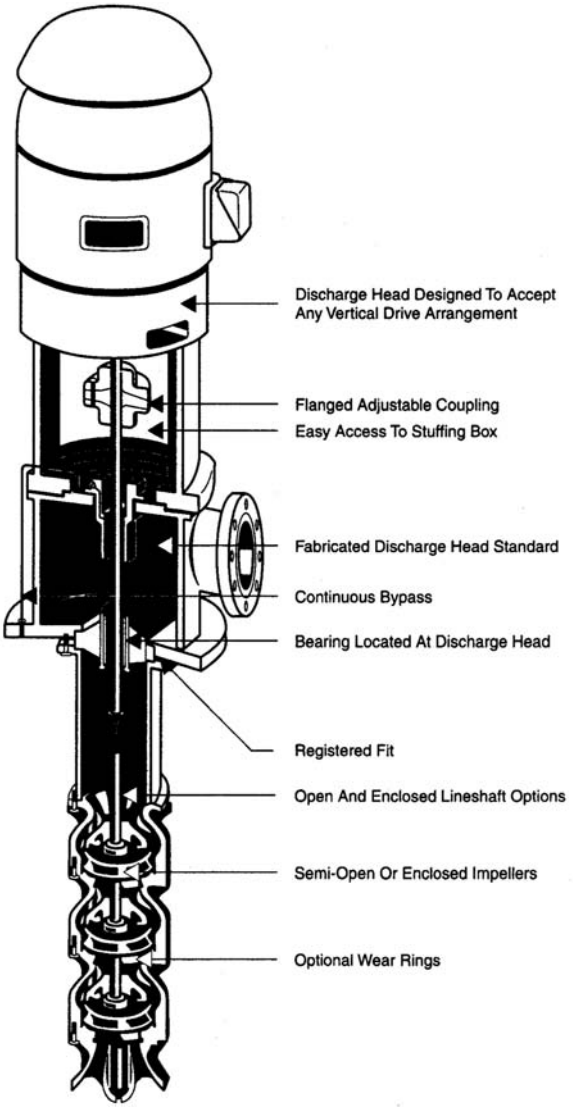


FIGURE 8.16 Typical vertical turbine pump.

APPLICATIONS. ***Horizontal or Vertical Nonclog Centrifugal Pumps.*** Horizontal or vertical nonclog centrifugal pumps (Figures 8.17 and 8.18) handle many types of wastewater (e.g., raw wastewater, return activated sludge, and recirculated trickling filter effluent). These pumps—the "workhorses" of centrifugal pumps—have an extensive history in wastewater pumping.

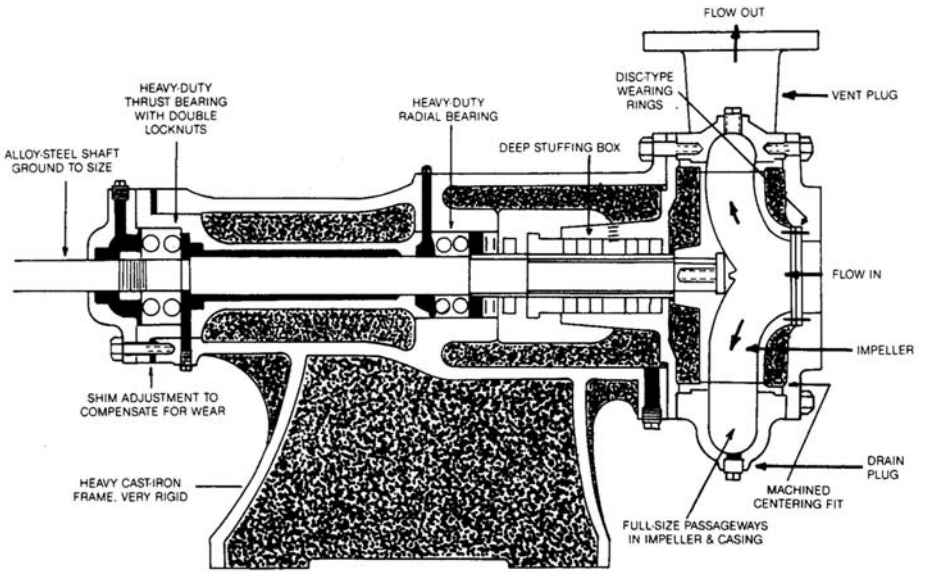


FIGURE 8.17 Typical horizontal pump for raw wastewater and return activated sludge.

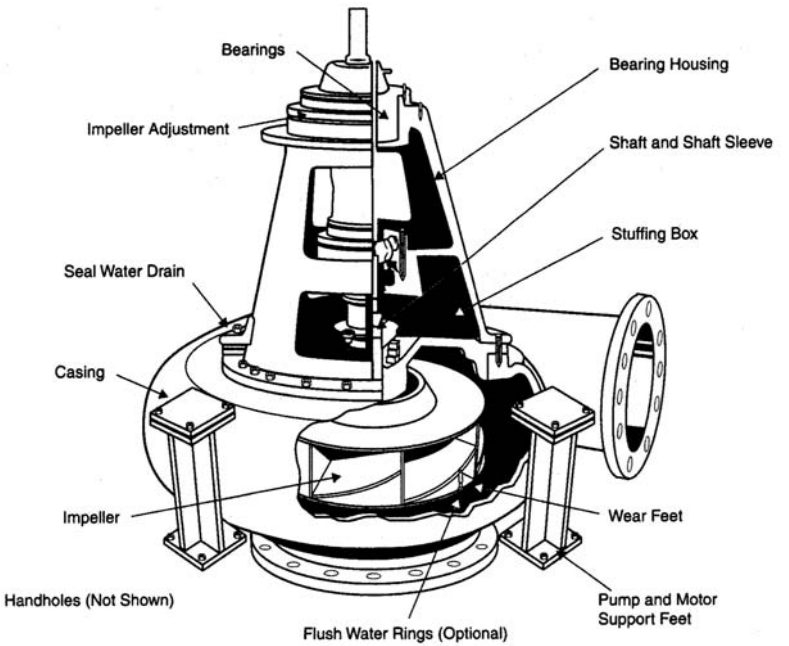


FIGURE 8.18 Typical vertical pump for raw wastewater and return activated sludge.

Vertical Centrifugal Pumps. Vertical turbine pumps typically handle "cleaner" wastewaters (e.g, secondary effluent, drainage, and washwater). For example, the City of Corona (California) Wastewater Treatment Plant uses vertical turbine pumps to transfer equalized secondary effluent to filters, and filtered, disinfected effluent to plant water systems. In these applications, the pumps are efficient (70% or more) and can achieve high head and flow rates.

Vertical wet-pit pumps are typically multistage units in which each stage handles a nearly equal share of the total head (Figure 8.16). The number of stages needed depends on how a manufacturer designed the impeller, the shaft, and the pump bowls (impeller housings). Turbine pumps with radial flow impellers may have up to 25 stages. Pumps with mixed-flow impellers typically have no more than eight stages. Propeller units are typically single-stage, but may be available in two stages, depending on the pump's size and characteristics (Figure 8.19). For most multistage applications, operators should consult manufacturers about the maximum number of stages available for a particular type of pump.

Most manufacturers provide inlet screens in the suction bells of vertical turbine pumps. These "standard" screens have such small openings that the suction can be rapidly and almost completely blocked (Canapathy, 1982), reducing inflow pressures, and playing havoc with pump operations. Operators should omit these screens. If screening is necessary, the utility should install either traveling-water or low-velocity screens at the pump inlet.

OPERATIONS AND MAINTENANCE. Pump manufacturers typically will provide literature or guidance on the O&M activities needed to keep a particular pump functioning optimally. The following information is a guideline that operators can use to develop or evaluate a utility's O&M plan.

Operations. The following activities directly affect the performance of liquid pumps.

Appurtenances. The type of drive system used is important. Drives can be electric, hydraulic, or engine- or steam turbine-driven. The choice of constant- or variable-speed drive depends on the specific pumping requirements, because pumps themselves can deliver a range of flow rates, depending on their design, speed, and total dynamic head.

Testing Procedures. The appropriate factory and field tests for centrifugal pumps depend on the pump's size and importance, design constraints, budget constraints, conditions of service, and installation. Two common factory tests are the hydrostatic test and the performance test. Hydrostatic tests typically are performed at 1.5 times the pump's shutoff head to determine how watertight the pump case and gaskets are. Performance

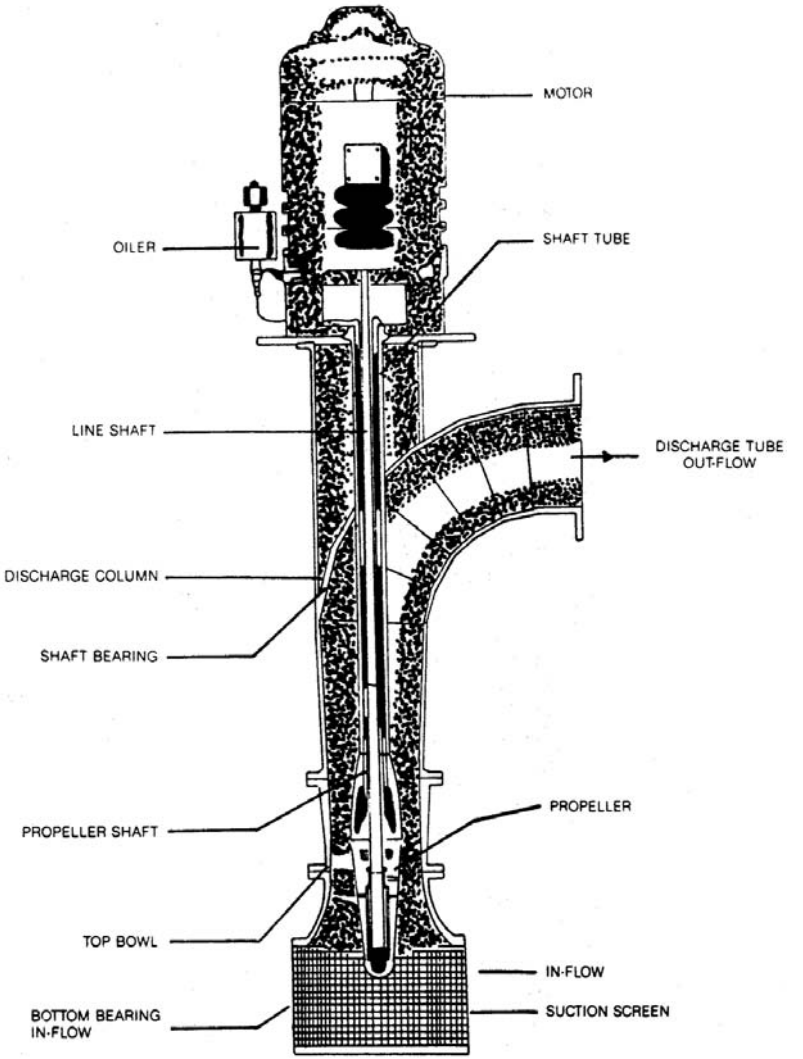


FIGURE 8.19 Typical wastewater effluent pump with propeller.

tests ensure that the pump meets all the specified design conditions. This test may or may not require witnesses.

Three common field tests are the performance test, vibration analysis, and noise testing. The results of field and factory performance tests will differ because of the equipment configuration and the accuracy of field instruments.

Startup. Before starting up a nonclog pump, operators must ensure that wastewater- and electrical-flow patterns are properly established by doing the following:

1. Close the tank or wet-well drain and bypass valves;
2. Open the valve on the suction line from the tank to the wet well;
3. Open the pump's suction and discharge valves;
4. Open the valve on the discharge line; and
5. Set the inlet gate valve to the desired position.

When opening and closing valves, operators should never treat gate valves like throttling valves, because they can trap material and ultimately plug. Once the flow pattern has been established, operators should turn on the pump's seal water (if applicable). They should adjust the seal-water pressure to exceed the discharge pressure by 100 to 140 kPa (15 to 20 psi). The seal-water flow should be adjusted according to the manufacturer's specifications.

Shutdown. To shut down a nonclog pump, operators should do the following:

1. Adjust the pump control to "manual";
2. Adjust the hands/off/automatic (H/O/A) switch to "off" (O);
3. Close all suction and discharge valves;
4. Adjust the circuit breaker disconnect at the motor control center to "off" (lock- and tag-out);
5. Shut off the seal water to the pump; and
6. If needed, follow the startup guidelines to put a standby pump into service;

If shutting down the pump for a long time (typically on the order of several months or more—please consult with the manufacturer to confirm the specific period because different types of pumps require different levels of care), operators also should do the following:

1. Drain all tanks and wells, flush pipelines, and thoroughly clean the system;
2. Open the electrical equipment's circuit breakers and lock and tag them out;
3. Rotate the pump shafts several times a month to coat bearings with lubricant, thereby retarding oxidation and corrosion;
4. Run the bubbler-tube air compressor once a month (if applicable); and
5. Apply rust inhibitor as needed.

Monitoring. The general O&M monitoring requirements listed above are sufficient.

Controls. The general O&M control requirements listed above are sufficient for centrifugal pumps, although operators may want to integrate pumping controls with overall treatment-process-optimization efforts.

Maintenance. The following maintenance activities can affect the longevity of successful pump performance.

Wear. All rotating parts in pumping equipment will eventually wear out, but wear can be exacerbated by operating a pump too fast or pumping too many solids. So, operators can profoundly affect the useful life of a pump.

Ideally, centrifugal pumps should operate as close as possible to their BEPs on the pump curve. If the pump runs to the right of the BEP, the high velocities inside the pump could lead to scouring, recirculation, and cavitation—accelerating wear and increasing the radial loads on the drive train. If the pump runs too far to the left of the BEP, separation and recirculation will occur, reducing efficiencies and increasing the chances of clogging, possible overheating (if the unit is pump-fluid cooled), and faster wear.

If abrasion is unavoidable, the centrifugal pump components most susceptible to wear are the suction nozzle, impeller vanes and tip, casing walls next to the impeller tip, and stuffing box seal and shaft. The pump impeller, volute, and seal area should be designed with generous wear allowances and made of abrasion-resistant materials. The pump shaft should include an abrasion-resistant sleeve, and if a mechanical seal is used, it should have abrasion-resistant faces.

Most bearings are designed for useful lives of 30 000 to 50 000 hours, so bearing wear is typically not a problem. Most bearings fail because of poor operating conditions, not because they wear out.

Standard Maintenance. Because of the wide variation in construction materials, operating conditions, and duty cycles, pump maintenance programs need to be site-specific, based on the manufacturer's recommendations, and address both preventive and corrective maintenance. Also, operators should be trained to recognize the signs of impending component wear.

In general, daily or weekly inspections and periodic cleanings are good operating procedures and will help operators detect early signs of trouble. Inspections only take a few minutes and could save a lot of money and downtime. Pump inspectors should

- Ensure that noise, vibration, and bearing and stuffing-box temperatures are normal;
- Look for abnormal fluid or lubricant leaks from the gaskets, O-rings, and fittings;

- Make sure that lubricant levels are adequate and the lubricant itself is in good condition;
- Change the lubricant as recommended by the manufacturer (based on pump run-time); and
- See whether shaft seal leaks are within acceptable limits.

Every 6 months, inspectors should

- Check that the stuffing box's gland (packing) moves freely, and clean and oil the gland's studs and nuts;
- Scrutinize the stuffing box for excessive leakage, adjust the gland to reduce leakage (if necessary), and replace the gland if adjusting it does not solve the problem;
- Look for corrosion on all fasteners and foundation bolts, and ensure that all are securely attached; and
- Ensure that couplings or belts are properly aligned, and check for wear.

The timing of complete overhauls depends on the pump's construction materials, operating conditions, run time, and preventive-maintenance schedule. When completely overhauling a pump, operators should:

- Check the impeller, case, wear rings, seals, bearings, shaft, and shaft sleeve for wear and corrosion;
- Replace all gaskets and O-rings;
- If necessary, wash out the bearings' housing with a brush and hot oil or solvent, flush the housing with a light mineral oil to remove all traces of solvent and prevent rust, wipe the bearings with a clean lint-free cloth, and clean them in the same way as the housing.

All pump work must only be done on an out-of-service pump (see the O&M manual for appropriate shutdown procedures). If parts need to be replaced, operators should consult the O&M manual for the proper procedure and double-check product compatibility.

Predictive Maintenance. Operators should monitor pump vibrations when the pump is started up and periodically throughout the pump's life. Excessive vibration indicates that something is mechanically or operationally wrong with the pump. Mechanical sources of vibration include improper installation or foundation; pump misalign-

ment; worn bearings; piping strain; loose bolts or parts; and unbalanced or damaged rotating components (impellers, shafts, or sleeves). Hydraulic sources of vibration include cavitation, recirculation, water hammer, air entrained in the pumped fluid, turbulence in the suction well, and pump operation far left or right of the BEP. If ignored, excessive vibration could damage pump components.

Spare Parts. The spare parts that should be kept onsite depend on the pump, its application, and its manufacturer. A centrifugal pump, for example, will typically need a complete set of gaskets, O-rings, and packing.

Troubleshooting. The recommended troubleshooting activities depend on the pump, its application, and its manufacturer. For example, Table 8.1 is a troubleshooting guide for recessed-impeller centrifugal pumps.

SOLIDS PUMPING

Maintaining proper solids handling when solids are moved from one process to another could be an operator's most demanding responsibility. One of the most common issues is using solids pumps correctly under various operating conditions.

Wastewater utilities produce a variety of solids with different characteristics (Table 8.2). As treatment processes are modified or upgraded, pumping systems also may need to be modified to accommodate the varying thixotropic nature of solids.

Thixotropy is the tendency of certain gels to be semisolid when still and fluid when stirred or shaken [e.g., an ice cream milkshake, which "sets up" in a container and will only flow out when the container is tapped or jarred (U.S. EPA, 1979).] Solids can become thixotropic if the pipelines are not properly flushed before shutdown (the thixotropic effect may occur in a few hours or days, depending on the solids characteristics) and will need more pressure to begin flowing in the pipeline after startup. Basically, when the solids begin to move, their friction is higher, so head losses in the pipeline are greater. As the solids move faster, both the friction and the head losses drop. (This is why a solids pump's total head varies so much, even when the speed is constant.)

The thixotropic effect is partially offset by slippage and seepage—a thin film of liquid on the pipe wall that solids "ride" when they begin flowing. This condition aids solids pumping (U.S. EPA, 1979).

TYPES OF SOLIDS PUMPS. There are many types of solids pumps: positive-displacement, centrifugal with recessed impellers, hose, pneumatic ejector, grit, grinder, and air-lift. Effective solids handling depends on properly matching the pump, solids characteristics, and actual system head requirements.

TABLE 8.1 Troubleshooting guide for recessed-impeller centrifugal pumps.

Problems	Causes	Solutions
No liquid delivered	Pump not primed. Speed too low.	Prime pump. Check voltage and frequency.
	Air leak in suction or stuffing box.	Repair leak.
	Suction or discharge line plugged.	Unplug line.
	Wrong direction of rotation.	Correct direction of rotation.
	Discharge valve closed	Open discharge valve.
Not enough pressure	Speed too low.	Check voltage and frequency.
	Air leak in suction or stuffing box.	Repair leak.
	Damaged impeller or casing.	Repair or replace.
	Wrong direction of rotation.	Correct direction of rotation.
Motor runs hot	Liquid heavier and more viscous than rating.	Increase dilution factor.
	Packing too tight.	Adjust packing.
	Impeller binding or rubbing.	Align impeller properly.
	Defects in motor.	Repair or replace motor.
	Pump or motor bearing overlubricated.	Lubricate bearing properly.
Stuffing box overheats	Packing too tight, not enough leakage of flush liquid.	Adjust packing.
	Packing not sufficiently lubricated and cooled.	Adjust packing.
	Wrong grade of packing.	Replace packing.
	Box not properly packed.	Properly pack box.
	Bearings overheated.	Grease properly, check tightness.
	Oil level too low or too high.	Adjust oil level to proper level.
	Improper or poor grade of oil.	Replace with proper grade of oil.
	Dirt or water in bearings.	Clean and regrease bearings.
	Misalignment.	Align properly.
	Overgreased.	Grease bearings properly.
Bearings wear rapidly	Misalignment.	Align properly.
	Bent shaft.	Repair or replace. Correct source of vibration.
	Lack of lubrication.	Lubricate bearings.
	Bearings improperly installed.	Reinstall bearings properly.

TABLE 8.1 Troubleshooting guide for recessed-impeller centrifugal pumps (*continued*).

Problems	Causes	Solutions
	Moisture in oil.	Replace oil.
	Dirt in bearings.	Clean and relubricate.
	Overlubrication.	Lubricate properly.
Not enough liquid delivered.	Air leaks in suction of stuffing box.	Repair leaks.
	Speed too low.	Check voltage and frequency.
	Suction or discharge line partially plugged.	Unplug line.
	Damaged impeller or casing.	Repair or replace.
Pump works for a while then loses suction vibration.	Leaky suction line.	Repair suction line.
	Air leaks in suction or at stuffing box.	Repair leaks.
	Misalignment of coupling and shafts.	Properly align coupling and shafts.
	Worn or loose bearings.	Replace or tighten bearings.
	Rotor out of balance.	Balance rotor.
	Shaft bent.	Repair or replace shaft.
	Impeller damaged or unbalanced.	Repair or balance impeller.

POSITIVE-DISPLACEMENT PUMPS. Most solids pumping at wastewater utilities is done by positive-displacement pumps (Figure 8.7). They typically handle thicker solids (more than 4% solids). Two common types of positive displacement pumps are: controlled-volume and rotating positive-displacement (e.g., progressing cavity and rotary lobe). These pumps can sometimes be used interchangeably, depending on the solids process downstream.

Controlled-Volume. Controlled-volume pumps move a discrete volume of fluid in each cycle. (They are also called *reciprocating pumps* because of how the pump driver moves.) Three types of controlled-volume pumps are discussed here: plunger, piston, and diaphragm.

Plunger Pumps. Plunger pumps (Figure 8.20) use a plunger to move fluid through a cylindrical chamber. The plunger moves along an axis to build pressure in the cylinder that actuates check valves on each side of the pump body (Figure 8.21). When the plunger lifts (upstroke), the resulting low pressure automatically closes the discharge

TABLE 8.2 Sludge types and their characteristics.

Sludge type	Total solids range, %	Viscosity	
		Low	High
Raw primary sludge	0.5–5.0	X	
Secondary sludges			
Waste activated sludge	0.3–2.5	X	
Trickling filter biological towers	0.25–1.5	X	
Biological nutrient removal	0.5–4.0	X	
Chemical sludges			
Lime sludges	2.0–10.0		X
Alum/iron salts sludges	1.0–5.0	X	X
Thickened sludges			
Thickened waste activated sludge	1.5–6.0		X
Thickened primary sludge	1.5–8.0		X
Thickened chemical sludge	2.0–1.5		X
Stabilized sludges			
Anaerobic digested sludge	1.5–7.0	X	X
Aerobic digested sludge	0.5–4.0	X	
Lime stabilized sludge	1.5–10.0		
Dewatered sludges			
Belt presses/centrifuge	10–25		X
Plate and frame filter presses	20–40		X

valve and opens the suction valve, allowing fluid to be drawn into the pump chamber. When the plunger lowers (downstroke), the resulting high pressure automatically closes the suction valve and opens the discharge valve, forcing the fluid out of the pump chamber. The volume of the fluid discharged is equal to the area of the plunger multiplied by its stroke length.

The flow rate can be altered by changing the stroke length (within the constraints of the pump body volume) or the number of strokes per minute. To increase capacity further, numerous plungers can be actuated by the same drive mechanism. Wastewater utilities typically use simplex, duplex, triplex, and quadruplex plunger pumps to deliver solids at the design flow rate. Their capacities typically range up to 32 L/s (500 gpm) at 690 to 1030 kPa (100 to 150 psi) of delivered pressure. When pumping dewatered sludge cake, capacities range from 0.6 to 6.3 L/s (10 to 100 gpm) at pressures up to 10 340 kPa (1500 psi).

Ball checks are readily accessible through quick-opening valve covers. Air chambers are installed on the discharge side of the pump (and often on the suction side to reduce the high-impact loading). Mounting the pressure gauges on the chambers helps reduce or eliminate gauge fouling.

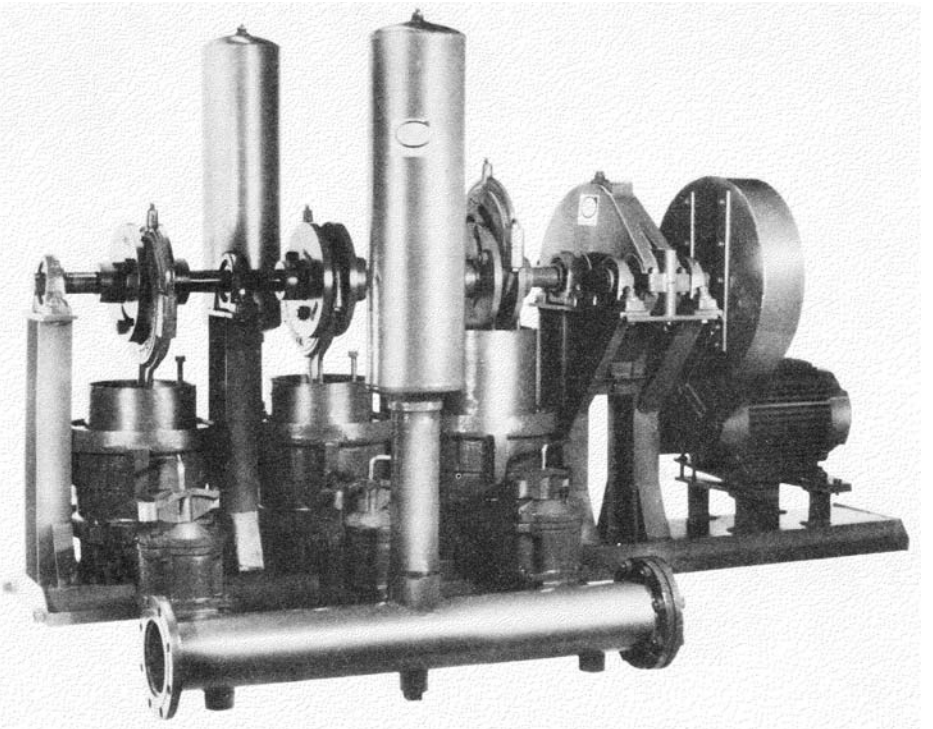


FIGURE 8.20 Triplex plunger pump.

Piston Pumps. Piston pumps are similar to plunger pumps, except they displace fluid via a piston rather than a plunger, are hydraulically driven, and have tighter tolerances. They are better suited for high-pressure applications than plunger pumps and are typically used to pump dewatered solids. The piston pump's most important component is a sequencing valve (typically, a poppet valve), which isolates the pump from the material in the pipeline and avoids harmful hammer effects due to pipeline backflow.

Diaphragm Pumps. In diaphragm pumps (Figure 8.22), a flexible membrane separates the solids from the driving force [a mechanical device (e.g., a cam shaft or an eccentric) or hydraulic fluid pressure]. The solids flow is controlled by the membrane's reciprocating action and valves or ball checks. The pump's capacities range up to 6 L/s (100 gpm) at discharge pressures up to 690 kPa (100 psi).

Double-Disc pumps™ (Figure 8.23) are based on a free-diaphragm® technology that combines the technologies of plunger and diaphragm pumps; they use two reciprocating connecting rods and discs, which operate in tandem to provide both pumping

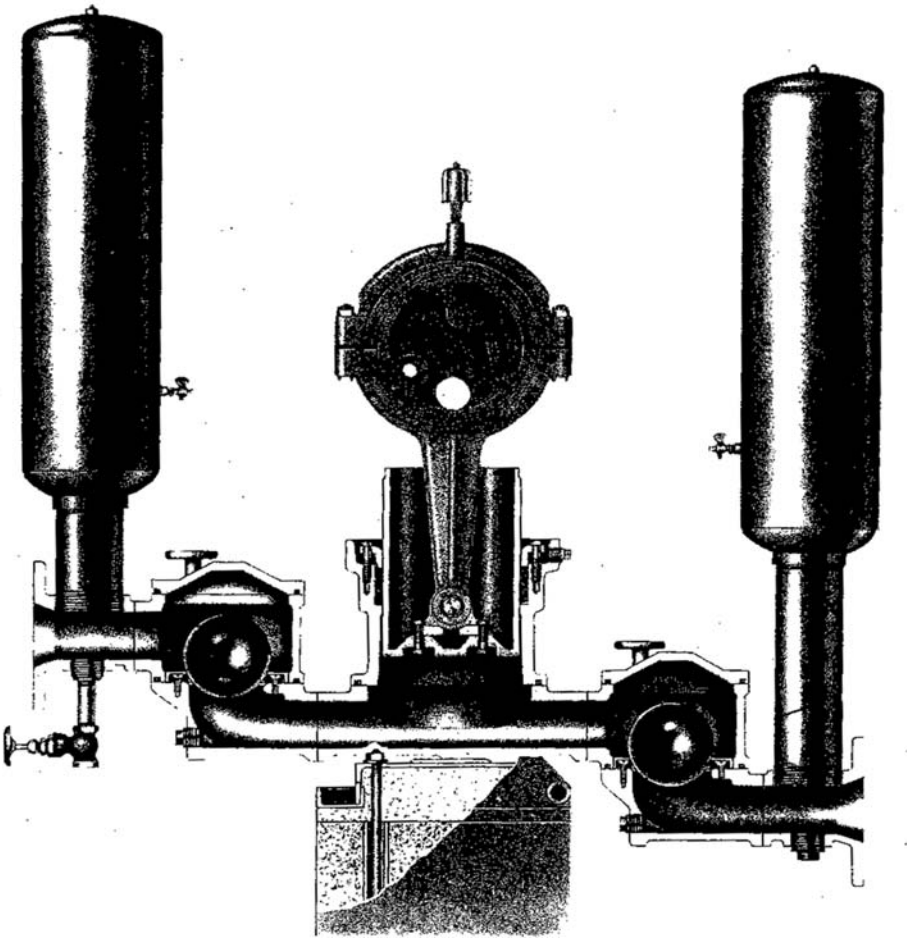


FIGURE 8.21 Positive displacement sludge pump. (Courtesy ITT Marlow.) (Steel and McGhee, 1979).

and valving. Their discharge capacities and pressures are similar to those of other controlled-volume pumps.

Rotating. These are several types of rotating positive-displacement pumps, including progressing-cavity, rotary-lobe, vane, and gear. Progressing-cavity pumps are most often used to pump solids. Lobe, vane, gear, and flexible-member pumps typically are used to meter fuel or chemical feeds rather than pump solids and other abrasive materials.

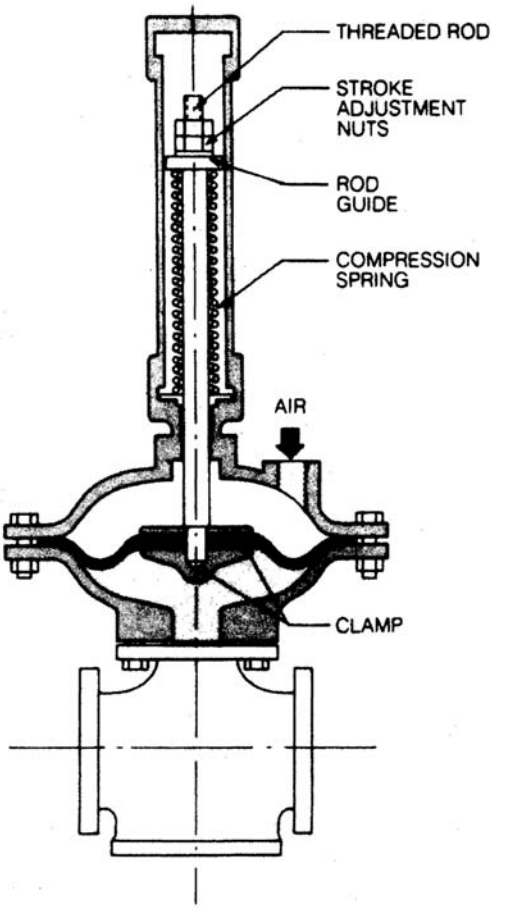


FIGURE 8.22 Diaphragm sludge pump.

Progressing-Cavity Pumps. Self-priming progressing-cavity pumps (also called *progressive-cavity pumps* in industrial applications) deliver a smooth flow of solids at discharge capacities up to 40 L/s (600 gpm) and pressures up to 1700 kPa (250 psi) (Figure 8.24). A continuous screw fitted into a matching stator moves fluid through the pump (the pumping action differs from that of a screw pump because the screw is fully enclosed and does not have an upper bearing. The pump's cast-iron body, chrome-plated tool steel rotor, and nitrite rubber stator (65 to 75 durometer hardness) can handle scum and secondary sludge, but for more abrasive solids containing high amounts of sand, grit, or other erosive materials (e.g., primary sludge), ceramic-coated oversize rotors with 50- to 55-durometer nitrite stators should be used.

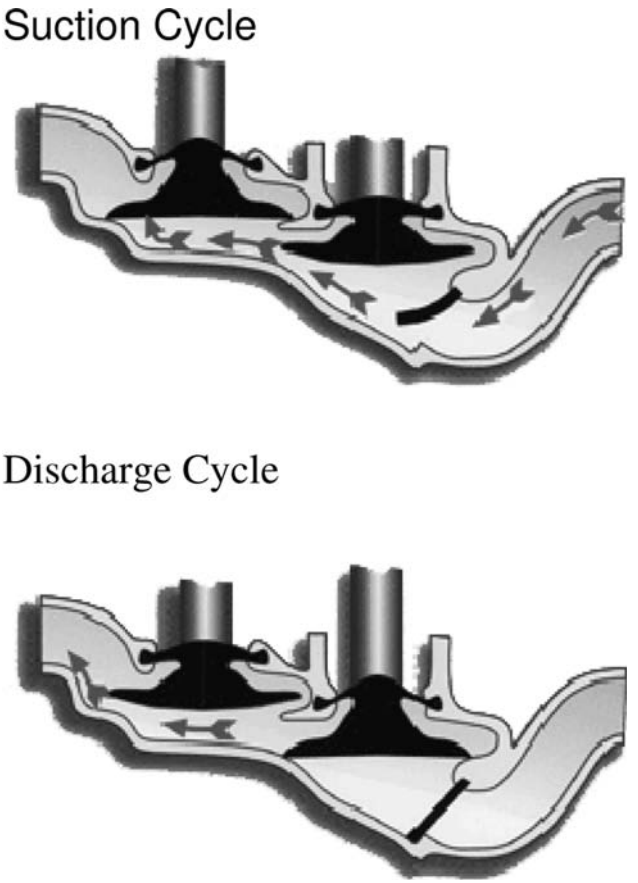


FIGURE 8.23 Grit pump section with cupped, recessed impeller (Courtesy of Penn Valley Pumps).

If run dry, the pump will be damaged in a matter of minutes. So, either the pump intake must be kept wet, or operators should use protective devices (e.g., capacitance-type flow detectors, low-pressure sensors or switches, and thermocouples imbedded in the stator).

Rotary-Lobe Pumps. Rotary-lobe pumps typically move solids by trapping the material between a rotating lobe and its housing, and then carrying the solids to the discharge port (Figure 8.25). The rotating lobes mesh at the discharge port, eliminating the space and forcing the solids into the pipeline. Timing gears phase the lobes. This phasing, the rotors' shape, and the constant velocity produce a continuous discharge.

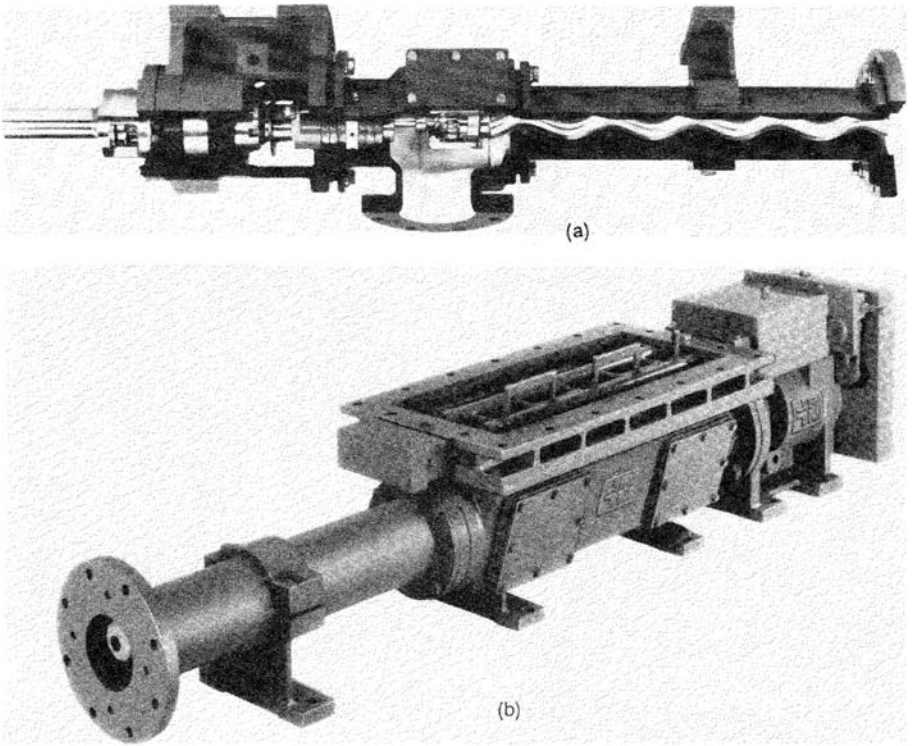


FIGURE 8.24 Progressing cavity pumps: (a) sludge pump and (b) pump with "bridge breaker" for sludge cake.

Other types of rotary-lobe pumps use arc-shaped pistons (rotor wings) in annular cylinders machined in the pump body (Figure 8.25). The pistons are driven in opposite directions by external timing gears. As they move, the rotors expand the cavity on the inlet side, allowing fluid to enter the pump chamber. The rotors then carry the fluid around the cylinder to the outlet side and then contract the cavity, thereby forcing the fluid out of the pump.

Other Types of Solids Pumps. Although the most common type of solids pump is the positive-displacement pump, solids also can be moved via recessed-impeller centrifugal pumps, hose pumps, pneumatic ejector pumps, grit pumps, grinder pumps, and air-lift pumps.

Recessed-Impeller Centrifugal Pumps. Two types of centrifugal pumps are typically used to pump solids: the open two-port radial nonclog pump and the vortex flow pump

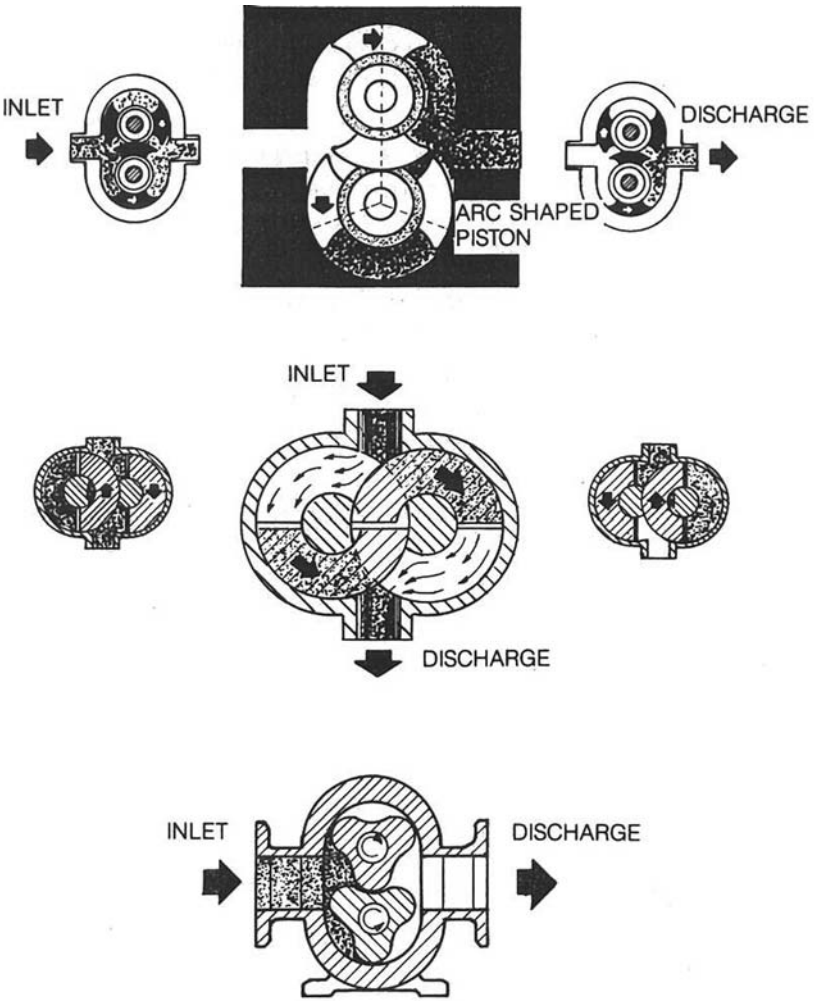


FIGURE 8.25 Rotary lobe pumps.

with a recessed impeller (Figure 8.26). Both pumps handle grit and liquid readily if the velocity is sufficient to overcome thixotropy. Special linings and impellers are needed to control wear when handling grit slurries or abrasive chemicals (e.g., lime slurry).

Hose Pumps. A hose pump operates as a positive-displacement pump in which the hose is completely squeezed between a roller and a track (Figure 8.27). Hose pumps avoid backflow and siphoning without any check valves, and none of their mechanical components touch the fluid being pumped. Servicing is relatively simple, because all

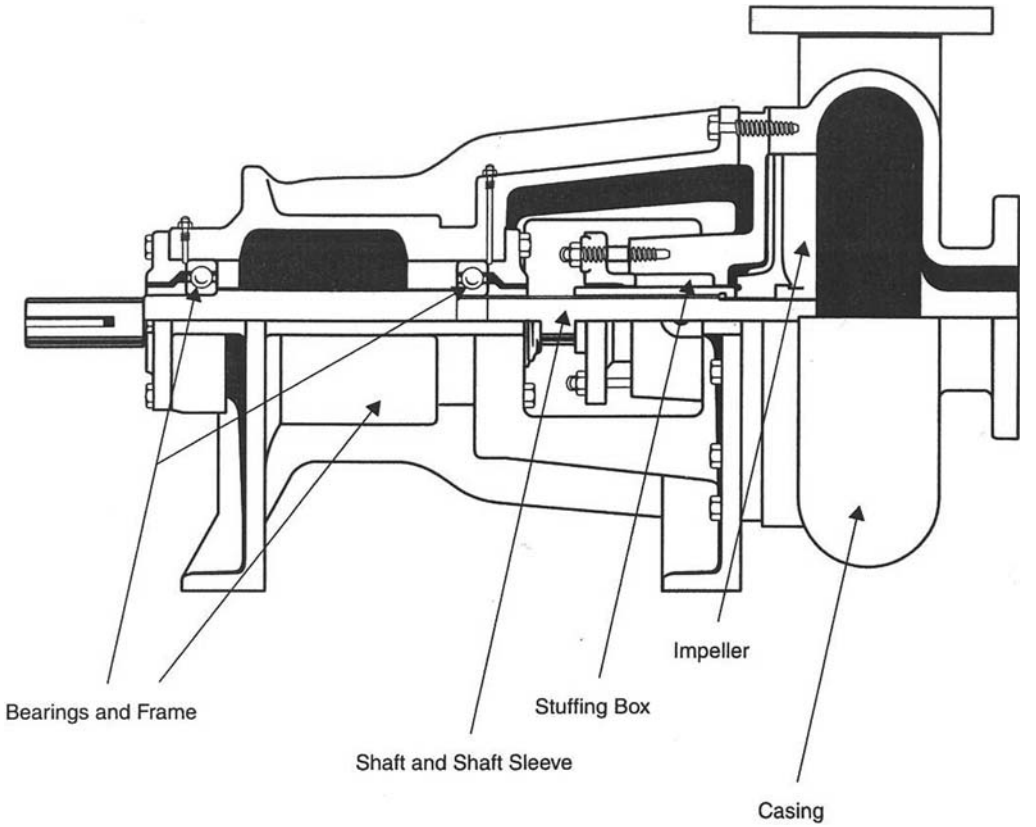


FIGURE 8.26 Recessed impeller solids-handling pump.

moving parts are external to the fluid or piping. However, they can only handle up to 350 gpm. Also, overoccluding (squeezing) the hose stresses it and the mechanical drive components unnecessarily; underoccluding it reduces pump efficiency and allows backflow to occur.

Pneumatic Ejector Pumps. A pneumatic ejector uses both air and the fluid to be pumped to pressurize its vessel. Then a discharge valve is opened, and the high pressure "ejects" the fluid–air mixture.

Grit Pumps. A "grit" pump is basically a centrifugal pump with a recessed impeller (Figure 8.28). Grit pumping can be more difficult than other solids pumping because the grit's sheer weight can clog pumps and its abrasive nature quickly deteriorates piping. To minimize these problems, the pumps are made of abrasion-resistant alloys and can be run more frequently, so large quantities of grit cannot accumulate.



FIGURE 8.27 Hose pump section (Courtesy of Watson-Marlow Bredel).

Grinder Pumps. A mechanical grinder can be fitted across the suction end of either a centrifugal or positive-displacement pump. The grinding mechanism "chews" influent solids into finer solids, minimizing potential clogging or "balls" of material that can clog downstream piping or processes.

Air-Lift Pumps. Air-lift pumps were once used to pump return activated sludge from clarifiers; now, they typically lift grit from vortex degritting devices. In these pumps, diffused air is added to the bottom of the air lift, mixing with the solids and making them less dense so the fluid surface rises above the discharge point. The required submergence of the air lift and the small allowable head limits the air lift's capability between the discharge pipe and the tank fluid surface.

The pumping rate is controlled by the airflow rate. Throttling the influent valve will eventually result in plugging and "backblow" into the clarifier or decant tank. A common problem is the tendency to make the flow rate too high (to avoid the spurting, inconsistent flow that is characteristic of the pump's discharge). To avoid this problem,

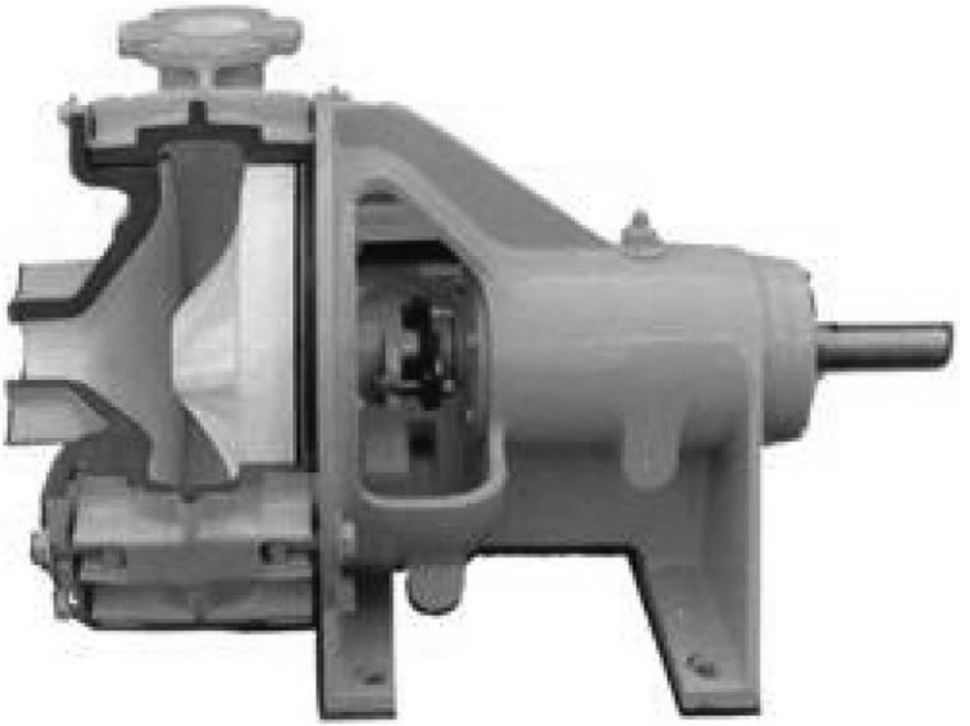


FIGURE 8.28 Grit pump section with cupped, recessed impeller (Courtesy of Wemco).

operators should periodically measure the pumping rates—if only with a bucket and stopwatch—and calculate the approximate flow rate.

Because fluid is not forced through them mechanically, air-lift pumps are prone to plugging, so they must be rodded periodically to keep them fully operational. If the air lift is plugged or not operating, operators should confirm that the air valve is fully open and then check the pump's air blower to ensure that it is working properly. If the pump still is not working, then operators should rod the air lift as follows:

1. Turn off the air supply;
2. Remove the plug in the T at top of air lift;
3. Rod the lift to break up the blockage;
4. Replace the plug in the T; and
5. Turn on the air supply.

CATEGORIZATION. Solids pumps can be classified based on impeller type, suction, location, and orientation.

Rotor or Impeller. Except for centrifugal pumps, solids pumps do not use conventional impellers to transfer energy from the mechanical device to the flow. Instead, progressing-cavity pumps use rotors, rotary-lobe pumps use lobes, positive-displacement pumps use other means of transferring energy. (Impellers are the most distinguishing feature of solids pumps.)

Suction. Solids pumps are typically designed as single-suction units.

Location. Solids pumps are typically installed outside the fluid being pumped. One exception is the air-lift pump, because the air injected into the suction piping must be submerged in the fluid being pumped.

Orientation. Solids pumps—especially progressing-cavity pumps—are typically mounted horizontally, but even progressing-cavity pumps can be mounted vertically. The motors can be mounted on top, at the side, or even axially. (The orientation issue is less significant for solids pumps than for liquids pumps.)

APPLICATIONS. ***Controlled-Volume Pumps.*** *Plunger Pumps.* For solids applications, plunger pumps should have a welded-steel base and a hardened cast-iron or steel body and valving. Pistons are often surface-hardened to reduce their wear rate.

Plunger pumps used to be the most popular choice for handling thick, abrasive solids because the pulsating effect of the reciprocating plungers helps reduce line clogging and avoid bridging the sludge hoppers. However, its popularity has declined now that sludge thickening and dewatering processes require a more constant feed flow to mix with polymers and other coagulant aids. Nonetheless, plunger pumps are sometimes used as a backup to help dislodge blockages in the piping systems. They also are used to pump dewatered sludge cake (in which case, they are called *power pumps*).

Piston Pumps. Piston pumps typically are used to pump dewatered solids.

Diaphragm Pumps. Diaphragm pumps can operate at any rate by adjusting the number of strokes per minute. They have no packing or seals and can run dry without any damage. If compressor capacity is available, air-operated diaphragm pumps can be used. These pumps cost less to install, but need five to six times more power than a pump driven by an electric motor.

Diaphragm pumps can handle the same materials as plunger pumps, without the abrasion problems. They also handle strong or toxic chemicals more safely, because

the diaphragm can prevent or substantially minimize leakage that could cause damage or threaten health and safety.

Rotating Positive-Displacement Pumps. *Progressing Cavity Pumps.* A progressing-cavity pump's stator is suitable for most solids applications but may need to be modified to accommodate special solids characteristics or chemical applications. The pump may be mounted horizontally or vertically without affecting its efficiency or operations. The pump delivers at a constant rate that can be changed quickly by changing the pump speed.

Regardless of the type of solids involved, this pump operates simply; operators can control the delivery rate by modulating the pump speed [maximum should be 300 rev/min and 240 kPa (35 psi) per pump stage]. However, they must sharply reduce the speed when pumping abrasive material under high head [maximum should be 200 rev/min and 100 kPa (15 psi) per pump stage].

Progressing-cavity pumps can handle both thickened sludge and even sludge cake with solids concentrations up to 65% (Figure 8.21, Part B). Because they impart minimal shear to the fluid being moved, progressing-cavity pumps also are used to pump polymers, which can be damaged by agitation. With the proper selection of pump materials, the progressing-cavity pump can handle chemical slurries (e.g., lime and ferric chloride).

Rotary-Lobe Pumps. Used for many years to pump nonabrasive material, rotary-lobe pumps are now increasingly being used to transport scum and municipal sludge (except screenings, grit, composted solids, and septage) (Cunningham, 1982). During operation, the lobes mesh together while rotating in opposite directions, forming cavities between the rotors and the casing that trap and move the solids (Figure 8.22). Pump speeds range from 200 to 300 rpm (lower speeds are used for more abrasive solids). Although one manufacturer reported achievable total system heads of 515 kPa (75 psi), operators should avoid higher discharge pressures to limit hydraulic slip, which is proportional to the net differential pressure.

OPERATIONS AND MAINTENANCE. For any given pump, the pump manufacturer will provide literature or guidance on particular O&M activities that should be followed. The following information is meant as guideline for developing or reviewing an O&M plan.

A well-planned O&M program will prevent unnecessary equipment wear and downtime. Utility staff should begin by determining the actual and projected quantities of solids (e.g., grit, screenings, primary sludge, primary scum, return sludge, waste sludge, and thickened and dewatered solids) to be pumped under various flow condi-

tions. Staff typically can find this information in the utility's O&M manual or engineering design report; otherwise, they can calculate loadings based on the size of the processing units and pumping systems. Then, they should evaluate the solids loadings and seasonal variations at various critical processes. With this information, staff can then determine how many solids pumps should be in service and the timing and length of the pump cycles under various conditions.

If the grit-handling pumps typically run 5 minutes an hour in dry weather, for example, staff may calculate that they need to run 8 minutes an hour after storms to handle the anticipated increase in volume. Likewise, the primary sludge pumps also may need to run longer under wet weather conditions. Also, as solids characteristics change, operators may need to change the polymer doses in the thickeners or respond to changes in alkalinity in the anaerobic digesters. Staff need to plan for such variations so they can respond promptly and appropriately.

Operations. The following operations activities directly affect solids pump performance.

Appurtenances. Positive-displacement pumps need a drive system that can operate the pump at the speed needed to perform adequately under all operating conditions. Sometimes, this involves manually and automatically timed starts and stops, as well as varied pump discharge rates. This variable-speed arrangement can be provided via mechanical vari-drives; variable pitch pulleys; direct-current, variable-speed drives; alternating-current, variable-frequency drives; eddy-current magnetic clutches; or hydraulic speed-adjustment systems. Each has various advantages and disadvantages with respect to cost, amount and ease of maintenance required, efficiency, turndown ratio, and accuracy. Because positive-displacement pumps are constant torque machines, operators should ensure that the variable-speed drive's output torque exceeds the pump's torque requirement at all operating points. Although variable-speed drives are often either a necessity or an enhancement to proper plant operation, the challenge is providing the continued maintenance and servicing required.

Testing Procedures. Positive-displacement pumps should be field-tested for flow, speed, amperage, voltage, pressure, and no-flow protection devices. These tests should only be performed by an authorized factory representative to avoid system overpressurization.

Startup. Before starting up a solids pump, operators should check the following items to ensure that each piece of equipment is installed correctly:

- Pump, driver, coupling, or sheave alignment;
- Water flush connections to the stuffing box; and
- Open valves on both the suction and discharge sides of the pump.

Positive-displacement pumps should not be operated against a closed discharge valve.

Before operating a solids pump for the first time, operators should:

- Ensure that the pump is filled with fluid;
- Confirm that adequate seal water flow and pressure for the stuffing box seal are available (unless mechanical seals are used); and
- Bump the drive to check for rotation.

Once the solids pump is started up, operators should check the following items:

- Inlet and outlet flow rate;
- Noise or vibration;
- Bearing housing temperature;
- Running amperage;
- Pump speed; and
- Pressure.

Dry operations can harm positive-displacement pumps, so they should never be allowed to run dry.

Shutdown. Before shutting down positive-displacement pumps, operators should ensure that all isolation or discharge valves are open. Then, follow the startup procedures in reverse order.

Monitoring. In addition to general pump maintenance activities, operators should seriously consider high-pressure protection because positive-displacement pumps will always deliver flow if the pump is running. A high-pressure protection device ensures that the pumping equipment will shut down at a preset pressure before a catastrophic failure occurs. If rupture or bursting discs are used, they should be enclosed in a secondary containment structure that can capture pumped material, because the discs break open to relieve pressure. Also, positive-displacement pumps run under tight tolerances or rely on pumped flow to lubricate and cool the pumping elements, so operators should consider a no-flow protection device. This device can be a low-pressure switch, presence–absence protector, flow switch, temperature sensor, or a combination of these.

Controls. The primary pumping controls include time clocks, elapsed-time meters, solids-content analyzers, flow-rate meters, pressure gages, pressure switches, flow switches, and sludge blanket indicators. The emphasis should be placed on ensuring

that these pumps do not develop too much head or run dry. Operators may use an indicating mode, a controlling mode, or both.

Maintenance. The following maintenance activities affect the longevity of solids pump performance.

Wear. Excessive wear is the most common problem for positive-displacement pumps. The wear rate depends on how the pump is operated and where it is used. More abrasive solids and higher rotational speeds, for example, increase pump wear.

Controlled-Volume Pumps. In plunger pumps, wear occurs between the piston packing and its cylinder. Excessive leakage around the shaft and plunger packing may exacerbate cylinder wear, which in turn will accelerate the destruction of the packing. If this happens, the entire worn shaft or plunger may need to be reworked or replaced. So, staff should frequently inspect the packing along the cylinder and evaluate the extent of leakage, so they will promptly re-pack or replace it when needed, thereby extending the life of the cylinder.

If the pump runs with a short stroke for long periods, the unit will wear excessively along a short length of the shaft, accelerating packing deterioration and leakage. Ideally, the pump should operate with a long, slow stroke so it moves more material per stroke and cycles less frequently, thereby reducing wear.

Also, the mechanical seals can be replaced with water-lubricated seals that are more suitable for abrasive conditions; however, staff still must evaluate seal leakage and wear to minimize cylinder wear.

Progressing-Cavity Pumps. As a progressing-cavity pump's rotors or stators become well worn, the pump capacity diminishes enough to prevent the transfer of solids because of slippage within the pump itself. Excessive wear indicates that the pump's operating speed has been too great. Under abrasive conditions, progressing-cavity pumps should not exceed 200 to 300 rpm.

Depending on wear, the stator and even the rotor may need to be replaced. Because the stator wears faster than the rotor, the rotor can be plated as much as 0.8 to 1.0 mm (0.030 to 0.040 in.) oversize, so worn stators can be reused. This plating, which doubles the effective life of the stators, can be used if wear is excessive.

Grinders or Grinder Pumps. Grinders or grinder pumps wear rapidly and will work inadequately if not adjusted, rebuilt, or repaired to offset this wear. Grinders need proper clearance adjustment to maintain adequate grinding and avoid excessive wear. The cutters are designed so they can be easily replaced and their hardened surfaces

rebuilt. For pumps with grinders, maintaining proper grinding will forestall wear or damage to the pump itself.

Standard Maintenance. Following are maintenance checklists for various solids pumps.

Plunger Pumps. To maintain plunger pumps properly, utility staff should do the following:

- Check primary solids pump motors for heat, noise, or excessive vibration.
- Check the oil level around the plunger pump (add oil if needed).
- Check the oil level in the eccentric oiler.
- Check the alignment of the connecting rod.
- Check the condition of the shear pin (it should not have any bends inside or outside the driving flange or eccentric).
- Check the fluid level in the air chamber.
- Check the gear reducer's operating temperature (and listen for unusual noise).
- Check the oil level inside the plunger (wrist pin lubrication). If the plunger is filled with fluid or sludge, drain and refill with clean oil.
- Grease the bearings on the main drive shaft weekly.
- Check the keys in the driving flange (they should be tight, preventing backlash).
- Flush (through the oiler) the babbitt-lined bearings with about 59 mL (2 oz) of kerosene. Then, refill weekly with the proper lubricant.
- Check the eccentric liner for unusual wear because of lack of lubrication.
- Check the main shaft for rust (if present, remove it and recoat the shaft with a film of grease).
- Check the oil level in the reducer.
- Check valve balls and seats. More frequent inspection may be needed if the slurry is abrasive.
- Check the condition of the coupling between motor and reducer.
- Check the plunger for sidewall wear.
- Replace the oil inside the plunger monthly.
- Check the wrist pin (it should not be excessively loose).
- Check the tightness of the set screws on the drive flange.
- Inspect the motor and reducer seals for leakage. Change the oil in the gear reducer monthly or after every 500 hours of operation.

Progressing Cavity Pumps. To maintain progressing cavity pumps properly, utility staff should do the following:

- Check the level and condition of the oil in the gear reducer.
- Confirm that the high-discharge-pressure shutoff switch is functioning properly.

- Check the shaft alignment.
- Check the condition of all painted surfaces.
- Visually inspect mounting fasteners for tightness.
- Clean dirt, dust, or oil from equipment surfaces.
- Check all electrical connections.
- Stop and start equipment, checking for voltage and amp draw and any movement restrictions because of failed bearings, improper lubrication, or other causes.
- Check the drive motor for any unusual heat, noise, or vibration.
- Check mechanical seals and packing for leakage or wear.

Rotary Lobe Pumps. To maintain rotary lobe pumps properly, utility staff should do the following:

- Check the preventive maintenance master schedule, lubrication master schedule, and equipment history sheets to schedule lubrication and preventive maintenance tasks.
- Update the equipment history record as work is done.
- Check all equipment fasteners for tightness.
- Check the condition of all visible parts of the pump and its related components.
- Check the pump casing and impellers for wear.
- Check the oil quantity and quality in the gear case.
- Check the controls and starter equipment for overall condition.
- Check and adjust belt tightness regularly.
- Check mechanical seals and packing for leakage or wear.

Predictive Maintenance. Vibration monitoring can be helpful. Because positive-displacement pumps produce a pulsed flow, some vibration is expected and the piping system should be isolated via properly designed foundations, expansion (flexible) joints, and pulsation dampeners. Excessive vibration, however, is typically caused by misalignment, loose foundation bolts, improperly supported piping, NPSH problems, or a mechanical problem.

Spare Parts. The spare parts needed depend on the application, pump type, and manufacturer.

Troubleshooting. The troubleshooting approach depends on the application, pump type, and manufacturer. Tables 8.3 through 8.5 are troubleshooting guides for plunger pumps, progressing cavity pumps, and rotary lobe pumps, respectively, that will help

TABLE 8.3 Troubleshooting guide for plunger pumps.

Problems	Causes	Solutions
Incorrect rotation	Incorrect connections.	Refer to connection diagram and reconnect according to instructions.
No sludge flow	Valve ball clogged or not installed.	Open valve chambers and inspect.
	Air leak in suction line.	Check line with clear water under pressure.
	Valve closed, clogged line.	Inspect valves, backflush sludge lines.
Low capacity	Pump stroke set too short.	Set to longer stroke.
	Air leak in suction piping.	Check line with clear water under pressure.
Excessive power	Pump packing too tight.	Check packing and readjust.
Shear pin failure	Excessive discharge pressure.	
	Eccentric bolts loose.	Tighten to proper torque.
	Flange faces dirty.	Wash face of both flanges and eccentric with kerosene and reassemble.
	Pump packing too tight.	Check packing and readjust per instructions.
	Eccentric bearing clearance too great.	Remove shims as required.
Overheating of gears or bearings	Inadequate lubrication.	Check oil level in gears and eccentric oiler.
	Excessive lubrication.	Check gear oil level. If correct, drain and refill with clean oil of recommended grade. Set eccentric oiler at prescribed rate.
Noise or vibrations	Suction valve slamming.	Open snifter valve.
	Excessive clearance in eccentric bearing.	Remove shims as required.
	Air chamber full of water.	Drain.
Runs hot	Insufficient lubrication.	Check lubrication level and adjust to recommended levels.
	Excessive lubrication.	Check lubricant level and adjust to recommended level.
	Wrong lubricant.	Flush out and refill with correct lubricant as recommended.

TABLE 8.3 Troubleshooting guide for plunger pumps (*continued*).

Problems	Causes	Solutions
Runs noisily	Loose hold-down bolts.	Tighten bolts.
	Worn disk.	Disassemble and replace disk.
	Level of lubricant in the reducer not properly maintained.	Check lubricant level and adjust to factory-recommended level.
	Damaged pins and rollers.	Disassemble and replace ring gear, pins, and rollers.
	Overloading of reducer.	Check load on reducer.
Output shaft does not turn in	Input shaft broken.	Replace broken shaft.
	Key missing or sheared off.	Replace key.
	Eccentric bearing broken, lack of lubricant.	Replace eccentric bearing. Flush and refill with recommended lubricant.
	Coupling loose or disconnected.	Properly align reducer and coupling. Tighten coupling.
Oil leakage	Worn seals caused by dirt or grit entering seal. Breather filter clogged.	Replace seals. Replace or clean filter.
	Overfilled reducer.	Check lubricant level and adjust to recommended level.
	Vent clogged.	Clean or replace element, being sure to prevent any dirt from falling into the reducer.
Motor fails to start	Blown fuses.	Replace fuses with proper type and rating.
	Overload trips.	Check and reset overload in starter.
	Improper power supply.	Check to see that power supply agrees with motor nameplate and load factor.
	Improper line connections.	Check connection with diagram supplied with motor.
	Open circuit in winding or control switch indicated by humming sound when switch is closed.	Check for loose wiring connections. Also see that all control contacts are closing.
	Mechanical failure.	Check to see if motor and drive turn freely. Check bearings and lubrication.

TABLE 8.3 Troubleshooting guide for plunger pumps (*continued*).

Problems	Causes	Solutions
	Short-circuiting.	Indicated by blown fuses. Rewind motor.
	Poor stator coil connection.	Remove end bells; locate with test lamp.
	Rotor defective.	Look for broken bars or end rings.
	Motor may be overloaded.	Reduce load.
Motor stalls	One phase may be open.	Check lines for open phase.
	Overloaded motor.	Reduce load.
	Low motor voltage.	See that nameplate voltage is maintained. Check connection.
	Open circuit.	Fuses shown. Check overload relay, stator, and push-buttons.
Motor runs and then shuts down	Power failure.	Check for loose ties, connections to lines, fuses, and controls. Check starter overloads.
Motor does not get up to speed.	Voltage too low at motor terminals because of line drop.	Use higher voltage or transformer terminals, former terminals, or reduce load. Check connections. Check conductors for proper size.
	Starting load too high.	Check what load motor is supposed to carry at start.
	Broken rotor bars or loose rotor.	Look for cracks near the rings. A new rotor may be required as repairs are typically temporary.
	Open primary circuit.	Locate fault with testing device and repair.
Motor takes too long to accelerate	Excess loading.	Reduce load.
	Poor circuit.	Check for high resistance.
	Defective squirrel cage rotor.	Replace with new rotor.
	Applied voltage too low.	Get power company to increase power tap.
Wrong rotation	Wrong sequence of phases.	Reverse connections at motor or at switchboard.
Motor overheats while running under load.	Overloaded.	Reduce load.

TABLE 8.3 Troubleshooting guide for plunger pumps (*continued*).

Problems	Causes	Solutions
	Frame or bracket vents may be clogged with dirt and prevent proper ventilation of motor.	Open vent holes and check for a continuous stream of air from the motor.
	Motor may have one phase open.	Check to make sure that all leads are well-connected.
	Grounded coil.	Locate and repair.
	Unbalanced terminal voltage.	Check for faulty leads, connections, and transformers.
Motor vibrates after corrections have been made.	Motor misaligned.	Realign.
	Weak support.	Strengthen base.
	Coupling out of balance.	Balance coupling.
	Driven equipment unbalanced.	Rebalance driven equipment.
	Defective ball bearing.	Replace bearing.
	Bearings not in line.	Line up properly.
	Balancing weights shifted.	Rebalance motor.
	Polyphase motor running single phase.	Check for open circuit.
	Excessive end play.	Adjust bearing or add washer.
Unbalanced line current on polyphase motors during normal operation	Unequal terminal volts.	Check leads and connections.
	Single-phase operation.	Check for open contacts.
Scraping noise	Fan rubbing fan shield.	Remove interference.
	Fan striking insulation.	Clear fan.
	Loose on bedplate.	Tighten holding bolts.
Noisy operation	Air gap not uniform.	Check and correct bracket fits or bearing.
	Rotor unbalanced.	Rebalance.
Hot bearings, general	Bent or sprung shaft.	Straighten or replace shaft.
	Excessive belt pull.	Decrease belt tension.

TABLE 8.3 Troubleshooting guide for plunger pumps (*continued*).

Problems	Causes	Solutions
	Pulleys too far away.	Move pulley closer to motor bearing.
	Pulley diameter too small.	Use larger pulleys.
	Misalignment.	Realign drive.
Hot ball bearings	Insufficient grease.	Maintain proper quantity of grease in bearing.
	Deterioration of grease or lubricant contaminated.	Remove old grease, wash bearings thoroughly in kerosene, and replace with new grease.
	Excess lubricant.	Reduce quantity of grease; bearings should not be more than 50% filled.
	Overloaded bearing.	Check alignment, side and end thrust.
	Broken ball or rough races.	Clean housing thoroughly, then replace bearing.

operators identify pumping problems and determine their solutions. Figure 8.29 is a manufacturer's published troubleshooting guide for rotary lobe pumps.

MISCELLANEOUS PUMPS OR PUMPING APPLICATIONS

Some pumps and pumping applications (e.g., grinding, chemical metering, and pneumatic ejectors) do not fit neatly into the kinetic or positive-displacement categories.

GRINDING. There are basically two types of sludge-grinding pumps: comminuting and pumping, and comminuting and grinding.

Comminuting and Pumping. Typically used to prevent oversized particles from damaging or plugging downstream piping and equipment, a comminuting and pumping device (Figure 8.30) both grinds and pumps liquids and solids. It also may be used to grind scum and screenings. In this device, the solids flow axially to a serrated, wobble-plate rotor, which grinds them and forces them through a matching set of discharge bars in the outlet. The size of the resulting particles depends on the size of the rotor's serrated edges and the spacing of the bars. Because the device functions like a

TABLE 8.4 Troubleshooting guide for progressing cavity pumps.

Problems	Causes	Solutions
Pump does not rotate	Incorrect power supply.	Check motor nameplate data; test voltage, phase, and frequency.
	Foreign matter in pump.	Remove foreign matter.
	If pump or stator is new, or too much friction.	Fill with liquid and hand turn. If still tight, lubricate stator with glycerine or liquid soap (household commercial product).
	Stator swells due to high liquid temperature.	Reduce liquid temperature or use an undersized rotor.
	Blockage due to solids in liquid.	Decrease solids-to-liquid ratio.
	Liquid settles and hardens after pump shutdown.	Clean and rinse pump after each use.
Pump does not discharge	Air in suction pipe.	Tighten connections to stop leaks.
	Pump speed too low.	Increase drive speed.
	Stator worn excessively.	Replace stator.
	Rotor worn excessively.	Replace rotor.
	Wrong direction of rotation.	Reverse drive motor polarity.
Discharge output low	Incorrect power supply.	Check motor nameplate data; test voltage, phase, and frequency.
	Air in suction pipe.	Tighten connections to stop leaks.
	Pump speed too low.	Increase drive speed.
	Stator worn excessively.	Replace stator.
	Rotor worn excessively.	Replace rotor.
	Discharge pressure too high.	Open discharge valve; remove obstruction.
	Suction pipe leaks.	Tighten pipe connections.
	Shaft packing leaks.	Tighten packing glands; replace packing.
No discharge	Improper rotation direction.	Reverse pump motor.
	Pump not primed.	Relieve internal pressure; carefully prime pump.
	Loose belt.	Tighten belt.

TABLE 8.5 Troubleshooting guide for rotary lobe pumps.

Problems	Causes	Solutions
Discharge under capacity	Sludge vaporizing in line to pump.	Check temperature of sludge; if above 35°C (95°F), correct temperature.
	Air entering inlet line.	Check and correct any leaks in inlet valve.
	Packing leaking excessively.	Adjust packing 5 to 10 drops/minute.
	Sludge too thick, unable to move through lines.	Check thickness of sludge; should not exceed 9%.
	Worn rotors.	Check thickness of rotors compared to manufactured specifications; if severely worn, replace rotors.
Pump stalls after starting	Sludge too thick.	Check sludge thickness; should not exceed 9%.
	Worn or unsynchronized timing gears.	Replace timing gears.
	Metal-to-metal contact on rotors.	Replace rotors.
Pump overheats	Sludge too thick.	Check sludge thickness; should not exceed 9%.
	Sludge temperature too high.	Sludge should not be above 35°C (95°F).
	Packing gland overtightened.	Adjust packing gland for 5 to 10 drops/minute; if no adjustment left, replace packing.
	Shaft bearing worn or failed.	Inspect bearing; if worn or damaged, replace.
	Worn or unsynchronized timing gear.	Replace timing gear.
	Gear case oil quantity low or quality poor.	Inspect oil; if contaminated, change; if low, add oil.
	Metal-to-metal contact on rotors.	Replace rotors.

TABLE 8.5 Troubleshooting guide for rotary lobe pumps (*continued*).

Problems	Causes	Solutions
Motor overheats	Sludge too thick.	Check sludge thickness; should not be above 9%.
	Packing gland too tight.	Adjust gland for 5 to 10 drops/minute.
	Overspeed.	Check motor for speed; adjust as necessary.
	Sheaves misaligned.	Properly align sheaves.
	Shaft bearing worn or failed.	Inspect bearing; if worn or damaged, replace bearing.
	Worn or unsynchronized timing gear.	Replace timing gear.
	Gear case oil quantity low or poor quality.	Add oil if needed; replace oil if contaminated.
	Metal-to-metal contact on rotors.	Replace rotors.
Noise and vibration	Air entering inlet line.	Check inlet lines for leaks; correct leaks.
	Sludge too thick.	Check sludge thickness; should not be above 9%.
	Sheaves misaligned.	Properly align sheaves.
	Loose pump and motor mountings.	Check for loose mounts; correct same.
	Shaft bearing worn or failed.	Replace bearing.
	Worn or unsynchronized timing gear.	Replace timing gear.
	Gear case oil quantity low or poor quality.	Add oil if needed; replace oil if contaminated.
	Metal-to-metal contact on rotors.	Replace rotors.
Pump element wear excessive	Sludge temperature too high.	Should not exceed 35°C (95°F).
	Sludge too thick.	Should not be above 9%.
	Shaft bearing worn or failed.	Replace bearing.
	Worn or unsynchronized timing gear.	Replace timing gear.
	Rotors contacting each other.	Replace rotors.

TABLE 8.5 Troubleshooting guide for rotary lobe pumps (*continued*).

Problems	Causes	Solutions
Overheating	Overload.	Reduce load or replace unit with one having sufficient capacity.
	Incorrect oil level.	Fill or drain to specified oil level.
	Vent plug not installed or is restricted.	Install vent plug provided or remove and clean in solvent.
	Excessive or insufficient bearing clearance.	Adjust tapered roller bearing to provide proper axial clearance.
	Incorrect grade of oil.	Drain unit and refill with correct grade of oil.
Bearing failure	Overload.	Reduce load or replace unit with one having sufficient capacity.
	Overhung load rating exceeded.	Reduce overhung load or replace unit with one having sufficient capacity.
	Excessive or insufficient bearing clearance.	Adjust tapered roller bearing to provide proper axial clearance.
	Insufficient lubrication.	Check oil level; fill if necessary.
Shaft failure	Improper coupling alignment.	Readjust as required.
	Overhung load rating exceeded.	Reduce overhung load or replace unit.
	High, repetitive shockloads.	Provide coupling with ability to absorb shock or replace unit with one having adequate service factor.
Gear wear or failure	Overload.	Reduce load or replace unit with one having sufficient capacity.
	High, repetitive shockloads.	Provide shock absorbing coupling or replace unit.
	Insufficient lubrication.	Check oil level and fill.
	Excessive bearing clearance.	Adjust bearing clearance.
	Incorrect grade of oil.	Drain unit and refill with new oil as specified.
Oil leaks	Incorrect oil level.	Fill or drain to specified oil level.
	Vent plug not installed or is restricted.	Install vent plug provided or remove and clean in solvent.
	Worn oil seals.	Check and replace as required.

TABLE 8.5 Troubleshooting guide for rotary lobe pumps (*continued*).

Problems	Causes	Solutions
	Loose pipe plugs, backstop cover, or input bracket.	Check and tighten as required. If problem still exists, remove clean mating surfaces, apply new sealant, and reassemble.
Noise	Loose mounting or coupling.	Check and tighten as required.
	Worn bearings.	Reduce load or replace with one having sufficient capacity. Reduce overhung load or replace unit with one having sufficient capacity. Adjust tapered roller bearing to provide proper axial clearance. Check oil; fill if necessary.
	Worn or damaged gears.	Reduce load or replace unit with one having sufficient capacity. Drain unit and refill with new oil.
Belt slip (sidewallks glazed)	Not enough tension.	Replace belts; apply proper tension.
Drive squeals	Shock load.	Apply proper tension.
	Not enough arc of contact.	Increase center distance.
	Heavy starting load.	Increase tension.
Belt turned over	Broken cord, caused by prying on sheave.	Replace set of belts correctly.
	Overloaded drive.	Redesign drive.
	Impulse loads.	Apply proper tension.
	Misalignment of sheave and shaft.	Realign drive.
	Worn sheave grooves.	Replace sheaves.
	Flat idler sheave.	Align idler. Reposition on slack side of drive close to drive sheave.
	Excessive belt vibration.	Check drive design. Check equipment for solid mounting. Consider use of banded belts.
Mismatched belts	New belts installed with old belts.	Replace belts in matched set only.
	Sheave groove worn unevenly; improper groove angle. Gives appearance of mismatched belts.	Replace sheaves.

TABLE 8.5 Troubleshooting guide for rotary lobe pumps (*continued*).

Problems	Causes	Solutions
	Sheave shafts not parallel. Give appearance of mismatched belts.	Align drive.
Belt breaks	Shock loads	Apply proper tension; recheck drive.
	Heavy starting loads.	Apply proper tension; recheck drive. Use compensator starting.
	Belt pried over sheaves.	Replace set of belts correctly.
	Foreign objects in drive.	Provide drive shroud.
Belts wear rapidly	Sheave grooves worn.	Replace sheaves.
	Sheave diameter too small.	Redesign drive.
	Mismatched belts.	Replace with matched belts.
	Drive overloaded.	Redesign drive.
	Belt slips.	Increase tension.
	Sheaves misaligned.	Align sheaves.
	Oil or heat condition.	Eliminate oil. Ventilate drive.

centrifugal pump, the influent should be dilute unthickened solids; however, it can break up large trash particles. The unit typically can handle flows ranging from about 1.5 to 20 L/s (25 to 300 gpm).

Comminuting and Grinding. A comminuting and grinding device (Figure 8.31) is not really a pump because its primary purpose is shredding solids. It only produces enough head to force the solids through the grinder. The device uses a high-energy impact blade to shear and shred solids before they flow through the slotted openings; depending on the application, capacity, and grinding configuration, it can reduce particle sizes to between 6 and 10 mm (0.25 and 0.38 in.). The device typically is used to comminute previously thickened solids, scum, and screenings to protect downstream dewatering devices from clogging. To reduce the pressure on its seals, the device typically is installed on the suction side of a solids pump. It requires intensive and thorough maintenance.

METERING. Similar to positive-displacement reciprocating pumps, metering pumps are designed to provide controlled discharges. The discharges can be controlled via the

VOGELSANG Service Manual | Service Manual Pump Models: Series Q Pumps

Troubleshooting

No Discharge	Below Capacity	Irregular Discharge	Lost Prime	Pump Stalls at Startup	Pump Overheats	Motor Overheats	Excessive Power Draw	Noise & Vibration	Pump Element Water	Seizure	Causes	Solution
X											Incorrect direction of rotation	Reverse Motor
X											Pump not primed	Expel gas from supply line and pumping chamber to introduce liquid.
X	X	X	X					X			Insufficient NPSH available	Increase supply line diameter. Increase suction head. Simplify piping and/or reduce length. Reduce pump speed. Decrease liquid temperature. Check effect of increased viscosity on available and permitted power inputs.
	X	X	X					X			Product vaporizing in supply line.	
X	X	X	X					X			Air entering supply line.	Remake pipe work
	X	X	X					X			Gas Supply	Expel gas from supply line and pumping chamber to introduce liquid.
X	X	X	X					X			Insufficient head above supply vessel outlet	False product level. Lower outlet position. Increase submergence of supply line.
		X	X					X			Foot valve strainer obstructed or blocked.	Service Fittings.
	X		X	X	X	X	X	X			Liquid viscosity above rated figure.	Decrease pump speed. Increase liquid temp.
	X										Liquid viscosity below rated figure.	Increase pump speed. Decrease liquid temp.

FIGURE 8.29 Rotary lobe troubleshooting guide (Courtesy of Vogelsang USA, Inc.).

VOGELSANG Service Manual | Service Manual Pump Models: Series Q Pumps

No Discharge	Below Capacity	Irregular Discharge	Lost Prime	Pump Stalls at Startup	Pump Overheats	Motor Overheats	Excessive Power Draw	Noise & Vibration	Pump Element Water	Seizure	Causes	Solution
					X			X	X	X	Liquid temp. above rated figure.	Cool the liquid prior to pumping
				X		X	X				Liquid temp. below rated figure.	Heat the liquid prior to pumping
								X	X	X	Unexpected solids in product.	Clean the system. Add strainer to supply line.
	X	X	X	X	X	X	X	X	X	X	Delivery pressure above rated figure.	Check for obstruction. Simplify supply line.
											Seal flushing inadequate	Check that fluid flows freely into seal. Increase flow rate.
	X					X	X	X			Pump speed above rated figure.	Decrease pump speed.
											Pump speed below rated figure.	Increase pump speed.
	X				X	X	X	X	X	X	Rotor case strained by pipe work.	Align pipes. Add flexible pipes or expansion fittings.
					X	X	X	X			Belt Drive Slipping	Tighten belt to specified tension.
								X			Flexible coupling misaligned.	Adjust flange alignment.
					X	X	X	X	X	X	Insecure pump drive mountings	Add lock washers and retighten.
				X	X	X	X	X	X	X	Shaft bearing wear or failure.	Call Vogelsang or distributor for advice.
					X	X	X	X		X	Worn unsynchronized timing gears	Call Vogelsang or distributor for advice.
				X	X	X	X	X	X	X	Gear case oil level incorrect.	Refer to oil level instructions.

FIGURE 8.29 (*continued*).

VOGELSANG Service Manual | Service Manual Pump Models: Series Q Pumps

No Discharge	Below Capacity	Irregular Discharge	Lost Prime	Pump Stalls at Startup	Pump Overheats	Motor Overheats	Excessive Power Draw	Noise & Vibration	Pump Element Water	Excessive Seal Wear	Seizure	Causes	Solution
X	X											Metal to metal contact of pumping element.	Check rated and duty pressures.
		X				X						Worn pumping element.	Install new components
		X					X					Relief valve leakage	Adjust pressure setting. Examine & clean seating surfaces. Install new components.
		X					X					Relief valve chatter	Check water sealing surfaces & guides. Install new components.

FIGURE 8.29 (*continued*).

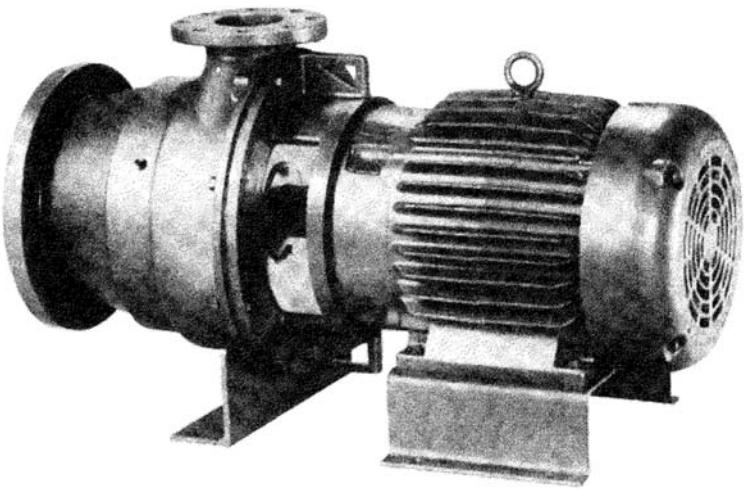


FIGURE 8.30 Trash and sludge grinder combined with a progressing cavity pump.

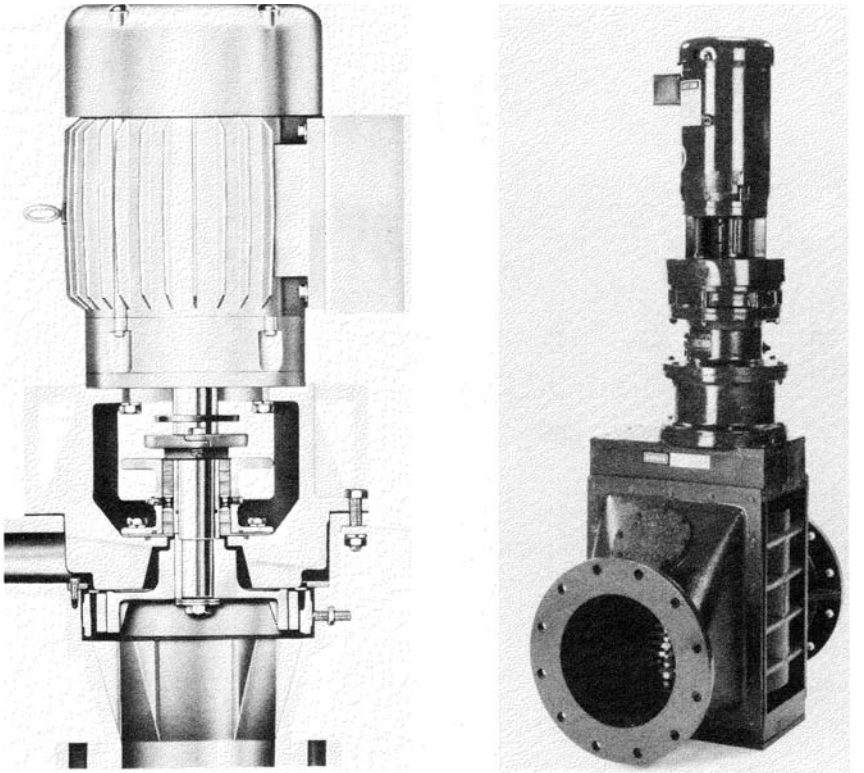


FIGURE 8.31 Sludge grinders.

stroke speed or volume displaced per stroke. Wastewater utilities typically use three types of metering pumps: packed plunger, mechanically actuated diaphragm, and hydraulically actuated diaphragm.

Overall, metering pumps' O&M needs are similar to those of positive-displacement pumps. But they also have suction and discharge check valves, which should be inspected and maintained about once every 6 months to ensure proper discharge metering.

PNEUMATIC EJECTORS. Pneumatic ejectors (Figure 8.32) have been used for years in collection systems—primarily in residential areas with low flows—but they required intensive maintenance, so many utilities replaced them with submersible pumping systems. However, the devices are excellent for conveying scum and floatables in wastewater treatment plants. The Anthony Ragnone Treatment Plant in Genesee County, Michigan, has used one to convey scum for 30 years.

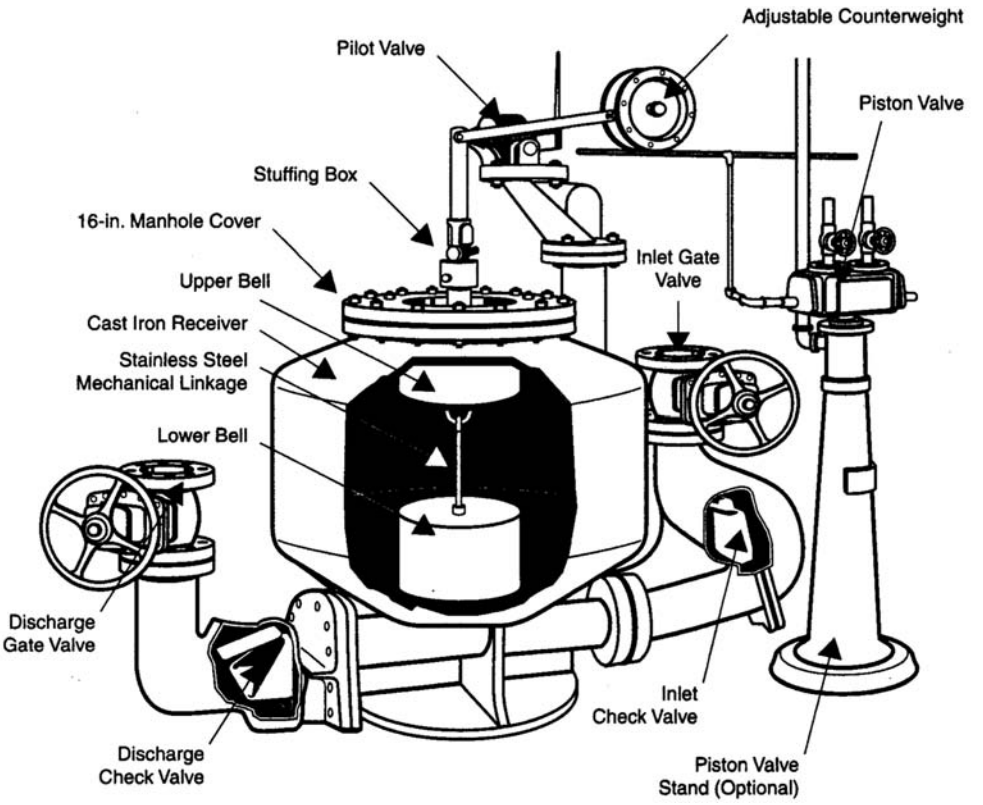


FIGURE 8.32 Pneumatic ejector (in × 25.4 = mm).

Preliminary Startup. Before starting a pneumatic ejector, operators should do the following:

1. Check, clean, and oil all external pivot points around upper bell rods, linkages, and level arms;
2. Confirm that all air, inlet, and discharge valves are still closed;
3. Open the gate valve on the air exhaust line at the piston valves; and
4. Open the inlet valve and half fill the injector pot.

If the counterweight tends to trip when the fluid enters, hold it up to allow the lower bell to fill with fluid. Then, close the inlet gate valve and balance the counterweight against the weight of the upper and lower bells. (This is the approximate loca-

tion for the counterweight when starting the ejector. Minor counterweight alterations may be necessary once the ejector is in full operation.)

Startup. To start up a pneumatic ejector, operators should do the following:

1. Allow compressors to build pressure to the required amount (the amount will depend on the head needed to convey fluid through the particular pumping system) and leave the controls in the "automatic" position.
2. Open the valve on the air pressure line.
3. Open the valve on the air exhaust line.
4. Open the valve on the discharge line.
5. Open the valve on the inlet line.
6. Close the inlet valve.
7. Bring the ejector up to full operation.

Shutdown. To shut down a pneumatic ejector, operators should do the following:

1. Close the inlet valve.
2. Hold down the counterweight to empty the injector receiver.
3. Close the discharge valve.
4. Close the air exhaust valve.
5. Close the air inlet valve.

Note that the valve in the air pressure line is the first to be opened for start-up and the last to be closed for shutdown.

Testing Procedures. There are several tests for pneumatic ejectors.

Inlet Check Valve Test. To test whether the inlet check valve is properly seated, close the discharge valve and allow the injector to fill and the air pressure to be applied as usual. If the ejector receiver empties—indicated by falling bells and rising counterweight—then the inlet check valve is malfunctioning.

Discharge Check Valve Test. To test whether the discharge check valve is properly seated, close the inlet valves, pull down the counterweight, and allow the ejector to empty. If it fills again—indicated by rising bells—then the discharge check valve is malfunctioning.

This test only applies when the discharge pipe can hold enough fluid to fill the ejector when it backflows. Otherwise, the ejector must be half or three-quarters full before the inlet valve is closed so the discharge pipe's content will be sufficient to fill the ejector.

Piston Valve Test. To test whether the piston valve is functioning properly, remove the heads and note whether the pistons move freely in both directions. (Do this only if the ejector receiver cannot be discharged and exhausted.)

Slide or Pilot Valve Test. To test whether the slide or pilot valve is functioning properly, close the inlet valve, move the piston valve's piston toward the exhaust end (closing the main pressure port), and turn on a little air. The 6-mm (0.25-in.) ports in one end of the piston valve should emit a blast of air. Then, move the piston toward the inlet end; the first blast should shut off, and the port in the other end of the piston valve should emit a blast of air. These blasts should alternate as the pilot valve lever is moved back and forth. (A little air may blow past the main piston on the pressure end because, with the heads removed, the piston retains less pressure than it would during actual operations.)

If the discharge pipe or pump is empty, the air may blow straight through the ejector into the discharge pipe. If the piston valves are positioned so the main pressure ports are open, the pressure would be insufficient to reverse the valve and close these ports, no matter which way the lever is moved. If this happens, leave the lever with the bell end down (the proper position if the ejector is empty and allows air to blow through). Quickly shut off the globe valve on the air pressure pipe. This typically reverses the piston valve. If it does not, close the inlet and discharge gate valves and allow air pressure to build up in the ejector. The valve will then reverse, cutting off the air. Open all valves, and repeat this process several times.

Upper Gear Assembly Cleaning. The ejector receiver should be blown out manually at least once a week to dispose of any accumulated scum, floatables, and solids. The easiest method is to hold down the counterweight for 2 minutes, clearing out all foreign matter from the ejector receiver.

If the counterweight sticks, remove the cotter pin from the upper bell rod and turn the nut to within one thread of the top. Then, tighten the lower nut against the trunnion. Doing this will postpone the need to completely disassemble the gear for about 6 to 8 months, depending on existing conditions.

When the counterweight sticks again, remove the gear assembly, clean the upper bell and the area around the receiver's throat, and reassemble.

PUMPING STATIONS

In this manual, a *pumping station* includes all the equipment, appurtenances, and structures needed to move a given fluid from one location to another (excluding the force main after it leaves the pump structure). Proper O&M of pumping systems should address all of these components, not just the pumps themselves.

Pumping stations typically include at least two pumps and a basic wet-well level control system. One pump is considered a "standby" pump, although the controls typically cycle back and forth during normal flows so they receive equal wear.

TYPES. Pumping stations can be configured in a wide variety of arrangements, depending on size and application. In this manual, pumping stations are classified based on whether the pumps and appurtenances are installed above, next to, or within the fluid being pumped. The classifications for such pumping-station configurations are: wet pit/dry pit, wet pit only/submersible pumps, and wet pit only/nonsubmersible pumps.

Wet Pit/Dry Pit. In this configuration, two pits (wells) are required: one to hold the fluid, and one to house the pumps and appurtenances. Required for fluids that cannot be primed or conveyed long distances in suction piping, this option is typically used to pump large volumes of raw wastewater, where uninterrupted flow is critical and wastewater solids could clog suction piping. It also is used to pump solids in pipe galleries between digesters or other solids-handling equipment. While construction costs may be higher and a heating, ventilation, and cooling (HVAC) system is necessary when installed below grade, this configuration is best for O&M activities because operators can see and touch the equipment.

Wet Pit Only/Submersible Pumps. In this configuration, one pit (well) holds both the pumps and the fluid being pumped. The pump impeller is submerged or nearly submerged in the fluid; no additional piping is required to convey the fluid to the impeller. This option is common worldwide, and the submersible centrifugal pumps involved can be installed and operated cost-effectively (Figures 8.33 and 8.34).

Wet Pit Only/Nonsubmersible Pumps. In this configuration, one pit (well) holds the fluid. The pumps are installed above the fluid, potentially at or above grade to prevent groundwater infiltration or other flooding. This option is used in areas where the fluid can be "pulled" through suction piping (e.g., treated or finished water) or where shutdowns or failures would not be immediately critical (e.g., a package plant's raw wastewater lift stations, equalization of secondary treated wastewater, and a utility's water systems).

PIPING AND APPURTENANCE REQUIREMENTS. The piping and appurtenance requirements for pumping stations typically include:

- Isolation valves for each pump;
- Check valves on the discharge side of each pump;

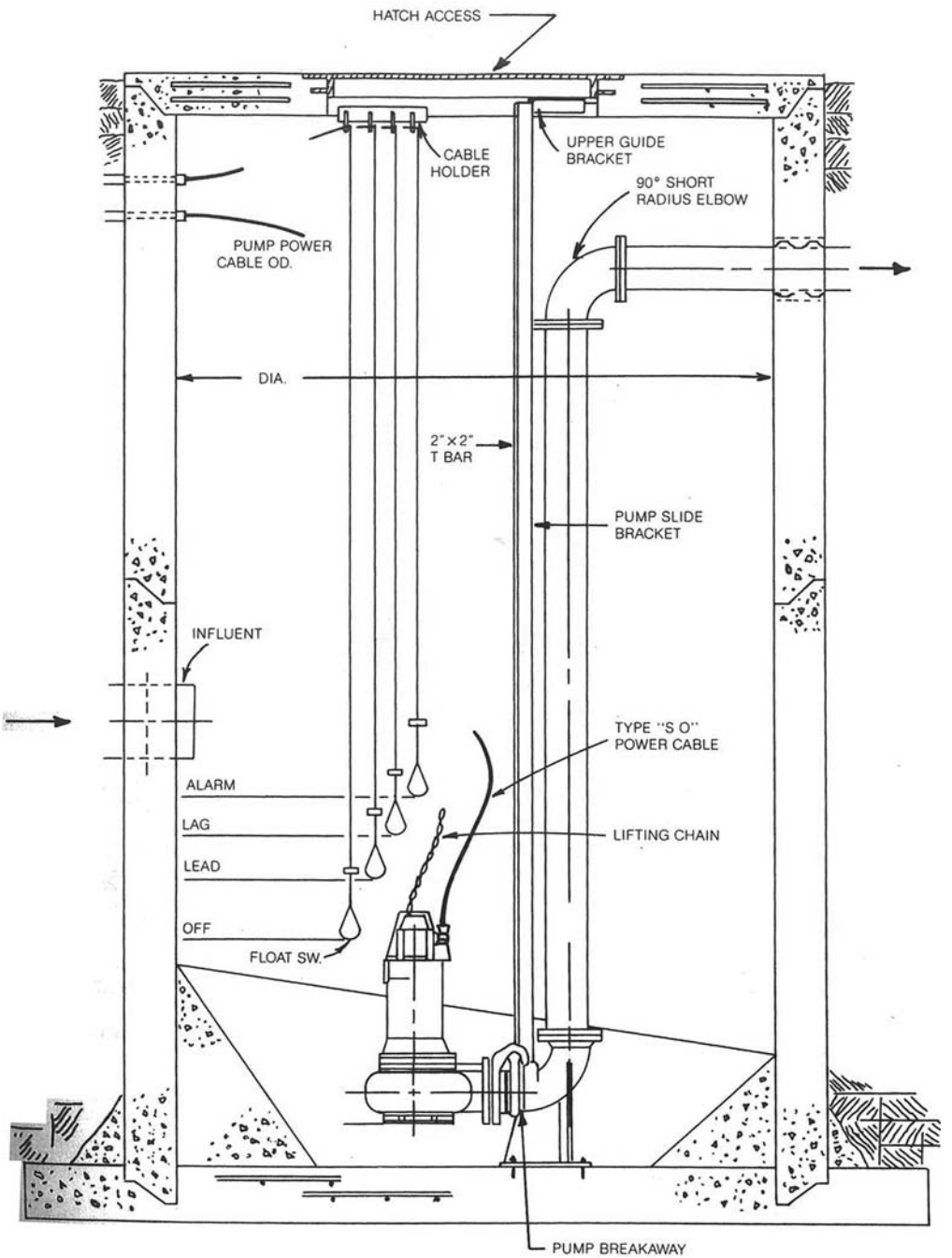


FIGURE 8.33 Typical submersible pumping station (in. × 25.4 = mm).

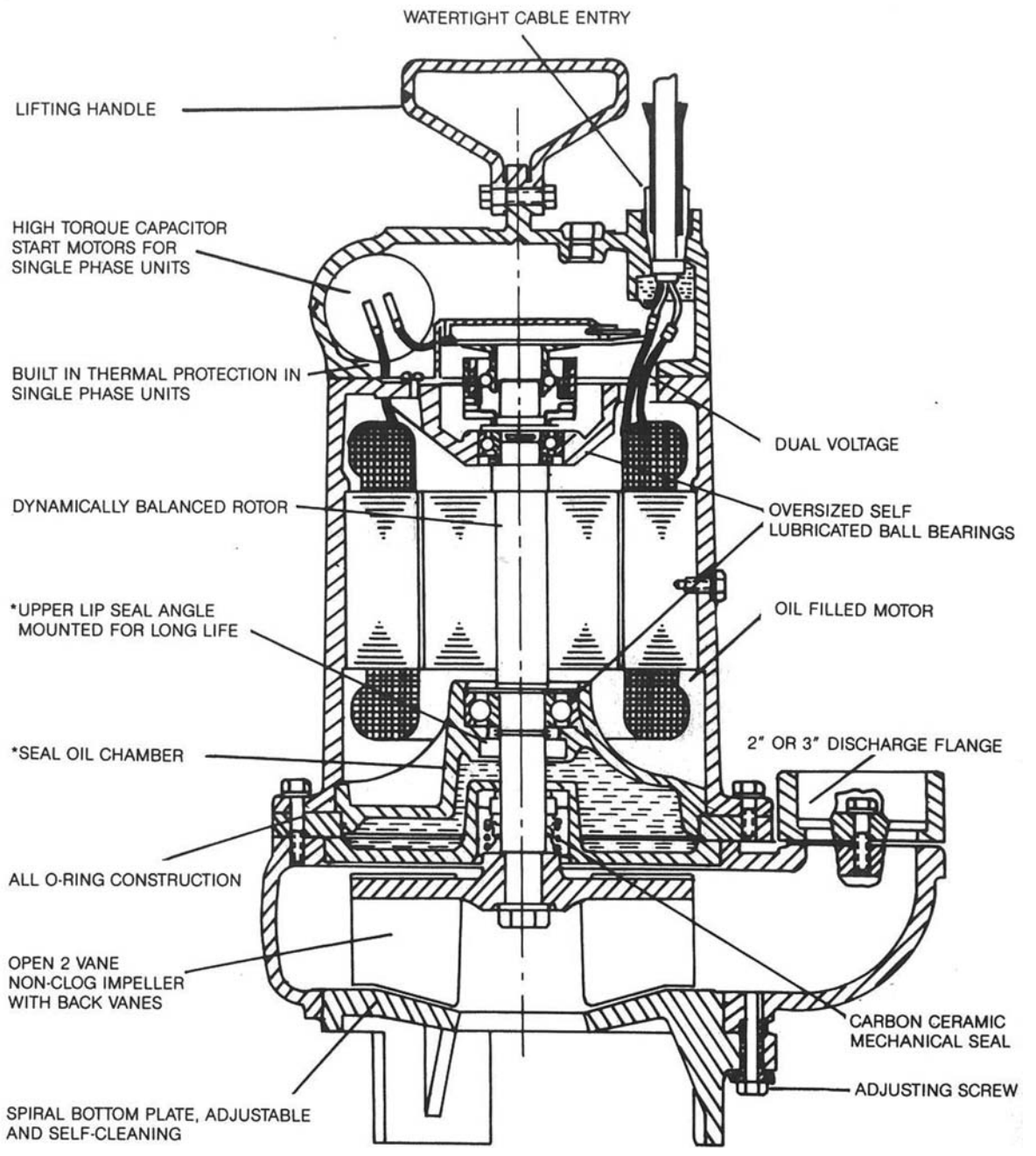


FIGURE 8.34 Typical submersible pump (in. × 25.4 = mm).

- Expansion joints where the pump connects to suction or discharge piping (to limit external loads on the pumps);
- Flow meter on the force main (to measure the pumping station's total pumped flow);
- Air-release valves (typically installed at high points along a pipeline to relieve high pressures);
- Vacuum-relief valves, which allow air to enter when the pipeline drains and prevent extremely low pressures from developing (used in areas where low pressures can cause the pipeline to collapse);
- Drains;
- Flushing system;
- Monitors; and
- Controls.

As part of a normal O&M program, operators should inspect each appurtenance to ensure that it is operating properly. "Frozen" isolation valves, for example, make pump removal more difficult. Malfunctioning check valves can increase operating costs by either impeding more flow or else leaking flow back to the wet well, thereby increasing pumping cycles.

PUMPING-STATION MAINTENANCE. A well-planned maintenance program for pumping systems can reduce or prevent unnecessary equipment wear and down-time. (The following maintenance information applies to both wastewater and solids pumping systems.)

Basic Maintenance. The following is a basic pumping-station maintenance checklist:

- Check the wet-well level periodically (preferably once a day, or more frequently when high flows are expected).
- Record each pump's "run time" hours (as indicated on the elapsed-time meters) at least once in that period and check that the pumps' running hours are equal.
- Ensure that the control-panel switches are in their proper positions.
- Ensure that the valves are in their proper positions.
- Check for unusual pump noises.
- At least once a week, manually pump down the wet well to check for and remove debris that may clog the pumps. [Follow the proper safety precautions (Chapter 5).]

- Inspect the float balls and cables and remove all debris to ensure that they operate properly. Untangle twisted cables that may affect automatic operations.
- If a lift-station pump is removed from service, adjust the lead pump selector switch to the number that corresponds to the pump remaining in operation. (This allows the lead pump levels to govern the operating pump's starts and stops.)
- Periodically inspect the pump-sequencing and alarm control functions as follows:
  1. Adjust each pump's H/O/A selector switch to "off" (O).
  2. Fill the wet well until the "high level" alarm is activated.
  3. Adjust each pump's H/O/A selector switch to "auto" (A). The pumps should start up sequentially. (If they start up simultaneously, insert short time delays between startups in the control algorithm.)
  4. Allow all three pumps to operate automatically. When the fluid level drops to the "low level" setpoint, shut off all the pumps.
  5. Fill the wet well until the lead pump starts, then shut off the fluid. Allow the pump to lower the fluid level until it shuts off.
  6. Again, fill the wet well until the second pump starts, then shut off the fluid. Allow the pump to lower the fluid level until it shuts off.
  7. Repeat this procedure for all pumps.
  8. Double-check that all three pumps' H/O/A selector switches are set to "auto" (A).

Startup. To start up a pumping station, operators should:

1. Turn off the local controls;
2. Turn on the main motor control center breaker;
3. Turn on the local controls for the main, all pumps, and the transformer;
4. Fully open each pump-discharge valve in the valve vault;
5. Fully close the pumpout bypass connection (if any);
6. Adjust the H/O/A selector switch or each pump to "hands" (H) and monitor pump operations for a short period (approximately 10 minutes, but make sure that the wet well does not pump empty);
7. Adjust the H/O/A selector switch to "auto" (A);
8. Repeat steps 6 and 7 for each pump; and
9. Adjust the lead selector switch to the desired position (1/auto/2). (Typically, the position would be "auto".)

To check for proper pump sequencing and level alarm functions, fill the wet well with fluid and monitor the system operations.

Shutdown. To shut down a pump, operators should:

1. Adjust its H/O/A selector switch to "off" (O);
2. Adjust the lead selector switch to the number corresponding to the pump(s) remaining in operation;
3. Place the pump's local disconnect switch to "off" (O);
4. Close its discharge valve; and
5. If repairs are necessary, have maintenance personnel remove the pump from the wet well.

PIPING AND APPURTENANCE MAINTENANCE. Properly maintaining pumping-station pipelines, valves, and other appurtenances can minimize pump loads. Excessive head losses on either the suction or discharge side of a pump can increase energy use and the wear rate and, therefore, the O&M costs. Excessive head losses also may lead to process or treatment problems because solids move slower, so the proper solids balance is not maintained. Operators can monitor head losses by routinely checking the pressure gauges on both sides of the pumps.

Piping. When operators notice excessive head losses (indicated by a pressure drop on the suction side of the pump or an increase in pressure on the discharge side), they should determine whether the losses are a result of partial clogging, a restriction somewhere in the line, or materials built up on the pipe wall. To find clogs, operators should start by checking the pressure at various points in the suction and discharge piping, looking for spots with abrupt head loss (e.g., valves or other constrictions). If something is caught in a valve or other appurtenance, backflushing with high-pressure water may remove it. Solids pumping systems typically have flushing systems to help with the O&M of pumps, appurtenances, and pipelines.

If backflushing fails, operators may need to dismantle the piping at the clog site. If this spot clogs repeatedly, it may be prudent to replace the valve or other appurtenance with one less prone to obstructions. (Manufacturers or design engineers typically can recommend a suitable replacement.)

The gradual buildup of scum, grease, or other materials in pipelines can be difficult to dislodge mechanically or chemically. If such buildups are persistent, operators should develop a routine procedure for anticipating and removing them before they disrupt operations. Pipes lined with glass or polytetrafluoroethylene are less prone to buildups, but most plants do not uses such piping. (If the plant does have glass- or polytetrafluoroethylene-lined pipe, operators should be careful not to damage the lining when mechanically removing deposits.)

Scum deposits can be removed from pipes via chemical washing or mechanical scraping. Chemical solutions (e.g., alkaline detergent mixtures) should be pumped into the pipeline and allowed to dissolve scum or grease over hours (or days, if necessary). They typically work best when hot. Afterward, depending on the chemical and downstream process involved, the chemical may have to be drained from the line before the line can be returned to service. (To determine the appropriate handling and disposal requirements, operators should ask suppliers or review the chemical's material safety data sheet.)

Mechanically scraping pipes is a last resort. It typically involves removing the pump from service and draining the piping.

Scum buildup problems typically are addressed via source control (e.g., installing grease traps in the collection system at locations suspected or known to generate grease—restaurants, etc.).

[Note: If the utility's pipes are not color coded, operators should establish a color-code system to simplify operator training and reduce the possibility of discharging solids, wastewater, or other substances into the wrong process unit. They also should stencil directional arrows on the pipes and note what the contents are and where they are going (e.g., "Raw Primary Sludge to Thickener No. 1").]

Valves. Valves should be lubricated regularly (per the manufacturer's instructions), and the valve stems should be rotated regularly to ensure ease of operation. These activities should be part of a regular pump-maintenance program.

A solids pump's flushing system should include a connection on the upstream side of the valve (or gate plunger in diaphragm pumps) so high-pressure water is available to wash out debris caught in the ball checks. Even if flushing is unsuccessful, it will clean solids from the pump before the access ports are opened.

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Chapter 9

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INTRODUCTION

This chapter focuses on the operation and maintenance of equipment used in the handling, storage, and feeding of chemicals for wastewater treatment. Chapter 24, Physical–Chemical Treatment, describes some specific uses of chemicals to improve wastewater treatment. Chemical addition must be evaluated for each specific treatment process while considering its potential effect on downstream treatment units and effluent toxicity. The procedures for choosing chemicals and chemical dosages are discussed under specific treatment processes in other chapters of this manual, in *Design of Municipal Wastewater Treatment Plants* (WEF and ASCE, 1998) and in *Control of Odors and Emissions from Wastewater Treatment Plants* (WEF, 2004).

CHEMICAL APPLICATION SYSTEMS

All chemicals, whether solid, liquid, or gas, require a feeding system to accurately and repeatedly control the amount applied. Effective use of chemicals depends on accurate dosages and proper mixing. The effectiveness of certain chemicals is more sensitive to dosage rates and mixing than that of others. The design of a chemical feed system must consider the physical and chemical characteristics of each chemical used for feeding, minimum and maximum ambient or room temperatures, minimum and maximum wastewater flows, minimum and maximum anticipated dosages required, and the reliability of the feeding devices. Chemical feed systems typically consist of transferring the chemical from the supplier to the plant storage area, storing the chemical, mixing the chemical with water (occasionally not done), and calibrating the chemical/solution feed rate.

The capacity of the system, potential delivery delays, and chemical use rates are important considerations in both storage and feeding. Storage capacity must take into account the economical advantages of bulk quantity purchases versus the disadvantages of construction cost, spill potential, and chemical degradation with time. Smaller shipments generally result in higher unit chemical costs, increased transportation costs, and greater handling (labor) costs at the treatment plant facility. However, bulk storage and feeding facilities typically require more equipment and/or larger equipment, resulting in higher costs associated with construction and operation of the facility. Storage tanks or bins for solid chemicals must be designed to allow the correct angle of repose of the chemical and to provide its necessary environmental requirements, such as temperature and humidity. Size and slope of feeding lines are important considerations. The selection of materials used for construction of storage tanks, feed equipment, pumps, piping, and valves are also extremely important because many chemicals are corrosive to many materials.

Chemical feeders are sized to meet the minimum and maximum feeding rates required. Manually controlled feeders typically have a common feed turndown range of 10:1 that can be increased to approximately 20:1 with dual-control systems. To provide operational flexibility, the operator should consider future design conditions when selecting the appropriate ranges for chemical feed rates. A common problem is not being able to adjust the pump to low enough feed rates. Chemical feeder control can be manual, automatically proportioned to flow, or dependent on a process parameter (such as pH). A combination of any two of these can also be used. If manual control systems are specified with the possibility of future automation, the feeders selected should be convertible with a minimum of expense. Standby or backup units are generally desirable but may not be necessary for each type of feeder used unless required by the regulating authority. The location and sizing of the chemical feed addition should provide sufficient operational flexibility for potential changes in wastewater quality. Designed flexibility in hoppers, tanks, chemical feeders, and solution lines is the key to maximum benefits at the least cost.

Because dry chemical characteristics vary considerably, the feeder must be selected carefully, particularly in a smaller-sized facility where a single feeder may be used for more than one chemical. Overall, the operator should make provisions to keep all dry chemicals cool and dry. Maintaining a low humidity is particularly important, as hygroscopic (water absorbing) chemicals may become lumpy, viscous, or even rock hard. Other chemicals that absorb water less readily become sticky from moisture on the particulate surfaces, causing increased bridging in hoppers. Typically, only limited quantities of chemical solutions should be made from dry chemicals at any one time because the shelf life of the diluted chemical, especially polymers, may be short. The operator should consult the chemical supplier about the recommended shelf life for each particular chemical and/or chemical solution.

The operator should keep dry chemical handling areas and equipment as dry as possible. Otherwise, moisture will affect the chemicals' density and may result in underfeed. Also, the effectiveness of dry chemicals, particularly polymers, may be reduced. Dust-removal equipment should be used at shoveling locations, bag dump stations, bucket elevators, hoppers, and feeders for neatness, corrosion prevention, and safety reasons. Collected chemical dust may often be used with stored chemicals.

SAFETY CONSIDERATIONS

Many chemicals used in wastewater treatment plants can be extremely hazardous when not stored, handled, or used properly. Plant operators should always check with state regulatory and local emergency management agencies for reporting and plan development requirements. Federal regulations require that a material safety data sheet

(MSDS) be available to employees. The MSDS provides information on the chemical, including hazards and safety procedures to be used when handling it. The MSDS should be kept in the area where the chemical is used and also on file in a central location at the plant. Operators must use the correct safety equipment and follow the safe handling procedures described in the MSDS. This would include using personal protective equipment such as face shields, eyewear, and protective clothing. Further, the plant should be adequately equipped with emergency eyewashes and showers, dust suppression equipment (for dry chemical systems), and secondary containment structures (for liquid chemical or solution systems).

Table 9.1 presents a summary of the physical properties and the principal safety considerations for handling chemicals typically used in a wastewater treatment plant. Table 9.2 summarizes uses, feed-system types, operating considerations, and other precautions for those same chemicals. For complete instructions, the operator should consult the MSDS for a specific chemical.

RISK MANAGEMENT

Some gaseous chemicals such as chlorine, sulfur dioxide, or ammonia are hazardous if released to the atmosphere. Compliance with all federal, state, and local regulations is required for the storage of certain chemicals and reporting procedures involved with spills, leaks, and disposal of chemicals. The U.S. Environmental Protection Agency's (U.S. EPA's) Risk Management Program (RMP) rule is specifically concerned with the accidental release of hazardous compounds. The rule was required as part of the Clean Air Act amendments of 1990 (Section 112r) (Prevention, 2002) and requires facilities to identify hazards and manage risks. Both the U.S. EPA and the Occupational Safety and Health Administration (OSHA) have similar regulations for the prevention of hazardous chemical release. The U.S. EPA's RMP generally addresses the protection of public health and the environment, whereas OSHA's Process Safety Management standard is intended for employee protection from chemicals in the workplace (29 CFR 1910.119) (Occupational, 2003).

U.S. EPA's RMP applies to wastewater facilities with processes using chemicals stored above certain threshold quantities. A facility that handles, produces, or stores any of the chemicals indicated in Table 9.3 equal to or above the regulated threshold limits is likely subject to all provisions of the rule. For a complete list of regulated toxic substances and threshold quantities for accidental release prevention, consult 40 CFR 68.130 (Tables 1 through 4) (List, 2003).

If these thresholds are exceeded, the facility operator must document serious accidents (five-year history), analyze worst-case chemical releases, contact and coordinate

TABLE 9.1 Wastewater treatment chemicals—physical properties and safety considerations.

Chemical name	Synonyms	Physical properties	Safety considerations
Ammonia	Anhydrous ammonia	Boiling point = –33.4 °C (–28.1 °F) highly soluble in water. LEL[a] = 15%, UEL[b] = 28%. Ammonia gas is lighter than air. Colorless gas with pungent, suffocating odor.	Contact with liquid causes severe burns. Extremely irritating to eye and lung tissue. Highly reactive with chlorine, acids. Odor is detectible at 5 ppm, irritating at 25 to 50 ppm. Moderate fire hazard. Ammonia in air and ammonia with chlorine are potential explosion hazards.
Chlorine		Poisonous, reactive, greenish-yellow gas. Boiling point = –34 °C (–29 °F). Slightly soluble in water. Chlorine gas is heavier than air.	Chlorine reacts with moisture to form acids. Very irritating and corrosive to eyes, mucous membranes, and teeth. Acute respiratory distress and asphyxiation can result from exposure. Reacts with many materials to cause fires and explosions.
Chlorine dioxide		Red-yellow or orange gas with a pungent odor. Oxidizer, bleaching agent. Boiling point = 10 °C (50 °F).	Irritates respiratory system. Avoid inhaling. Will damage eyes. Inhalation poison. Violently reacts with organic matter. Explosion hazard. Unstable in sunlight.
Defoamers	Antifoam agents	Many commercial products available. Properties vary.	Some antifoam agents may be corrosive or flammable. Avoid contact with eyes and skin. Avoid breathing vapors.
Ferric chloride	Iron trichloride, ferric trichloride, ferric perchloride	Available in solid and liquid solution; sp gr of solution, 1% = 1.0084; 45% = 1.487. Very soluble in water. Solutions above 33% will crystalize.	Corrosive liquid. Avoid contact with eyes and skin. Moderately toxic. Inhalation of mist will irritate throat and upper respiratory tract. Releases large amount of heat when anhydrous solid is diluted with water.
Ferric sulfate	Iron sulfate	Corrosive in liquid solution.	Avoid contact with eyes and skin.

TABLE 9.1 Wastewater treatment chemicals—physical properties and safety considerations (*continued*).

Chemical name	Synonyms	Physical properties	Safety considerations
Hydrochloric acid	Muriatic acid, hydrogen chloride, chlorohydric acid	Normally available as a solution in concentrations of 31% and 35%; sp gr of solutions are 31% = 1.16 and 35% = 1.18. Highly volatile liquid. Gas vapor is heavier than air.	Highly corrosive liquid and gas. Avoid contact with skin, eyes, and especially respiratory systems. Hydrochloric acid is detectable at 0.1 to 5 ppm, irritating at 5 to 10 ppm. Highly reactive. Liberates potentially explosive hydrogen gas or chlorine gas at high temperatures or on contact with metals. Incompatible with concentrated sulfuric acid.
Hydrogen peroxide	Peroxide, hydrogen dioxide	Boiling point of pure liquid = 151 °C (304 °F). Very reactive and potentially unstable. Powerful oxidizer and corrosive. Available commercially in 30, 35, 50, and 70% solutions. Typically stored in concentrations of 50% or less; sp gr of solutions are 30% = 1.112 and 50% = 1.196.	Irritates skin, eyes, and mucous membranes. Avoid breathing mist. Highly reactive. Incompatible with most metals and organic material. Dangerous fire and explosive hazard in higher concentrations. Dust or metal contamination of solutions can result in violent decomposition and potential failure of storage tank.
Lime	Calcium hydroxide, hydrated lime, calcium oxide, quicklime	Solid, white powder with bitter taste. Slightly soluble in water. Dry form of quicklime has great affinity for water and liberates large amount of heat when mixed.	Irritating to skin and lungs. Dust problem can result from handling solid. Use dust mask and goggles.
Ozone	Triatomic oxygen	Colorless gas with a boiling point = –112 °C (–169 °F).	Oxidizing agent, irritant and toxic. Can irritate eyes, mucous membranes, and respiratory system. ACGIN TWA = 0.1 ppm in air. Odor detectible at 0.01 ppm. Incompatible with oils and other combustible materials. Can intensify fires.

Polymers	Anionic, cationic, non-ionic polymers,	Many available in dry and concentrated forms.	Some polymers are corrosive in water. Some are extremely viscous and slippery. Avoid contact with eyes and skin. Use caution when preparing solutions.
Potassium permanganate	Permanganate of potash	Strong oxidant with a characteristic purple color. Bulk density of between 90 and 100 lb/cu ft.[c]	Toxic. Suspected poison. Can react with organics, peroxides, and sulfuric acid. Can form chlorine when in contact with hydrochloric acid. Avoid contact with eyes and skin. Avoid breathing dust. Can react violently and explosively with organic materials. Contact with wood may cause a fire.
Sodium bisulfide	Sodium hydrogen sulfide, sodium hydrosulfide, sodium sulfhydrate	White to yellow flakes with hydrogen sulfide odor (rotten eggs).	Irritates eyes, skin, and mucous membranes. Avoid contact, especially with eyes. Contact with acids will generate toxic hydrogen sulfide gas.
Sodium hydroxide	Caustic, caustic soda, soda lye	Available in dry solid and solution. Melting point of 50% solution = 11.6 °C (53 °F); sp gr of 50% solution = 1.53.	Very corrosive to body tissues. Avoid inhaling dust or mist. Mixing with water can release large quantities of heat. Incompatible with acids and some metals such as tin, zinc, and especially aluminum.
Sodium hypochlorite	Chlorine bleach	Pale-yellow or greenish liquid solution with chlorine odor. Available in 5%, 10%, and 15% solutions.	Strong oxidizer and corrosive to eyes and mucous membrane tissues. Avoid contact with eyes and skin and avoid breathing fumes and mist. Decomposes to chlorine and sodium oxide when heated. Incompatible with acids, ammonia, organics, and some metals. Store out of direct sunlight.

TABLE 9.1 Wastewater treatment chemicals—physical properties and safety considerations (*continued*).

Chemical name	Synonyms	Physical properties	Safety considerations
Sulfur dioxide	Sulfurous anhydride, sulfurous oxide	Colorless gas with strong suffocating odor. Boiling point = –10 °C (14 °F). Heavier than air.	Gas is irritating to mucous membranes and toxic. Inhalation poison. Odor detected at 0.5 pm. OSHA[d] TWA limit of 2 ppm. Avoid breathing. Will form an acid mist with water vapor.
Sulfuric acid	Hydrogen sulfate, vitriol, oil of vitriol	Colorless, clear, oily liquid. Available in several concentrations but typically used as 93% solution; sp gr of 93% solution is 1.834.	Highly corrosive. Can burn and char skin when exposed. Especially harmful to eyes. Releases a large amount of heat when diluted with water. Can react with organics, chlorates, permanganates, fuminates, or powdered metals, causing fires or explosions.

[a]LEL = lower exposure limit.
[b]UEL = upper exposure limit.
[c]lb/cu ft × 16.02 = kg/m^3.
[d]OSHA = Occupational Safety and Health Administration.

TABLE 9.2 Wastewater treatment chemicals—operating considerations.

Chemical name	Uses	Feed system type	Operating considerations	Other comments
Ammonia	Nutrient addition, disinfection	Gas	Handle cylinders with care. Ventilate top of storage rooms.	Never use copper or brass in ammonia service. Iron or steel is satisfactory.
Chlorine	Disinfection, taste and odor control	Gas	Store chlorine containers in a cool, dry, well-ventilated area. Use care when handling chlorine containers.	Use rag dipped in ammonia water to detect leaks. Do not put water directly on a leak.
Chlorine dioxide	Disinfection	Gas	Typically generated on site.	
Defoamers	Controlling foaming in activated sludge systems or in ponds	Liquid		
Ferric chloride	Sludge conditioning, coagulation, phosphorus removal	Solid or liquid		Corrosive to most metals, especially aluminum, copper, and carbon steel, and to nylon.
Ferric sulfate	Coagulation, phosphorus removal	Solid		
Hydrochloric acid	Neutralization	Liquid		Iron or steel is not satisfactory in hydrochloric acid service.
Hydrogen peroxide	Odor control, supplemental dissolved oxygen, control of bulking	Liquid	Store in cool area. Keep away from combustible materials.	Iron and steel are unsatisfactory in hydrogen peroxide service. Avoid copper. Stainless steel, aluminum, and some plastics perform well.
Lime	Coagulation, pH adjustment, sludge conditioning, phosphate removal	Solid	Lime slakers produce large amounts of heat and must be watched carefully for excessive heat buildup. Absorbing water can cause caking or swelling.	

TABLE 9.2 Wastewater treatment chemicals—operating considerations (*continued*)..

Chemical name	Uses	Feed system type	Operating considerations	Other comments
Ozone	Odor control, disinfection	Gas	Typically generated on site.	
Polymers	Coagulant, filter aids, sludge conditioning	Solid or liquid		Iron or steel typically are not satisfactory.
Potassium permanganate	Taste and odor control, iron removal	Solid	Do not store in open containers. Avoid mixing with combustible materials.	Contact with wood can cause fire.
Sodium bisulfide	Dechlorination, chromium treatment, pH control, bactericide	Solid	Reacts with acids to form hydrogen sulfide gas, which is both flammable and toxic.	
Sodium hydroxide	pH control, odor control, cleaning	Liquid	Concentrated caustic freezes at high temperatures. Plugged or frozen caustic lines increase risk of exposure.	Do not use near aluminum. Galvanized piping is not suitable for caustic service.
Sodium hypo-chlorite	Disinfection, odor control	Liquid	Can decompose in storage. Keep away from light and heat.	
Sulfur dioxide	Dechlorination, pH control, chrome reduction	Gas	Will reliquify in system piping if allowed to cool.	Can be more corrosive than chlorine if wet at elevated temperatures.
Sulfuric acid	pH control	Liquid	Store in dry containers.	Iron and steel is permissible in concentrated sulfuric acid service, but dilute sulfuric is very corrosive to steel.

TABLE 9.3 Partial list of regulated toxic substances and threshold quantities for accidental release prevention.

Chemical name	Chemical abstracts service (CAS) no.	Threshold quantity (lb)
Chlorine	7782-50-5	2500
Ammonium (anhydrous)	7764-41-7	10 000
Ammonia (aqueous with concentration 20% or greater)	7764-41-7	20 000
Sulfur dioxide (anhydrous)	7446-09-5	5000
Propane	74-98-6	10 000
Methane	74-82-8	10 000

local emergency response personnel, and submit a RMP to governmental agencies, state emergency response commissions, and local emergency planning committees. A prevention program within the RMP includes the identification of hazards, documented operating procedures, training programs for personnel, maintenance requirements, emergency response programs, and complete accident investigation. When storing more than a specific quantity of gaseous chemicals such as chlorine or sulfur dioxide, requirements for secondary containment and emergency scrubber systems should be considered to prevent or minimize the spread of chemical releases. Emergency response procedures should be developed in cooperation with local emergency officials. Federal regulations require that local emergency planning agencies be notified when specific amounts of certain chemicals are stored (see Chapter 5, Occupational Safety and Health, for further discussion).

UNLOADING AND STORING CHEMICALS

Special precautions are necessary for the safe unloading and storage of chemicals. Because a complete discussion of these precautions would be impractical, the operator must obtain such information directly from the chemical manufacturer or supplier for each chemical storage and handling system within the treatment plant.

UNLOADING CHEMICALS. In general, chemicals are delivered to a wastewater treatment plant in dry, liquid, or gaseous form. Liquid chemicals can be in various combinations of phases and viscosity. For instance, liquid polymers are available in single-phase liquids, multiphase emulsions, Mannich (a special type of highly viscous solution polymer), and gel. Chemicals are also delivered in a variety of containers, in-

cluding bags, drums, totes, cylinders (gas), ton containers, bulk trucks, and railroad tank cars. Dry chemicals are generally available in either bagged, drummed, mini-bulk, or bulk form. Mini-bulk includes super sacs or bulk bags. When daily requirements are small, bagged chemicals are preferred because their handling and storage are relatively simple, involving either manual labor or mechanical handling. Bagged chemicals, delivered either in loose bags or on pallets in trucks or boxcars, are transferred to storage by hand lifts or forklift. For loose bags, conveyors may be used if there is a long distance between the unloading point and the storage area. For bag shipments on pallets, using a forklift to move the loaded pallets to storage and then to the point of use reduces the manual labor. Drums contain more chemical (typically approximately 181 kg [400 lb] per drum) than bags but are more difficult to handle. Mechanical drum movers and dumpers are available and can be used were chemical is received in drum form.

For intermediate usage rates and where chemicals can be purchased in mini-bulk form, super sacs or bulk bags can be used to reduce the amount of manual labor involved. Mini-bulk containers typically contain 907 kg (1 ton) of chemical, which equals approximately forty 23-kg (50-lb) bags. Feed equipment for mini-bulk containers generally includes support frames to hold the container above the feeder and valves on the bag and/or feeder to control the flow of chemical into the feeder. In addition, forklifts generally are used to move the bags to and from storage and to lift the bag into a support frame located over the feeder. Therefore, forklift access to the feeder through adequately sized aisles and/or roll-up doors is required. Even though the cost of feed equipment and operating space requirements can be somewhat more for mini-bulk containers than for bags or drums, the amount of manual labor required for chemical handling can be reduced.

Bulk shipments of dry or liquid chemicals are delivered in trucks or by rail in boxcars and hopper cars. Bulk unloading facilities typically must be provided at the treatment plant. Rail cars constructed for top unloading will require an air-supply system and flexible connectors to pneumatically displace the chemical from the car. Bottom unloading can be accomplished by using a transfer pump or a pneumatic transfer system. The U.S. Department of Transportation (U.S. DOT) regulations concerning chemical tank car unloading should be observed.

Bulk unloading areas should be arranged to contain the chemical for recovery, neutralization, or disposal in case of a spill. Spill control measures such as spill booms and mats, neutralization chemicals, and waste disposal drums should be readily available near the unloading area. Special training is required for operators responsible for spill response. All unloading areas should be level and allow tank trucks to pull away in a forward direction. Pavement design for heavier truckloads may require the use of concrete for roads and the unloading area. In addition, consideration must be given to

appropriate truck turning radius. Before any unloading operation, the operator should verify that the storage tank will hold the contents of the tank car or tank truck and that the tank is well vented. When transferring with air, an air surge will occur at the end of the product transfer, so it is important to have properly sized relief vents. Level indication at the unloading station is highly recommended to help the operator monitor the filling operation and avoid overfilling a bulk tank. Generally, a quick-disconnect should be provided at the unloading station for connection to the supply hose from the chemical tank car or truck. Consulting with the chemical vendor will help the operator determine the type and size of quick-disconnect needed to simplify the chemical transfer.

Properly trained employees must supervise all unloading operations. If the operator must leave the transfer operation, the operation should be shut down. The operator must use protective eyewear, gloves, and clothing during the unloading operations. Emergency showers and eyewashes should be adjacent to the unloading station area and tested at least monthly for proper operation. In addition, smoking should not be allowed in any chemical unloading area, and unloading should be done during daylight hours unless adequate lighting is provided for nighttime unloading operations.

Both U.S. DOT and the U.S. Coast Guard classify chlorine, ammonia, and sulfur dioxide as nonflammable compressed gases. As such, when shipped in the United States by rail, water, or highway, they must be packaged in containers that comply with both U.S. DOT and U.S. Coast Guard regulations regarding loading, handling, and labeling.

Chlorine gas is commonly available in 45- and 68-kg (100- and 150-lb) steel cylinders; in 907-kg (1-ton) steel containers; and (for large quantities) in railroad tank cars, tank trucks, or barges. *The Chlorine Manual* (The Chlorine Institute, Inc., 1986) addresses in detail the appropriate loading and handling of chlorine containers.

Various mechanical devices, such as skids, troughs, and up-ending cradles, simplify handling of 68-kg (150-lb) chlorine cylinders. When unloaded from trucks or platforms, cylinders must not be dropped to ground level. If cylinders must be lifted or lowered and an elevator is not available, specially designed cradles or carrying platforms in combination with a crane or derrick are recommended. Chains, lifting magnets, and rope slings that encircle the cylinders are unsafe and should not be used. For lateral movements, a properly balanced hand truck is useful. Cylinders being moved should always have valve-protection hoods in place. Because these hoods are not designed to hold the weight of cylinders and their contents, the cylinders should never be lifted by their hoods.

Ton containers may be moved by various methods, including rolling, a crane hoist monorail system, or by specially fitted trucks or dollies. When it is necessary to lift

them, as from a multiunit railroad car or truck, it is good practice to use a suitable lift clamp or lifting beam in combination with a hoist or crane with at least a 1814-kg (2-ton) capacity.

Receiving and unloading areas and safety precautions applicable to handling single-unit railroad tank cars, tank trucks, or other shipping containers are subject to federal, state, and local regulations.

STORING CHEMICALS. The equipment used for storing and handling chemicals varies with the type of chemical used, form of the chemical (liquid or dry), quantity of chemical, and plant size.

Storage tanks and vessels must be labeled to show their contents. Each tank and/or storage area should be clearly labeled indicating both the contents and the National Fire Protection Association (NFPA) Hazard Identification System (National Fire Protection Association, 2001).

The layout and design of a chemical storage area must comply with all local codes and ordinances. Storage areas for chemicals should be clean, temperature controlled, properly ventilated, and protected from corrosive vapors. In some cases, humidity control also may be necessary, especially with dry chemicals. Cylinders and ton containers should be stored in a fire-resistant building away from heat sources, flammable substances, and other compressed gases. Storage and use areas should be equipped with suitable mechanical ventilators for normal occupancy and proper controls and leak-detection equipment to contain and hold extremely hazardous gases. State and local ordinances that have adopted all aspects of the NFPA guidelines will require scrubbers. Additional discussion regarding chlorine and sulfur dioxide emergency gas scrubbers is presented in Chapter 26, Effluent Disinfection. Sulfur dioxide scrubbers are similar to those used for chlorine. At some locations, secondary containment of individual bulk containers can be provided in place of scrubbers. In all cases, however, it is always a good practice to equip gas storage areas with proper ventilation control (i.e., normal ventilation is terminated when a leak is detected) and emergency gas scrubbing equipment (typically sized to neutralize the largest single container). Cylinders and ton containers should not be stored outdoors. Both local and remote alarms should be provided to alert the operator of any potential leak of chemicals such as chlorine, sulfur dioxide, and ammonia in both storage and use areas.

Bulk Storage. Figure 9.1 presents a typical packaged-type bulk-storage tank (or bin) for dry chemicals. Dust collectors should be provided on both manually and pneumatically filled tanks. Airborne chemical dust is not only hazardous to employee health, but also may be an explosion hazard. The construction material for the storage tank

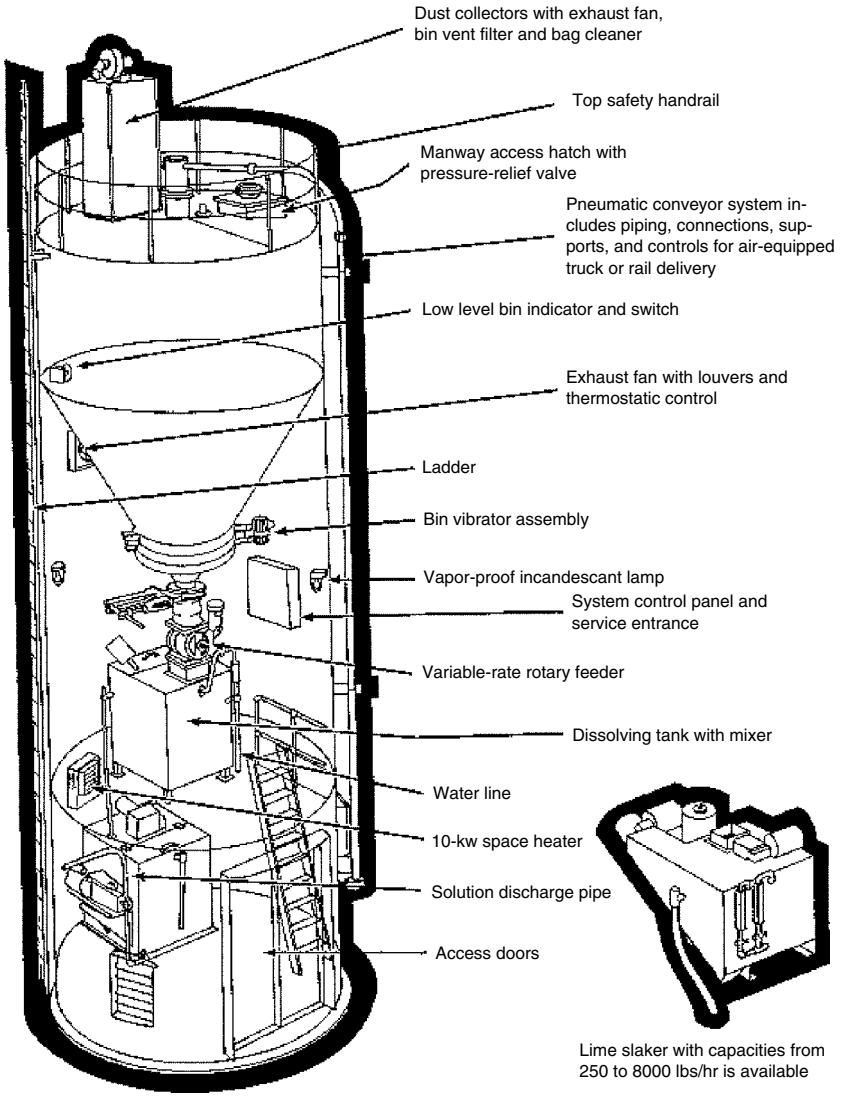


FIGURE 9.1 Typical packaged-type bulk storage tank and accessories (lb/h × 0.453 6 = kg/h) (National Lime Association, 1995).

and the required slope and baffling at the outlet may vary with the type of chemical stored. Some dry chemicals, such as lime, require airtight bins to reduce the potential for moisture within the storage vessel. Bulk storage tanks for dry chemicals are often equipped with bin vibrators to lessen chemical bridging in the storage vessel.

Bulk-storage tanks for liquid or dry chemicals should be sized according to normal (average) chemical feed usage rates, shipping time required, and quantity of shipment. The total storage capacity should be at least between 1.25 and 1.5 times the largest anticipated supplier shipment and should provide at least a 15- to 30-day supply of the chemical at the design average usage. Gas storage areas also should be sized to accommodate a sufficient number of cylinders and bulk containers to provide similar supply volumes based on average chemical feed usage rates. In many cases, the minimum number of storage days is dictated by regulatory requirements. Storage tanks for most liquid chemicals can be either inside or outside. However, outdoor tanks must be insulated or heated or both if the chemical can crystallize or become sufficiently viscous to impede chemical flow at the minimum ambient temperature for that specific geographic location. In addition, outdoor tanks should be constructed of materials that are resistant to both deterioration from ultraviolet (UV) light and cracking because of wide variations in external temperatures. All liquid storage tanks must have an air vent to avoid excessive pressure or vacuum in the tank. Vents for chemical systems should be carefully located so that air ventilation intakes are not affected. In addition, the vent should not be in an area that can be routinely accessed by personnel. Some liquids, such as hydrochloric acid with a vent scrubber, also should have a pressure- and/or vacuum-relief valve or system to protect the tank from excessive pressure or vacuum if the normal vent path becomes plugged.

Leak Detection. Liquid-storage tanks generally are located at ground level and should include secondary containment for both catastrophic and minor leaks. Secondary containment, such as concrete structures or double-walled tanks, should be provided for spills and/or leaks of chemicals. Containment volume should be a minimum of the largest bulk storage tank volume plus an additional 10%. Whenever possible, pump control panels should be outside the containment area and valves located so that they are operable and accessible from outside the containment area. Pumps and other equipment should always be elevated on concrete pads to avoid damage from minor leakage. Automated leak-detection interlocked with alarm systems can be included in the secondary containment areas for bulk storage tanks. The detection of the chemical fluid allows an operator to be notified of potential problems at storage areas. In addition, regularly scheduled (as frequent as daily) visual inspections should be conducted within containment areas to confirm that spills or leaks have not occurred. The plant should avoid installing chemical storage tanks underground, if possible, and provide secondary containment or double-walled tanks with leak detection systems if underground installation must be used. Without secondary containment, soil and groundwater contamination could result if a leak occurs.

Two relatively common pressurized liquid feed systems are flooded suction systems with an overhead storage tank (Figure 9.2) and suction lift systems using ground

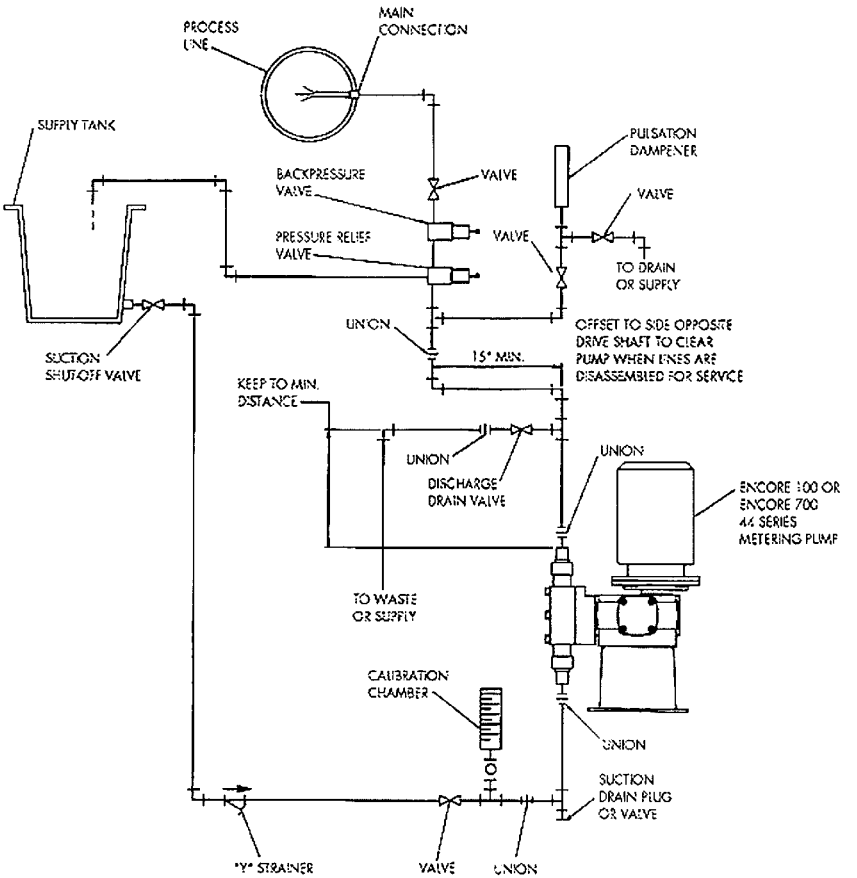


FIGURE 9.2 Flooded suction system (USFilter/Wallace and Tiernan) (in. × 25.40 = mm).

storage (Figure 9.3). Figure 9.2 shows an overhead storage system used to gravity feed the chemical metering pump. A rotodip-type feeder or rotameter can be used for a gravity feed system also. Figure 9.3 shows a ground storage system with a suction lift transfer pump. The metering pump (diaphragm type) is often used for pressure-feed systems.

Bag, Drum, and Tote Storage. Typically, the determination of what type of storage method is acceptable will depend on plant size, average chemical feed usage rates, chemical storage space available, and the amount of labor that can be allocated to chemical handling. Small plant facilities may only use bags or drums (or possibly totes) to meet an adequate chemical storage. As stated earlier, chemical storage should provide a minimum of 15 to 30 days of chemical storage at average chemical feed us-

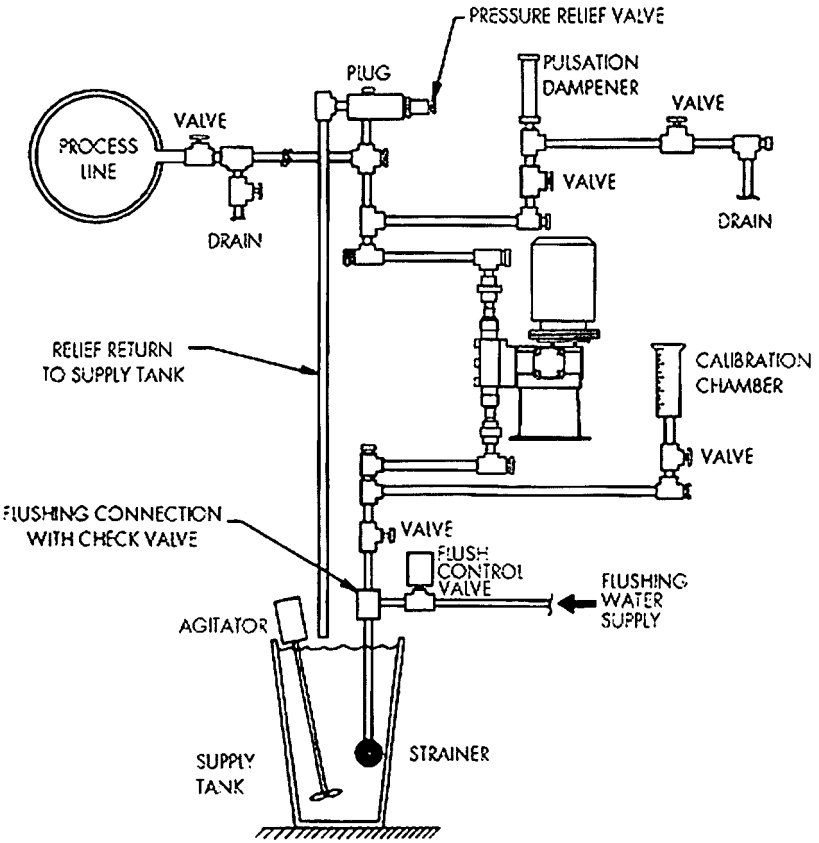


FIGURE 9.3 Suction lift system (USFilter/Wallace and Tiernan).

age rates. Small plants may have sufficiently low average chemical feed usage rates that the small number of bags, drums, or totes required may not take up much storage space and may not require much labor for handling. However, large plant facilities, with larger average chemical feed usage rates, will require bulk storage tanks to minimize the amount of storage space required to meet minimum storage requirements and the amount of labor required for chemical handling. Bulk storage systems use additional material-handling equipment to provide a more efficient, less labor intensive, and less costly approach to chemical handling as compared with storing and handling a significant number of chemical bags or drums or totes. For an intermediate size of plant, bulk bags or totes can provide a cost-effective approach to chemical handling compared with bulk storage or bag/drum storage. For an intermediate size of plant, the amount of labor required to handle the larger containers is typically less than the

labor required to handle the many bags or drums because fewer of the larger containers must be handled. The larger container size also can require less storage space to maintain minimum chemical inventories. However, bulk bags or totes do require some additional chemical handling equipment (compared with handling bags/drums) to handle the large size of container. However, the amount of additional equipment required is typically less than the additional equipment required for bulk storage systems.

Typically, bags, drums, or totes are stored in a dry, temperature-controlled, low-humidity area and should be used in proper rotation: first in, first out. Bags should be stored off the floor level and liquid drum or tote storage areas must be properly contained in case of a spill. Bag- or drum-loaded hoppers are frequently sized for a storage capacity of eight hours at the nominal maximum feed rate, so personnel are not required to fill or charge the hopper more than once per shift.

Cylinder and Ton Container Storage. Whether in storage or in use, cylinders (68-kg [150-lb]) need proper support to prevent accidental tipping. Cylinders should be supported by chaining or anchoring to a fixed wall or support and should be readily accessible and removable. Bulk containers should be stored horizontally, slightly elevated from the floor level, and blocked to prevent rolling. Monorails are often used for movement of bulk containers within the storage area. In addition, beams may be used as a convenient storage rack for supporting both ends of the containers. Bulk containers should not be stacked or racked more than one high. Chlorine cylinders and containers should be protected from impact, and handling should be kept to a minimum. Full and empty cylinders and bulk containers should be stored separately and tagged or identified according to their disposition.

Chaining or anchoring chlorine cylinders in place during use is also important. Chlorine piping, cylinder connections, and other equipment could be damaged during any type of movement if not properly anchored.

Proper, forced, mechanical ventilation in storage and feed areas is important for the safety and health of operating personnel. If the gas is heavier than air, such as chlorine, ventilation should be drawn from the floor. On the other hand, if the gas is lighter than air, such as ammonia, the ventilation should be drawn from near the ceiling. One air change per minute (60 air changes per hour) is considered adequate ventilation when personnel occupy chlorine storage and feed areas, per *Recommended Standards for Wastewater Facilities* (Great Lakes, 1997). The International Fire Code suggests a ventilation rate of approximately 5.08×10^{-3} $m^3/m^2 \cdot s$ (1 cfm/sq ft) of building, but this yields fewer air changes per hour (International Fire Code, 1999). Typically, room ventilation is automatically activated (through the use of door switches or other means to

detect entry) when the room or area is occupied by plant operators. The point of ventilation discharge should be carefully placed so it does not exhaust near other air inlets or occupied external areas. In addition, where required by law, gas scrubbers may be necessary in the ventilation discharge. Ventilation rates for discharge to an emergency scrubber are typically based on the rupture of the single largest container. For example, the release from a 907-kg (1-ton) container rupture would typically require a ventilation rate of 1.42 m^3/s (3000 cfm).

Leak detection and containment in the storage and feed areas are extremely important. Automatic leak-detection equipment for chlorine gas and sulfur dioxide are effective in detecting relatively small concentrations of the subject chemicals. Interlocks should be provided that shut down the normal ventilation in the event that a leak is detected. Local and remote alarms are typically initiated and the emergency scrubber and fan are started. Leak-repair kits, self-contained breathing apparatus meeting the requirements of the National Institute for Occupational Safety and Health, and all other safety equipment should be available outside the storage/feed area and properly maintained. Only operating personnel that have been thoroughly trained and certified in emergency response should be involved in a chemical-handling emergency.

Chemical Purity. Typically, technical grade chemicals are used in wastewater treatment to minimize the chemical purchase costs. High-purity chemicals are not required and can significantly increase the cost for chemicals. However, care must be exercised to avoid chemicals that contain excessive quantities of hazardous impurities that could result in wastewater treatment plant upsets or violations of the wastewater treatment plant effluent limitations. The effluent limitations that could be exceeded may be either an actual numerical limit listed in the effluent permit for each individual hazardous compound or a limit based on a whole effluent toxicity (WET) test. A very low concentration of many hazardous compounds, such as heavy metals, can be toxic to the biological organisms used in the WET test, resulting in test failure and associated violation of the effluent limitation. For heavy metals such as lead, mercury, copper and zinc, the wastewater treatment plant can have very low effluent limitations and the typical wastewater treatment processes will not be able to adequately remove these compounds to meet the very stringent limits. In addition, many heavy metals can accumulate in the sludge generated by the wastewater treatment processes. Other chemicals such as chlorine and sulfur dioxide can be detrimental to the discharge water quality. Low concentrations of chlorine exhibit effluent toxicity and sulfur dioxide can deplete dissolved oxygen. The actual quantity of allowable contaminate will depend on any effluent limitation and the maximum quantity of chemical used at the wastewater treatment plant.

Once the chemical is received at the treatment plant, care should be exercised to avoid contamination of the chemical. Material safety data sheet documents and supplier instructions should be consulted to determine types of contamination that must be avoided. Depending on the chemical, contamination can result in significant degradation of the effectiveness of the chemical and, in some cases, the formation of extremely hazardous and even life-threatening conditions in the plant. For example, metal contamination (such as rust) in hydrogen peroxide can destroy significant quantities of active chemical and even result in an explosive release of gas.

TROUBLESHOOTING. Chemical unloading and storage systems can have operating problems. Table 9.4 presents a brief troubleshooting guide for chemical unloading and storage systems that will help the operator to identify problems and develop possible solutions.

PUMPING, PIPING, AND HANDLING MATERIALS

Piping and accessories for transporting and feeding various chemicals should be provided only after specific chemicals have been selected for use in the wastewater treatment plant. The operator should use only materials that are compatible with each

TABLE 9.4 Troubleshooting guide for chemical unloading and storage systems.

Observations	Checks and remedies
Pneumatic conveying (low pressure)	
Material not moving from car or truck to silo.	Check pressure at blower. If high, line may be plugged. Shut off, discharge to system, clear line, and restart.
	If pressure is normal or low, material is not entering conveying line. Check discharge gate on truck or rail car.
Dust discharging from silos.	Ensure that dust filter on silo is operational.
	Check dust filter for broken or torn bags or tubes.
	Ensure that silo dust filter capacity is sufficient for blower discharge.
Bucket elevators and screw conveyors	
Material backing up at inlet.	Listen to determine whether system is operating. If so, reduce amount at inlet to unit and continue.
	If unit is stopped but motor is running, check for broken shear pins.
	If motor is tripped out, check for broken or overloaded conveyor.

chemical. For example, many chemical-handling systems require special materials for construction and special types of piping; tubing; and transport channels, pumps, valves, and gaskets. Table 9.5 gives a summary of tank, pump, piping, and valve materials compatible with several commonly used chemicals and offers an overview on general material compatibility for these chemicals. The operator should always consult equipment manufacturers and chemical suppliers before selecting materials of construction. Sodium hypochlorite is one of many chemicals that require special handling precautions. As an example of material selection consideration, more detailed information on feeding and handling equipment for this chemical is listed in Table 9.6.

TABLE 9.5 Materials of construction—chemical handling facilities.

Chemical	Tanks	Pumps	Pipe	Valves
Alum	FRP[a]	Nonmetallic	PVC,[b] CPVC,[c] FRP	Nonmetallic
Chlorine	Steel cylinders	N/A	Carbon steel to vaporizer	Carbon steel
Ferric chloride	FRP, rubber-lined steel	Nonmetallic or rubber lined	FRP, CPVC, PVC, rubber-lined steel	Rubber-lined, CPVC
Ferrous sulfate	FRP	Nonmetallic	PCV, CPVC, FRP	Nonmetallic
Hydrogen peroxide	Aluminum alloy 5254, Type 316L stainless steel	Type 316 stainless steel, Teflon	Aluminum, Type 316L stainless steel	Type 316 stainless steel, Teflon
Methanol	Carbon steel	Cast steel	FRP, carbon steel	Carbon steel
Ozone	N/A	N/A	Type 316 stainless steel	CF-8M
Polymers	FRP	Nonmetallic	PVC, CPVC	Nonmetallic
Sodium bisulfite	FRP	Nonmetallic	PVC, CPVC, FRP	Nonmetallic or plastic lined
Sodium hydroxide	FRP, special construction	Stainless or carbon steel	CPVC, FRP, stainless steel	Stainless steel, nonmetallic
Sodium hypochlorite	FRP, special construction	Nonmetallic	FRP, CPVC	Nonmetallic or plastic lined
Sulfur dioxide	Carbon steel	N/A	Carbon steel	Carbon steel
Concentrated (93%) sulfuric acid	Phenolic lined steel	CN-7M (Alloy 20)	Type 304 stainless, 1.8 m/s maximum	CN-7M for throttling, CF-8M for shut-off

[a]FRP = fiber-glass-reinforced plastic.
[b]PVC = polyvinyl chloride.
[c]CPVC = chlorinated polyvinyl chloride.

TABLE 9.6 Materials suitable for use with sodium hypochlorite (The Chlorine Institute, 2000).

Components	Materials of construction compatible with sodium hypochlorite solutions
Rigid pipe	Lined (PP,[a] PVDF,[b] PTFE[c]) steel, CPVC[d]/PVC[e] (Sch 80) and titanium
Fittings	Same as rigid pipe
Gaskets	Viton™
Valves	PVC, CPVC, PP
Pumps (centrifugal)	
Body	Nonmetallic (PVC, TFE, Kynar, Tefzel, Halar)
Impeller	Same as body
Seals	Silicon carbide
Storage tanks	Rubber-lined steel, fiber glass, and HDPE[f]

[a]PP = polypropylene.
[b]PVDF = fluorinated polyvinylidene.
[c]PTFE = polytetrafluoroethylene.
[d]CPVC = chlorinated polyvinyl chloride.
[e]PVC = polyvinyl chloride.
[f]HDPE = high-density polyethylene tanks.

Because of the concern about chemical leaks and spills from system piping, recent trends show that the use of double-walled pipe (with leak-detection sensors) or single-walled pipe placed in a containment trough or trench should be given serious consideration in the design of new systems. A variety of issues involving safety, legal liability, government legislation, insurance risk issues, and so forth, may require the use of double-contained piping systems to reduce soil and groundwater contamination and to protect plant personnel from leakage of hazardous chemicals from conventional piping systems. Providing systems with double containment will avoid serious leaks or spills from the chemical piping. Double-walled pipe-containment systems are designed to contain a leak as it occurs, detect the leak, and alarm the plant operators.

Frequently, welded pipe and fittings are used for hazardous chemical piping whenever possible and recommended to minimize the potential for leaks. Plastic materials generally can be solvent welded, heat welded, or heat fusion bonded. Metallic materials can be heat welded, such as electric arc, or brazed. If flanges must be used, then specially designed secondary containment bags that fit around the flange or shields can be used to contain any chemical spray from leaks.

Chemical piping should include an adequate number of valved drain locations to allow chemical to be drained from piping, valves, and equipment before removal for maintenance. Each valve should include a removable cap to minimize leakage through the valve before and after use.

CHEMICAL FEEDING SYSTEMS

This section discusses gas, liquid, and solids feeding systems with on-site generation. Table 9.7 lists types of feed systems for specific chemicals. A complete chemical addition system for any given process unit has provisions for receiving and storing the chemical, transferring and metering the chemical, and mixing and injecting the chemical to the process stream.

GAS FEEDERS. Chemicals fed as a gas include chlorine, ammonia, and sulfur dioxide. Typically, these chemicals are transported and stored as a liquefied, compressed gas and then metered or fed to the wastewater treatment process as a gas.

Description of Equipment. If chlorine or sulfur dioxide is drawn as a liquid, an evaporator is used to vaporize the chlorine. An example of an evaporator system is shown in Figure 9.4. A chlorine evaporator consists of a chlorine chamber in a hot-water bath tank. Liquid chlorine is fed to the chamber, the heat vaporizes it, and gaseous chlorine is delivered to the point of application (White, 1986). An electric heater, recirculating hot-water bath, or steam can supply heat to the evaporator. Typical operating problems associated with evaporators are frosting or icing because of liquid particles being entrained with the gas leaving the chamber, scaling outside the chamber, and concentration of impurities in the chlorine inside the chamber. Frosting or icing is caused by demand exceeding the capacity of the evaporator and can be alleviated temporarily by reducing chlorine flow. Scaling and impurities will reduce the capacity of the evaporator. Regular shutdowns for cleaning will help prevent unscheduled service interruptions resulting from scaling and impurities.

Gas feeders are classified as either solution feed or direct feed. Solution-feed, vacuum-type feeders are most commonly used in chlorination and in dechlorination with sulfur dioxide (White, 1986). An example of vacuum-type feeders is shown in Figure 9.5. A gas can also be fed in a pressure system (Figure 9.6), but a vacuum system is preferred because of safety issues. Some state regulations, in fact, will allow only remote vacuum systems to eliminate releases from pressurized gas systems.

The main advantage of a gas-feed system is the relative simplicity of the transfer and feed system. Often, the vapor pressure of the material itself can be used to transfer the material, greatly reducing the equipment requirements.

The chemical can be injected directly to the process as a gas; however, there are several potential problems associated with direct feed. Some wet gases are extremely corrosive, leading to maintenance and reliability problems with the mixer. Also, direct-feed systems could allow water to back up into the gas lines at low gas feeds, damaging the equipment.

TABLE 9.7 Chemical-specific feeding recommendations (*Wastewater Treatment*, 1997).

Common name/ formula use	Best feeding form	Chemical-to-water ratio for continuous dissolving[a]	Types of feeders	Accessory equipment required	Suitable handling materials for solutions[b]
Alum: $Al_2(SO_4)_3 \cdot XH_2O$ Liquid 1 gal 36°Be = 5.38 lb of dry alum: 60 °F Coagulation at pH 5.5 to 8.0 Sludge conditioner Precipitate PO_4	Full strength under controlled temperature or dilute to avoid crystallization Minimize surface evaporation; causes flow problems Keep dry alum below 50% to avoid crystallization	Dilute to between 3 and 15% according to application conditions, mixing, etc.	*Solution* Rotodip Plunger pump Diaphragm pump 1700 pump Loss in weight	Tank gauges or scales Transfer pumps Storage tank Temperature control Eductors or dissolvers for dilution	Lead or rubber-lined tanks, Duriron, FRP,[c] Saran, PVC-1, vinyl, Hypalon, epoxy, 16 SS, Carpenter 20 SS, Tyril
Aluminum sulfate: $Al_2(SO_4)_3 \cdot 14H_2O$ (alum, filter alum) Coagulation at pH 5.5 to 8.0 Dosage between 0.5 and 9 gpg Precipitate PO_4	Ground, granular, or rice Powder is dusty, arches, and is floodable[d]	0.5 lb/gal Dissolver detention time 5 min for ground (10 min for granules)	*Gravimetric* Belt loss in weight *Volumetric* Helix Universal *Solution* Plunger pump Diaphragm pump 1700 pump	Dissolver Mechanical mixer Scales for volumetric feeders Dust collectors	Lead, rubber, FRP, PVC-1, 316 SS, Carpenter 20 SS, vinyl, Hypalon, epoxy, Ni-resistant glass, ceramic, polyethylene, Tyril, Uscolite
Ammonia anhydrous: NH_3 (ammonia) Monel, Chlorine-ammonia treatment Anaerobic digestion Nutrient	Dry gas or as aqueous solution: see "Ammonia, aqua"	—	Gas feeder	Scales	Steel, Ni-resistant, 316 SS, Penton, Neoprene

TABLE 9.7 Chemical-specific feeding recommendations (*Wastewater Treatment*, 1997) (*continued*).

Common name/ formula use	Best feeding form	Chemical-to-water ratio for continuous dissolving[a]	Types of feeders	Accessory equipment required	Suitable handling materials for solutions[b]
Ammonia, aqua: NH_4OH (ammonium hydroxide, ammonia water, ammonium hydrate) Chlorine-ammonia treatment pH control Nutrient	Full strength	—	*Solution* Loss in weight Diaphragm pump Plunger pump Bal. diaphragm pump	Scales Drum handling equipment or storage tanks Transfer pumps	Iron, steel, rubber, Hypalon, 316 SS, Tyril (room temperature to 28%)
Calcium hydroxide: $Ca(OH)_2$ (hydrated lime, slaked lime) Coagulation, softening pH adjustment Waste neutralization Sludge conditioning Precipitate PO_4	Finer particle sizes more efficient, but more difficult to handle and feed	Dry feed: 0.5 lb/gal maximum Slurry: 0.93 lb/gal (i.e., a 10% slurry) (light to a 20% concentration maximum) (heavy to a 25% concentration maximum)	*Gravimetric* Loss in weight Belt *Volumetric* Helix Universal *Slurry* Rotodip Diaphragm Plunger pump[e]	Hopper agitators Non-flood rotor under large hoppers Dust collectors	Rubber hose, iron, steel, concrete, Hypalon, Penton, PVC-1 No lead
Calcium hypochlorite: $Ca(OCl)_2 \cdot 4H_2O$ (H.T.H., Perchloron, Pittchlor) Disinfection Slime control Deodorization	Up to 3% solution maximum (practical)	0.125 lb/gal makes 1% solution of available Cl_2	*Liquid* Diaphragm pump Bal. diaphragm pump Rotodip	Dissolving tanks in pairs with drains to draw off sediment Injection nozzle Foot valve	Ceramic, glass, rubber-lined tanks, PVC-1, Penton, Tyril (room temperature), Hypalon, vinyl, Usolite (room temperature), Saran, Hastelloy C (good) No tin

Calcium oxide: CaO (quicklime, burnt lime, chemical lime, unslaked lime) Coagulation Softening pH adjustment Waste neutralization Sludge conditioning Precipitate PO_4	0.25 to 0.75 in. pebble lime Pellets Ground lime arches and is floodable Pulverized will arch and is floodable Soft burned, porous best for slaking	2.1 lb/gal (range from 1.4 to 3.3 lb/gal according to slaker, etc.) Dilute after slaking to 0.93 lb/gal (10%) maximum slurry	*Gravimetric* Belt Loss in weight *Volumetric* Universal Helix	Hopper agitator and non-flood rotor for ground and pulverized lime Recording thermometer Water proportioner Lime slaker High-temperature safety cut-out and alarm	Rubber, iron, steel, concrete, Hypalon, Penton, PVC-1
Carbon, activated: C (Nuchar, Norit, Darco, Carbodur) Decolorizing, taste and odor removal Dosage between 5 and 80 ppm	Powder: with bulk density of 12 lb/cu ft Slurry: 1 lb/gal	According to its bulkiness and wetability, a 10 to 15% solution would be the maximum concentration	*Gravimetric* Loss in weight *Volumetric* Helix Rotolock *Slurry* Rotodip Diaphragm pumps	Washdown-type wetting tank Vortex mixer Hopper agitators Non-flood rotors Dust collectors Large storage capacity for liquid feed Tank agitators Transfer pumps	316 SS, rubber, bronze, Monel, Hastelloy C, FRP, Saran, Hypalon
Chlorine: Cl_2 (chlorine gas, liquid chlorine) Disinfection Slime control Taste and odor control Waste treatment Activation of silica[f]	Gas: vaporized from liquid	1 lb to 45 to 50 gal or more	Gas chlorinator	Vaporizers for high capacities Scales Gas masks Residual analyzer	*Anhydrous liquid or gas* Steel, copper, black iron *Wet gas* Penton, Viton, Hastelloy C, PVC-1 (good), silver, Tantalum *Chlorinated H_2O* Saran, stoneware, Carpenter 20

TABLE 9.7 Chemical-specific feeding recommendations (*Wastewater Treatment*, 1997) (*continued*).

Common name/ formula use	Best feeding form	Chemical-to-water ratio for continuous dissolving[a]	Types of feeders	Accessory equipment required	Suitable handling materials for solutions[b]
					SS, Hastelloy C, PVC-1, Viton, Uscolite, Penton
Chlorine dioxide: ClO_2 Disinfection Taste and odor control (especially phenol) Waste treatment 0.5 to 5 lb $NaClO_2$ per mil. gal H_2O dosage	Solution from generator Mix discharge from chlorinizer and $NaClO_2$ solution or add acid to mixture of $NaClO_2$ and NaOCl. Use equal concentrations: 2% maximum	Chlorine water must contain 500 ppm or more of Cl_2 and have a pH of 3.5 or lower Water use depends on method of preparation	*Solution* Diaphragm pump	Dissolving tanks or crocks Gas mask	*For solutions with 3% ClO_2* Ceramic, glass, Hypalon, PVC-1, Saran, vinyl, Penton, Teflon
Ferric chloride: $FeCl_3$ - anhydrous $FeCl_3$ - $6H_2O$ = crystal $FeCl_3$ - solution (Ferrichlor, chloride, or iron) Coagulation pH 4 to 11 Dosage: 0.3 to 3 gpg (sludge conditioning 1.5 to 4.5% $FeCl_3$) Precipitate PO_4	Solution or any dilution up to 45% $FeCl_3$ content (anhydrous form has a high heat of solution)	*Anhydrous to form:* 45%: 5.59 lb/gal 40%: 4.75 lb/gal 35%: 3.96 lb/gal 30%: 3.24 lb/gal 20%: 1.98 lb/gal 10%: 0.91 lb/gal (Multiply $FeCl_3$, by 1.666 to obtain $FeCl_3 \cdot 6H_2O$ at 20 °C)	*Solution* Diaphragm pump Rotodip Bal. diaphragm pump	Storage tanks for liquid Dissolving tanks for lumps or granules	Rubber, glass, ceramics, Hypalon, Saran, PVC-1, Penton, FRP, vinyl, epoxy, Hastelloy C (good to fair), Uscolite, Tyril (Rm)
Ferric sulfate: $Fe_2(SO_4)_3 \cdot 3H_2O$ (Ferrifloc) $Fe_2(SO_4)_3 \cdot 2H_2O$ (Ferriclear) (iron sulfate)	Granules	2 lb/gal (range) 1.4 to 2.4 lb/gal for 20-minute detention (warm water permits shorter detention)	*Gravimetric* Loss in weight *Volumetric* Helix Universal *Solution*	Dissolver with motor-driven mixer and water control Vapor remover solution tank	316 SS, rubber, glass, ceramics, Hypalon, Saran, PVC-1, vinyl, Carpenter

Coagulation pH 4 to 6 and 8.8 to 9.2 Dosage: 0.3 to 3 gpg Precipitate PO_4		Water insolubles can be high	Diaphragm pump Bal. diaphragm pump Plunger pump Rotodip		20 SS, Penton, FRP, epoxy, Tyril
Ferrous sulfate: $FeSO_4 \cdot 7H_2O$ (Copperas, iron sulfate, sugar sulfate, green vitriol) Coagulation at pH 8.8 to 9.2 Chrome reduction in waste treatment Wastewater odor control Precipitate PO_4	Granules	0.5 lb/gal (dissolver detention time 5 min minimum)	*Gravimetric* Loss in weight *Volumetric* Helix Universal *Solution* Diaphragm pump Plunger pump Bal. diaphragm pump	Dissolvers Scales	Rubber, FRP, PVC-1, vinyl, Penton, epoxy, Hypalon, Uscolite, ceramic, Carpenter 20 SS, Tyril
Hydrogen peroxide: H_2O_2 Odor control	Full strength or any dilution	—	Diaphragm pump Plunger pump	Storage tank, water metering and filtration device for dilution	Aluminum, Hastelloy C, titanium, Viton, Kel-F, PTFE, chlorinated polyvinylchloride (CPVC)
Methanol: $CH_3 \cdot OH$ Wood alcohol denitrification	Full strength or any dilution	—	Gear pump Diaphragm pump	Storage tanks	304 SS, 316 SS, brass, bronze, Carpenter 20 SS, cast iron, Hastelloy C, buna N, EPDM, Hypalon, natural rubber, PTFE, PVDF, NORYL, Delrin, CVPC

TABLE 9.7 Chemical-specific feeding recommendations (*Wastewater Treatment*, 1997) (*continued*).

Common name/ formula use	Best feeding form	Chemical-to-water ratio for continuous dissolving[a]	Types of feeders	Accessory equipment required	Suitable handling materials for solutions[b]
Ozone: O_3 Taste and odor control Disinfection Waste treatment Odor: 1 to 5 ppm Disinfection: 0.5 to 1 ppm	As generated Approximately 1% ozone in air	Gas diffused in water under treatment	Ozonator	Air-drying equipment Diffusers	Glass, 316 SS, ceramics, aluminum, Teflon
Phosphoric acid, ortho: H_3PO_4 Boiler water softening Alkalinity reduction Cleaning boilers Nutrient feeding	50 to 75% concentration (85% is syrupy; 100% is crystalline)	—	*Liquid* Diaphragm pump Bal. diaphragm pump Plunger pump	Rubber gloves	316 SS (no F) Penton, rubber, FRP, PVC-1, Hypalon, Viton, Carpenter 20 SS, Hastelloy C
Polymers, dry High-molecular-weight synthetic polymers	Powdered, flattish granules	Maximum concentration 1% Feed even stream to vigorous vortex (mixing too fast will retard colloidal growth) 1 to 2 hours detention	*Gravimetric* Loss in weight *Volumetric* Helix *Solution (Colloidal)* Diaphragm pump Plunger pump Bal. diaphragm pump	Special dispersing procedure Mixer: may hang up; vibrate if needed	Steel, rubber, Hypalon, Tyril Noncorrosive, but no zinc Same as for H_2O of similar pH or according to its pH

Polymers, liquid and emulsions[g] High-molecular-weight synthetic polymers Separan NP10 potable grade, Magnifloc 990; Purifloc N17 Ave. Dosage: 0.1 to 1 ppm	*Makedown to:* Liquid 0.5 to 5% *Emulsions:* 0.05 to 0.2%	Varies with charge type	Diaphragm pump Plunger pump Bal. diaphragm pump	Mixing and aqueous tanks may be required	Same as dry products
Potassium permanganate: $KMnO_4$ Cairox Taste odor control 0.5 to 4.0 ppm Removes Fe and Mn at a 1-to-1 ratio	Crystals plus anticaking additive	1.0% concentration (2.0% maximum)	*Gravimetric* Loss in weight *Volumetric* Helix *Solution* Diaphragm pump Plunger pump Bal. diaphragm pump	Dissolving tank Mixer Mechanical	Steel, iron (neutral and alkaline), 316 SS, PVC-1, FRP, Hypalon, Penton, Lucite, rubber (alkaline)
Sodium aluminate: $Na_2Al_2O_4$, anhydrous (soda alum) Ratio Na_2O/Al_2O_3 1/1 or 1.15/1 (high purity) Also $Na_2Al_2O_4 \cdot 3H_2O$ hydrated form Coagulation Boiler H_2O treatment	Granular or solution as received Standard grade produces sludge on dissolving	Dry 0.5 lb/gal Solution dilute as desired	*Gravimetric* Loss in weight *Volumetric* Helix Universal *Solution* Rotodip Diaphragm pump Plunger pump	Hopper agitators for dry form	Iron, steel, rubber, 316 SS, Penton, concrete, Hypalon
Sodium bicarbonate: $NaHCO_3$ (baking soda) Activation of silica pH adjustment	Granules or powder plus TCP (0.4%)	0.3 lb/gal	*Gravimetric* Loss in weight Belt *Volumetric* Helix Universal *Solution* Rotodip Diaphragm pump Plunger pump	Hopper agitators and non-flood rotor for powder, if large storage hopper	Iron and steel (dilute solutions: caution), rubber, Saran, SS, Hypalon, Tyril

TABLE 9.7 Chemical-specific feeding recommendations (*Wastewater Treatment*, 1997) (*continued*).

Common name/ formula use	Best feeding form	Chemical-to-water ratio for continuous dissolving[a]	Types of feeders	Accessory equipment required	Suitable handling materials for solutions[b]
Sodium bisulfite, anhydrous: $Na_2S_2O_5$ ($NaHSO_3$) (sodium pyrosulfite, sodium meta-bisulfite) Dechlorination: about 1.4 ppm for each ppm Cl_2 Reducing agent in waste treatment (as Cr)	Crystals (do not let set) Storage difficult	0.5 lb/gal	*Gravimetric* Loss in weight *Volumetric* Helix Universal *Solution* Rotodip Diaphragm pump Plunger pump Bal. diaphragm pump	Hopper agitators for powdered grades Vent dissolver to outside	Glass, Carpenter 20 SS, PVC-1, Penton, Uscolite, 316 SS, FRP, Tyril, Hypalon
Sodium carbonate: Na_2CO_3 (soda ash: 58% Na_2O) Water softening pH adjustment	Dense	Dry feed 0.25 lb/gal for 10-minute detention time, 0.5 lb/gal for 20-minute Solution feed 1.0 lb/gal Warm H_2O and/or efficient mixing can reduce retention time if material has not sat around too long and formed lumps—to 5 min	*Gravimetric* Loss in weight *Volumetric* Helix *Solution* Diaphragm pump Bal. diaphragm pump Rotodip Plunger pump	Rotolock for light forms to prevent flooding Large dissolvers Bin agitators for medium or light grades and very light grades	Iron, steel, rubber, Hypalon, Tyril

Sodium chlorite: $NaClO_2$ (technical sodium chlorite) Disinfection, taste, and odor control Industrial waste treatment (with Cl_2 produces ClO_2)	Solution as received	Batch solutions 0.12 to 2 lb/gal	*Solution* Diaphragm Rotodip	Chlorine feeder and chlorine dioxide generator	Penton, glass, Saran, PVC-1, vinyl, Tygon, FRP, Hastelloy C (fair), Hypalon, Tyril
Sodium hydroxide: NaOH (caustic soda, soda lye) pH adjustment, neutralization	Solution feed	NaOH has a high heat of solution	*Solution* Plunger pump Diaphragm pump Bal. diaphragm pump Rotodip	Goggles Rubber gloves Aprons	Cast iron, steel For no contamination, use Penton, rubber, PVC-1, 316 SS, Hypalon
Sodium hypochlorite: NaOCl (Javelle water, bleach liquor, chlorine bleach) Disinfection, slime control Bleaching	Solution up to 16% Available Cl_2 concentration	1.0 gal of 12.5% (available Cl_2) solution to 12.5 gal of water gives a 1% available Cl_2 solution	*Solution* Diaphragm pump Rotodip Bal. diaphragm pump	Solution tanks Foot valves Water meters Injection nozzles	Rubber, glass, Tyril, Saran, PVC-1, vinyl, Hastelloy C, Hypalon
Sulfur dioxide: SO_2 Dechlorination in disinfection Filter bed cleaning Approximately 1 ppm SO_2 for each ppm Cl_2 (dechlorination) Water treatment Cr^{+6} reduction	Gas	—	*Gas* Rotameter SO_2 feeder	Gas mask	Wet gas: Glass, Carpenter 20 SS, PVC-1, Penton, ceramics, 316 (G), Viton, Hypalon

TABLE 9.7 Chemical-specific feeding recommendations. (*Wastewater Treatment*, 1997) (*continued*).

Common name/ formula use	Best feeding form	Chemical-to-water ratio for continuous dissolving[a]	Types of feeders	Accessory equipment required	Suitable handling materials for solutions[b]
Sulfuric acid: H_2SO_4 (oil of Vitriol, Vitriol) pH adjustment Activation of silica Neutralization of alkaline wastes	Solution at desired dilution H_2SO_4 has a high heat of solution	Dilute to any desired concentration: NEVER add water to acid but rather always add acid to water	*Liquid* Plunger pump Diaphragm pump Bal. diaphragm pump Rotodip	Goggles Rubber gloves Aprons Dilution tanks	*Concentration >85 %:* Steel, iron, Penton, PVC-1 (good), Viton *40 to 85%:* Carpenter 20 SS, PVC-1, Penton, Viton *2 to 40%:* Carpenter 20 SS, FRP, glass, PVC-1, Viton

[a]To convert g/100 mL to lb/gal, multiply figure (for g/100 mL) by 0.083. Recommended strengths of solutions for feeding purposes are given in pounds of chemical per gallon of water (lb/gal) and are based on plant practice for the commercial product.
The following table shows the number of pounds of chemical to add to 1 gallon of water to obtain various percent solutions:

% Solution	lb/gal	% Solution	lb/gal	% Solution	lb/gal
0.1	0.008	2.0	0.170	10.0	0.927
0.2	0.017	3.0	0.258	15.0	1.473
0.5	0.042	5.0	0.440	20.0	2.200
1.0	0.084	6.0	0.533	25.0	2.760
				30.0	3.560

[b]Iron and steel can be used with chemicals in the dry state unless the chemical is deliquescent or very hygroscopic, or in a dampish form and is corrosive to some degree.
[c]FRP, in every case, refers to the chemically resistant grade (bisphenol A+) of fiber-glass-reinforced plastic.
[d]*Floodable* as used in this table with dry powder means that, under some conditions, the material entrains air and becomes "fluidized" so that it will flow through small openings, like water.
[e]When feeding rates exceed 100 lb/h, economic factors may dictate use of calcium oxide (quicklime).
[f]For small doses of chlorine, use calcium hypochlorite or sodium hypochlorite.
[g]Informtion about many other coagulant aids (or flocculant aids) is available from Nalco, Calgon, Drew, Betz, North American Mogul, American Cyanamid, Dow, etc.
Note: gal $\times$ 3.785 $\times$ 10^{-3} = m^3; in. $\times$ 25.40 = mm; lb/cu ft $\times$ 16.02 = kg/m^3; lb/gal $\times$ 0.119 8 = kg/L; and ppm = mg/L.

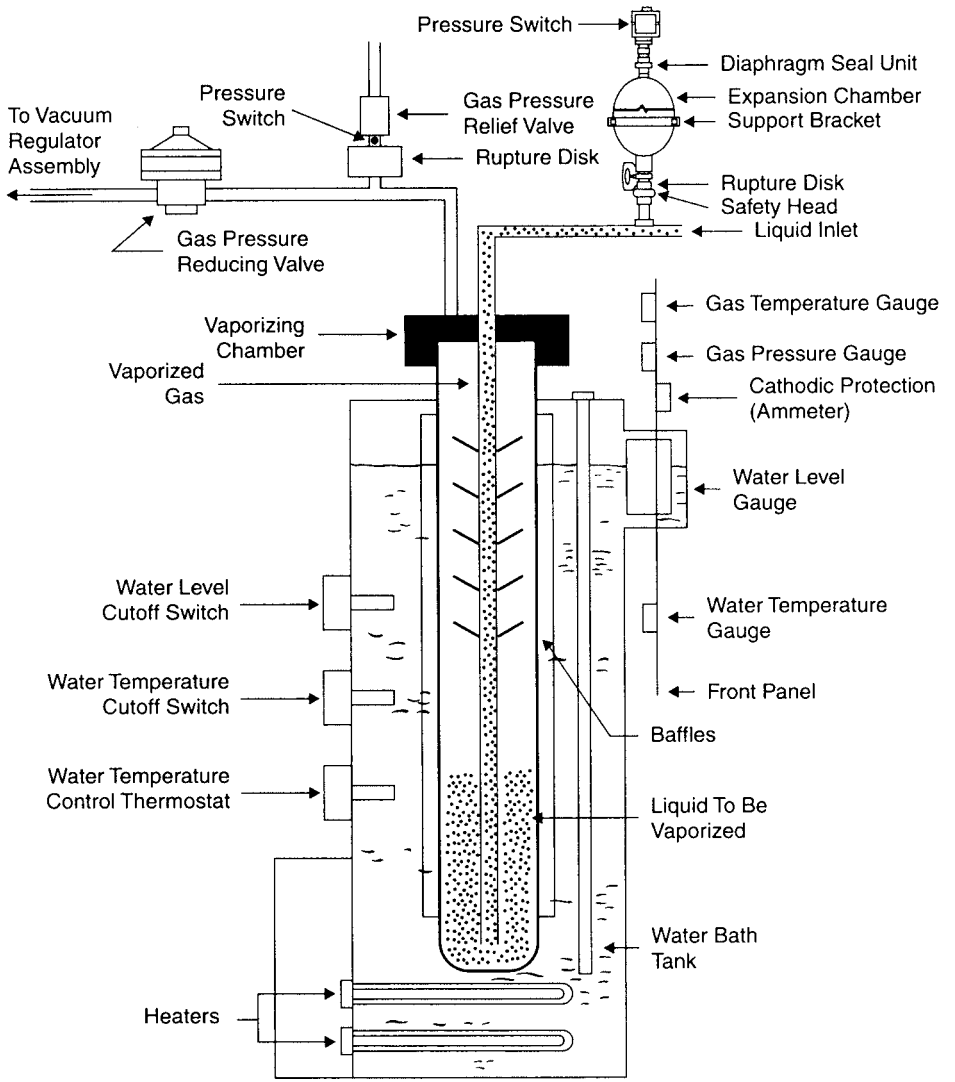


FIGURE 9.4 Typical gas evaporator.

Most typical gas-feed systems mix the gas with water in an eductor (injector) to form a solution before injecting it to the process. The advantage of a solution-feed system is that it can limit corrosion problems to a small piece of equipment, such as an ejector, that can be coated economically or be made of corrosion-resistant materials.

The mixing of the solution with the process stream is a critical aspect of solution feeding. Without adequate mixing, the solution can lose much of its effectiveness, caus-

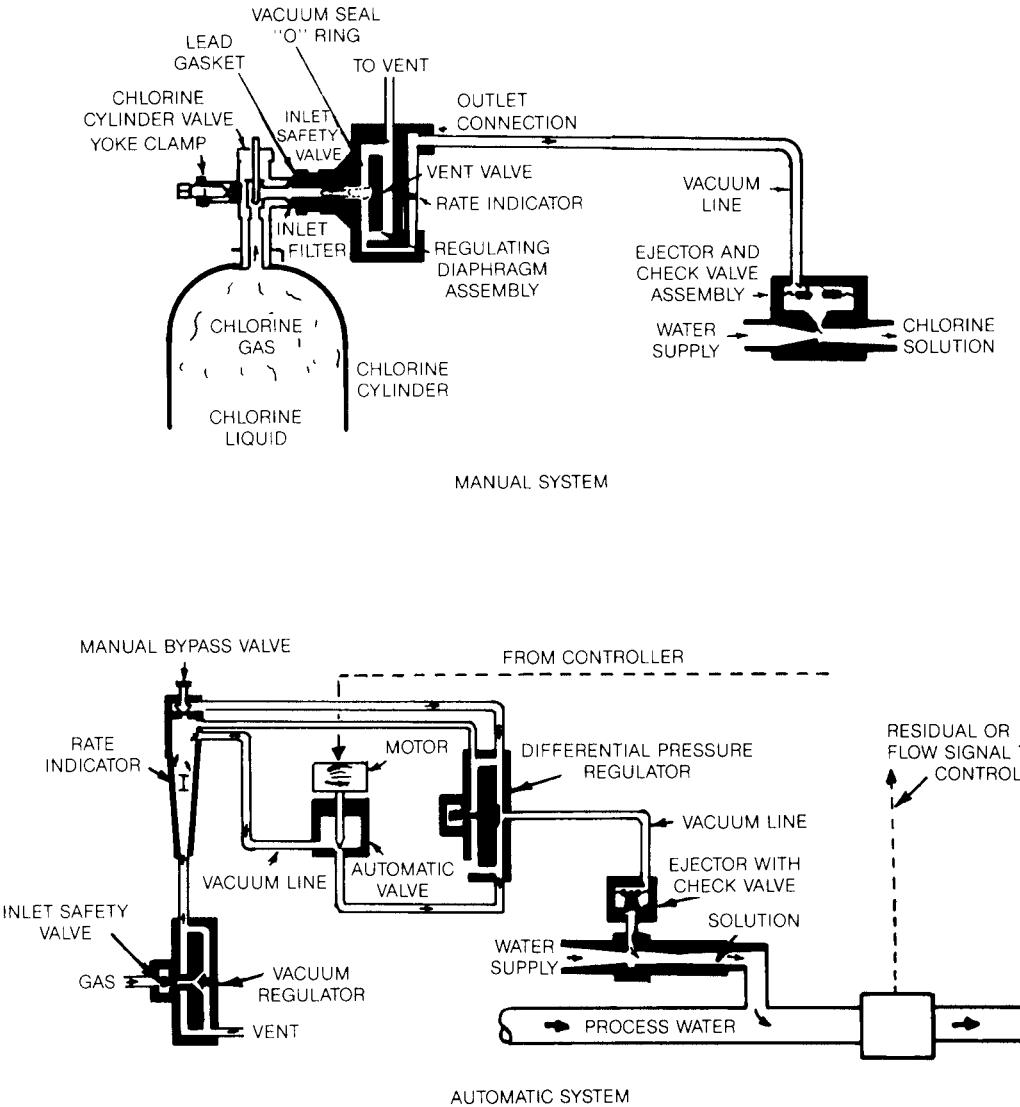


FIGURE 9.5 Typical gas vacuum-feed systems.

ing overfeeding of the chemical and even process upsets in extreme situations. Careful selection of the injection point is required so that adequate mixing in the plant can be achieved. Under some highly turbulent conditions, adequate mixing within a pipe can require a pipe length as short as 10 pipe diameters. In-line static mixers also can be used to enhance mixing; however, consideration should be given to the mixing appli-

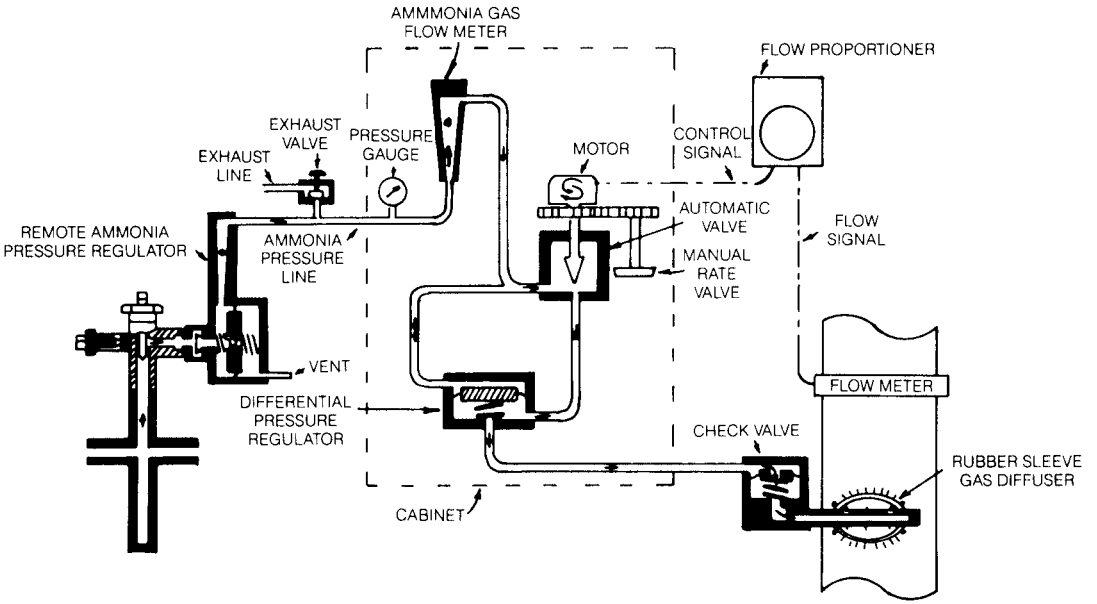


FIGURE 9.6 Typical ammonia gas pressure-feed system.

cation because certain process streams could foul the mixer and render it ineffective or nonoperational. In addition, the effect on any process control systems should be evaluated before using only a static mixer. Static mixers can provide good axial mixing across the diameter of the pipe but generally provide little, if any, radial or longitudinal mixing. Frequently, chemical feed systems use diaphragm-type chemical metering pumps that provide a pulsing flow and not a continuous flow. Therefore, if the control parameter, such as pH, is measured after the static mixer, the measured pH may show significant fluctuations with each flow pulse delivered by the pump. These control parameter fluctuations may prevent proper operation of the control system unless a mixed tank is used to smooth out the control parameter fluctuations. For injection to larger-diameter pipes, a pipeline diffuser can be used to inject the solution evenly across the diameter. Solution injected at a tee or saddle may tend to stay along the wall of the pipe and not enter the bulk fluid at the center of the pipe.

Pumps and valves can aid mixing. A hydraulic jump is sometimes used to mix chemical solutions with the process but requires careful analysis of hydraulic conditions under all possible flow regimes that may occur. Static mixers are used to improve mixing efficiencies. Mechanical devices such as vertical mixers, in-line mixers, and side-entry mixers can also be installed.

Operational Considerations. Operational problems with sulfonators, chlorinators, and ammoniators can generally be traced to problems with the operation of the injector or clogging of the feed equipment by impurities. When problems occur in feeding with vacuum-type feeders, the operator should check the injector water supply to ensure that it conforms with the flowrate and pressure required by the equipment. If the injector is operating properly and producing sufficient vacuum, the operator should trace back through the vacuum system to the metering equipment, looking for an obstruction in the gas supply system. Automatically controlled systems can have a control malfunction that will drive the rate control device closed when it should be open. In that case, the unit should be switched to manual control until the automatic controls can be repaired.

Another operational consideration concerns verifying the amount of chemical fed each day. Gas cylinders should be mounted on scales and their loss in weight noted each day to determine the amount of chemical feed and check the chemical flow meter reading. Cylinder weighing also allows the operator to anticipate an empty cylinder and change it promptly without interrupting treatment. Equipment scales are available to handle multiple cylinders and automatic switch-over from an empty cylinder to a full cylinder.

LIQUID FEEDERS. Sodium hypochlorite, some polymers, phosphoric acid, and ferric chloride are typically examples of chemicals fed as liquids. Caustic soda (sodium hydroxide) and hydrogen peroxide are also fed as liquids but are not commonly used in municipal wastewater treatment plants. Like the gas systems, liquid-feed systems have some means of receiving and storing the chemical, transporting and measuring it, and mixing and injecting it to the process. Liquid systems generally require pumps for conveyance.

The use of sodium hypochlorite (NaOCl) solution has become more prevalent in many plants today as a replacement for chlorine gas (Cl_2) as a disinfectant. There are certain advantages in the use of hypochlorite, such as safety issues, but it is important to consider some basic factors before converting to a liquid hypochlorite feed system. For example, to replace a 907-kg (1-ton) container of chlorine, at least 7.6 m^3 (2000 gal) of hypochlorite solution may be required. Hypochlorite solutions decompose over time and lose available chlorine for disinfection, so storage considerations are extremely important. In addition, there are several chemical differences. Hypochlorite solutions exhibit high pH (greater than 12) and add alkalinity to the water; however, chlorine creates an acidic solution when added to water and decreases the alkalinity.

Because chlorine gas is highly toxic, sodium hypochlorite provides an alternative even though the solution is corrosive and is a severe skin and eye irritant. One impor-

tant safety consideration when using sodium hypochlorite is proper venting. Certain metals can cause the sodium hypochlorite solution to decompose to oxygen and salt. Pressure buildup in tanks, piping sections, and valves can be a concern if not properly vented.

Description of Equipment. A typical solution-feed system consists of a bulk storage tank, transfer pump, day tank (sometimes used for dilution), and liquid feeder. Some liquid chemicals can be fed directly without dilution, and these may make the day tank unnecessary, unless required by a regulatory agency. Nonetheless, dilution water can be added to prevent plugging, reduce delivery time, and help mix the chemical with the wastewater. However, sometimes, the dilution water can have adverse chemical effects. For instance, dilution water that has not been softened can potentially cause calcium carbonate scale to build up on the piping. Special consideration should be given to the final water chemistry of the solution before adding dilution water. Figure 9.7 shows a typical solution-feed schematic.

Liquid feeders are typically metering pumps. Metering pumps are generally of the positive-displacement type using either plungers or diaphragms. An example of a diaphragm pump is presented in Figure 9.8. For details on pump maintenance and operation, the operator should consult the pump manufacturer's literature or the *Metering Pump Handbook* (McCabe et al., 1984). Positive-displacement pumps can be set to feed over a wide range (10:1) by adjusting the pump stroke length. In addition, the feed range can sometimes be extended by adjusting the pump speed as well. Sometimes control valves and rotameters may be sufficient; in other cases, the rotating dipper wheel-type feeder may be satisfactory. For uses such as lime slurry feeding, centrifugal pumps with open impellers or double-diaphragm pumps can be used. The type of liquid feeder used depends on the viscosity, corrosivity, solubility, suction, discharge head, and internal pressure-relief requirements.

The chemical addition rate can be set manually by adjusting a valve or the stroke/speed on a metering pump. The operators should obtain or develop a set of calibration curves showing the percent of full stroke versus the pump discharge. Alternatively, those adjustments can be made automatically with instrumentation. Automatic-feed systems can be designed to control the feed flow based on a process variable such as influent flow, residual chlorine concentration, or pH. For instance, a control scheme could pace the pump speed based on wastewater flow and use another measured parameter to "trim" the pump stroke. Whatever the control scheme used, to ensure control of the chemical addition the operator needs to carefully check the process treatment units, maintain storage and day tank inventories, and understand the equipment.

Pressure relief should be provided for positive-displacement metering pumps to prevent line failures if all discharge valves or pump isolation valves are closed. Evi-

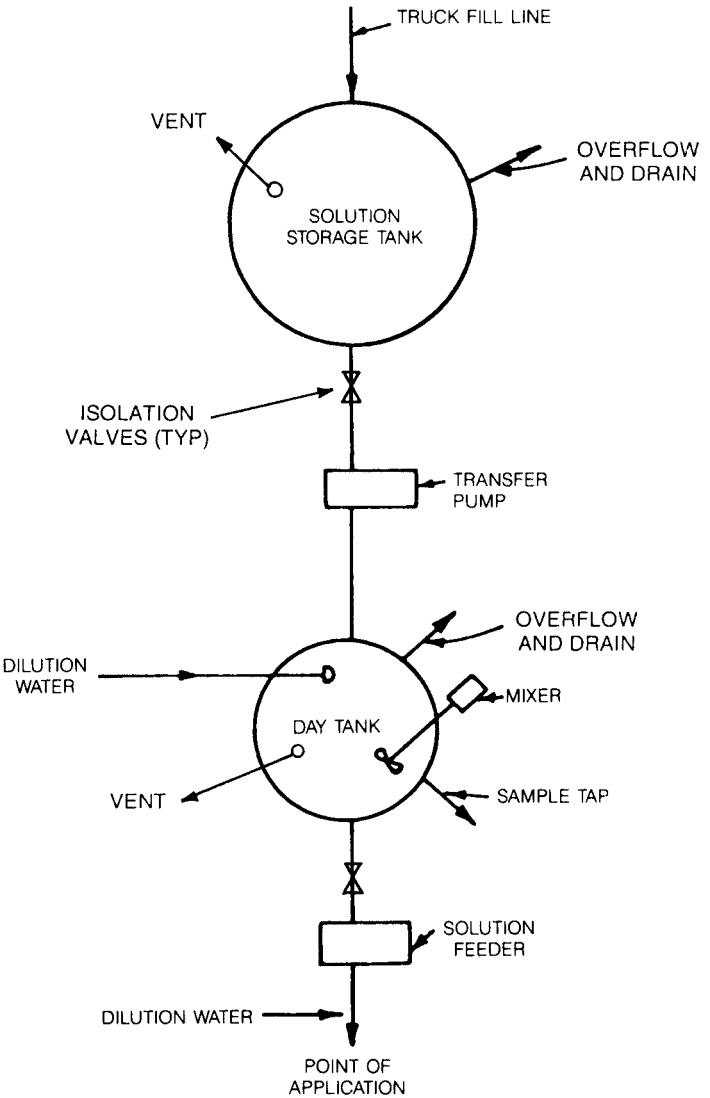


FIGURE 9.7 Typical solution-feed system.

dence of discharges from expansion-relief valves should be reported at once and the cause investigated and corrected. Backpressure valves are also required with positive-displacement pumps to ensure proper pressure differential between the suction and discharge valves and to provide sufficient backpressure to seat the pump discharge check valve. Most metering pumps should have a 34- to 69-kPa (5- to 10-psi) differen-

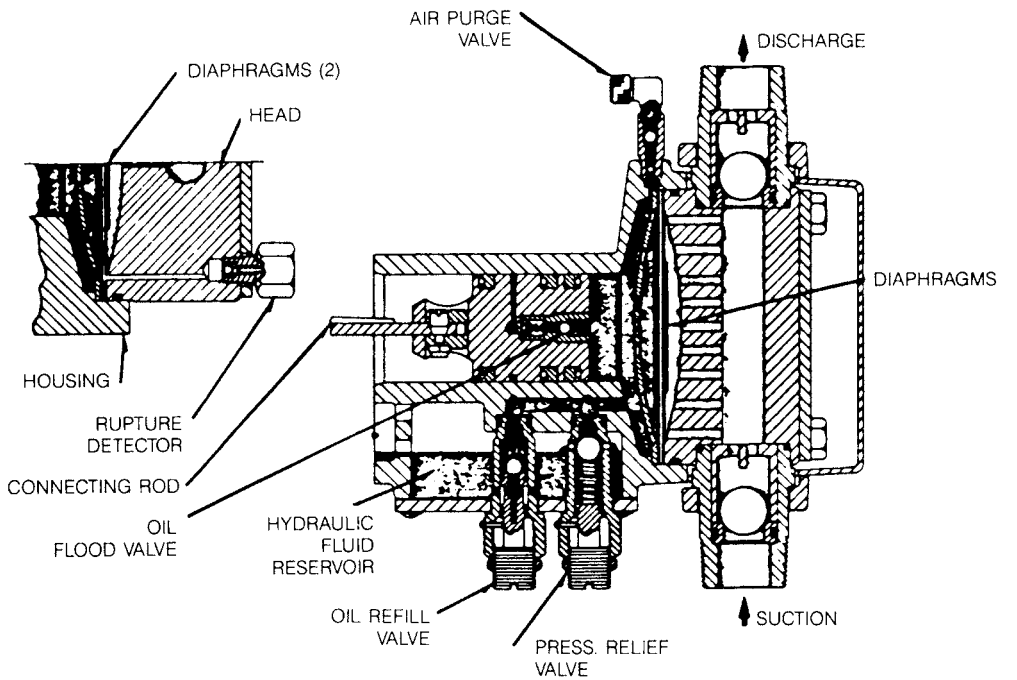


FIGURE 9.8 Diaphragm pump.

tial across the valves. If this differential is not available, the installation of a backpressure valve can develop additional head pressure close to the pump discharge connection (McCabe et al., 1984). A good liquid-feed system also includes valving so that the lines, pumps, and meters can be isolated from the process, cleaned and/or drained, and prepared for maintenance.

In addition, the operator should make provisions for other accessories as part of a chemical metering pump system using positive-displacement pumps. The installation of a pressure gauge in the discharge line is used for monitoring pressure at the pump and for assisting with setting relief-valve pressures or charging pulsation dampeners (McCabe et al., 1984). Pulsation dampeners are typically located in the discharge piping as close to the pump discharge connection as possible. Dampeners are also sometimes placed in the suction side of the pump. The location of the discharge pulsation dampener is critical to absorb the maximum fluid accelerations created by a positive-displacement pump. The pulsation dampener should be isolated with a valve to allow for maintenance. Most plastic pipe chemical-feed systems should include provisions for pulsation dampeners.

Polymers added to aid settling often require special attention for adequate mixing. For optimum performance, the manufacturer's instructions for preparing the dilute solution and locating the addition point should be followed explicitly. These instructions may include an initial dilution of the polymer with water followed by an hour or more of mixing to age the polymer before feeding the solution. Feeding a polymer solution that has not been properly aged will reduce the chemical's effectiveness and increase processing costs. A second dilution may be required just before injecting the polymer solution to the process.

Operational Considerations. Chemical and liquid feeders, such as metering pumps, can have many operating problems that prevent the feeder from delivering the correct amount of chemical. To monitor feeder delivery, all liquid feeders, especially metering pumps, should be equipped with a calibration cylinder. The cylinder can be either empty or full, and the time needed to empty or fill the cylinder should be noted. By knowing the volume of the calibration cylinder and the time for filling or emptying the cylinder, the operator can calculate the exact pump output. This determination serves as a check on the pump capacity.

Many metering pump systems handle chemicals that coat or build a layer of residue or slurries that can settle out solids during operation. Strainers are helpful in removing large particulate, but the operator must keep these cleaned. Periodic flushing to remove residues and deposits is often required. Piping and valve arrangements should allow the system to be isolated so that a clear liquid, such as water, can be used to pressurize the system for flushing the residue or solid buildup. Such flushing systems can be operated manually using hand-operated valving or can be automatically operated using solenoid valves with a timer control system. Systems where the metering pumps and piping are periodically shut down will require flushing connections to remove solids. In addition, an allowance for tees and wye cleanouts should be included for the piping system where longer horizontal piping runs cannot be adequately flushed.

A metering pump will lose capacity and become erratic when the suction or discharge valves become worn or when poor hydraulic conditions exist. These conditions will be indicated by the cylinder test described above. Also, debris in the chemicals being fed may obstruct or block the check valves, thus impeding their operation and decreasing the pump's performance.

Some chemicals such as hydrogen peroxide and sodium hypochlorite need metering pumps specially designed to handle offgassing. Offgassing is gas produced from the chemical during storage and feeding. Other types of offgas-relief systems can be incorporated to the feed pump piping also.

DRY CHEMICAL FEEDERS. Lime, alum, and activated carbon are typical of the kinds of chemicals used with a dry chemical-feed system. These systems are complex because of their many storage and handling requirements. The simplest method of feeding dry or solid chemicals is by hand. Solid chemicals may be preweighed and added or poured by the bagful into a dissolving tank. This method generally applies only to small plants where dry chemical-feed equipment is used.

Description of Equipment. A dry installation (Figure 9.9) consists of a feeder, a dissolver tank, and a storage bin or hopper. Dry feeders are of either the volumetric or gravimetric type. Volumetric feeders are generally used only where low initial cost and low feed rates are desired, and less accuracy is acceptable. These feeders deliver a constant, preset volume of chemical and do not respond to changes in material density. The volumetric feeder is initially calibrated by trial and error and then readjusted periodically if density of the material changes.

Most volumetric feeders are included in the positive-displacement category. All designs of this type use some form of moving cavity of a specific or variable size. A belt, screw, or auger can provide the cavity. The chemical falls into the cavity and is almost fully enclosed and separated from the hopper's feed. The rate at which the cavity moves and empties and the cavity size govern the amount of chemical fed (National Lime Association, 1995). Some types of volumetric feeders can be subject to flooding. This can be especially important for those feeding from bins or large hoppers. Flooding occurs when chemical is forced through the feeder (such as by chemical weight or momentum) in an uncontrolled fashion such as through the center of a helical screw auger. Rotary valves or other devices may be required upstream of these feeders to prevent a flooding condition.

When extreme accuracy and reliability are required, the gravimetric or weigh feeder is recommended. Most of the feeding principle differences lie in the system of scales, levers, and balances necessary to maintain a continuous flow of material at a predetermined weight versus time rate. Although the material may change in form, size, or density, the gravimetric feeder automatically compensates for the difference.

Gravimetric feeders take many forms but generally are classified into three groups: the pivoted-belt group, the rigid-belt group, and the loss-in-weight group. Gravimetric feeders are not "official" scales. The feeder feeds first and then checks and adjusts the feed through weighing (National Lime Association, 1995). For feeding critical processes, weigh feeders should be checked periodically as noted in the discussion of operational considerations.

Slide gates, knife gate valves, or other devices are typically installed between the bin or hopper and the feeder. These devices allow the feeder to be isolated from the bin

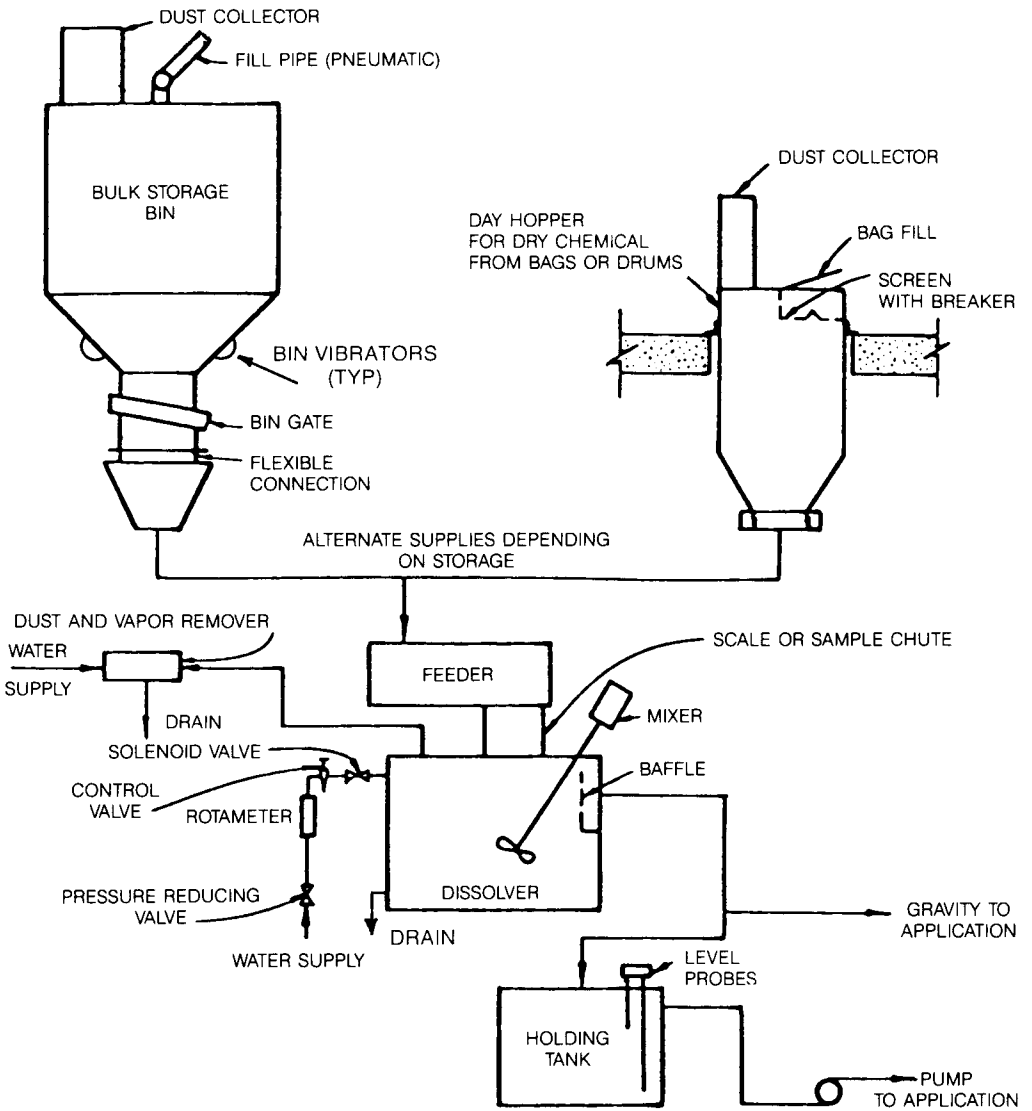


FIGURE 9.9 Typical dry-feed system.

or hopper so that the feeder can be maintained or replaced without emptying the bin or hopper. A flexible coupling also is frequently installed below the gate or valve to isolate vibrations produced by the feeder.

Dissolvers are a key component of dry-feed systems because any metered chemical must be wetted and mixed with water to provide a chemical solution free of lumps

and undissolved particles. Most feeders, regardless of type, discharge their material to a small dissolving tank equipped with a nozzle system or mechanical agitator, depending on the solubility of the chemical being fed. The surface of each particle needs to be completely wet before it enters the feed tank to ensure thorough dispersal and avoid clumping, settling, or floating. When feeding some chemicals, such as polymers, into dissolvers, care must be taken to keep moisture inside the dissolver from backing up into the feeder. Moisture or moist air in the feeder can collect on the surface of the dry chemical in the feeder and result in clumps of chemical that clog the feeder. Methods of isolation can be used between the feeder and dissolver or heaters can be installed in the feeder to dry any moisture that gets into the feeder.

A dry chemical feeder can, by simple adjustment and change of speed, vary its output tenfold. The dissolver must be designed to closely match its application. A dissolver suitable for handling a feed rate of 4.5 kg/h (10 lb/h) may not be suitable at a rate of 45 kg/h (100 lb/h). Typically, the dissolver must provide a minimum detention time to allow the chemical to properly dissolve and must operate with a chemical concentration less than a maximum chemical concentration. The maximum chemical concentration must be below the chemical solubility in the water used to dissolve the chemical. Therefore, even though the chemical feeder may be made to feed a much higher feed rate, the dissolver may not be large enough to provide the minimum detention time or maximum chemical concentration required for proper dissolving. However, long detention times in dissolvers also should be avoided to minimize the delay between changing the feeder feed rate and a change in dosage of chemical in the wastewater. The longer the detention time, the longer the delay and the higher the potential for either adding too much or too little chemical for a period of time.

Most dry feeders are of the belt, grooved-disk, screw, or oscillating-plate type. The feeding device (belt, screw, disk, etc.) is typically driven by an electric motor. Many belt feeders, particularly the gravimetric type, also contain a material flow-control device such as a movable gate or rotary inlet for metering or controlling flow of the chemical to the feed belt. An example of a screw-type volumetric feeder is shown in Figure 9.10.

Operational Considerations. Dry chemical-feeder output should be checked periodically by taking a "catch". That is, the output from the feeder is caught in a pan or similar device for a known period (such as one minute) and then the pan is weighed. The chemical output per day can then be calculated based on the precise measure of the amount added during the short interval.

A feed curve for the particular feeder should be developed, determining relationships between the capacity setting on the machines and the actual kilograms (pounds) fed per hour. The "catch" can then verify the expected capacity from the feed curve.

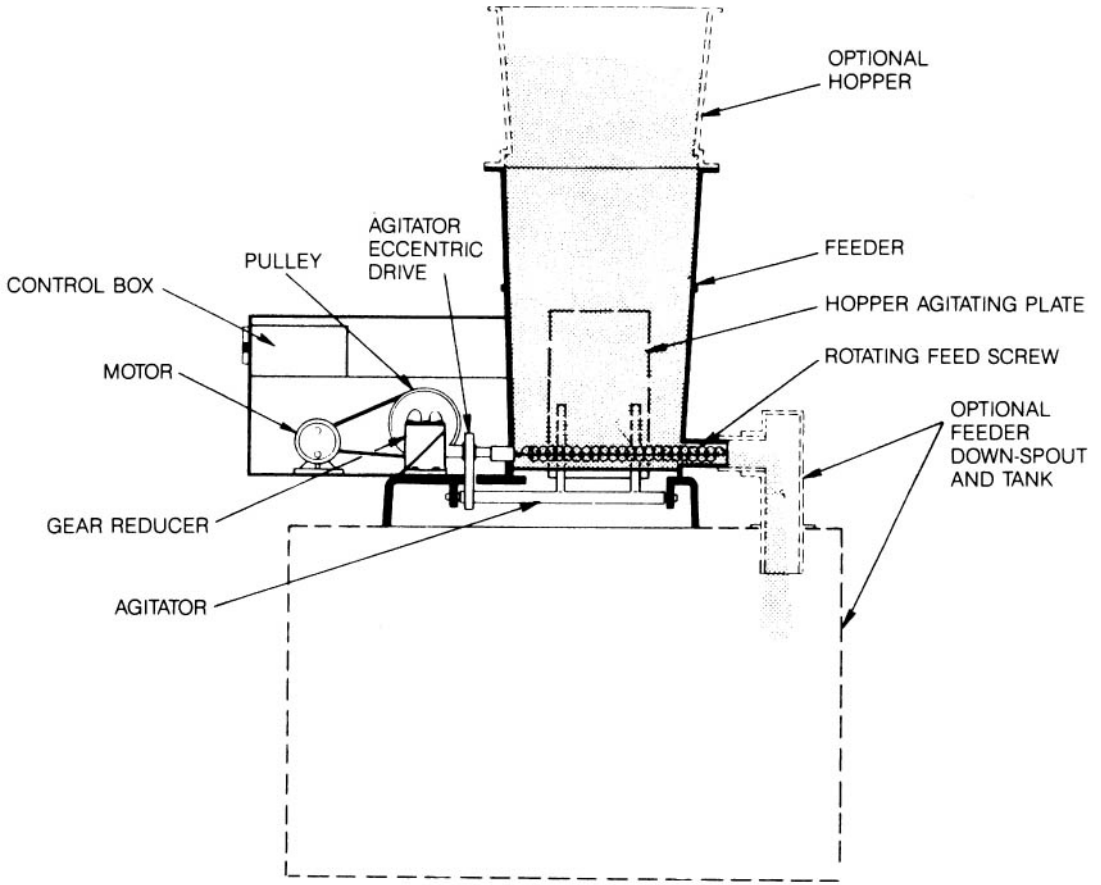


FIGURE 9.10 Typical helix-or screw-type volumetric feeder.

ON-SITE GENERATION. Generation of chemical at the treatment plant site has limited application but is available for some chemicals such as sodium hypochlorite. On-site generation can have a number of advantages over chemical delivery and storage. On-site generation can eliminate the dependence on commercial chemical suppliers and concerns associated with transportation, handling, and storage of chemical. In addition, on-site generation can reduce or eliminate degradation that may occur during chemical storage.

Sodium hypochlorite is a chemical that can be generated at the treatment plant site and can be generated on demand through the electrolysis of a brine solution. Figure 9.11 shows a flow diagram of one system that is available to generate hypochlorite.

Standard skid-mounted generation units are available, as shown in Figure 9.12, that can be installed in the treatment plant. Local regulatory issues can limit the use of chlorine gas, requiring the use of sodium hypochorite for disinfection. Because sodium hypochlorite can experience significant degradation during storage, on-site generation can potentially reduce the total quantity of hypochlorite used and potentially the total chemical cost when compared to off-site purchase. However, a site-specific cost analy-

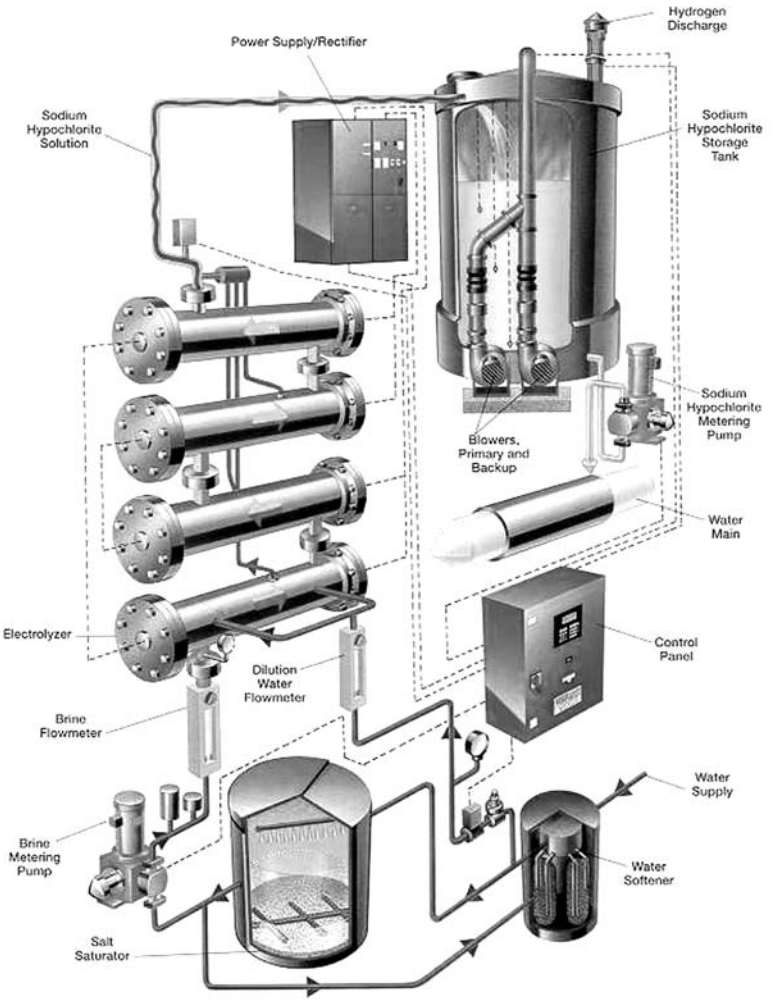


FIGURE 9.11 Flow schematic for on-site hypochlorite generation.



FIGURE 9.12 Standard skid-mounted generation units.

sis should be performed to confirm the cost effectiveness of on-site generation and determine the amount of savings, if any, available to pay off the additional equipment cost.

HELPFUL HINTS

- Verify chemical delivered for proper type, amount, and concentration (if applicable).
- Always supervise the unloading. Never leave the chemical delivery truck unattended.
- Coordinate type of pipe connection and size with both chemical supplier and transportation company (this is important because many chemical suppliers broker the transportation). Verify that compressors for dry chemical unloading are available from the transportation company.
- When unloading dry bulk chemical (such as lime, alum, and soda ash), check interlocks, before unloading chemical, with dust collection systems to ensure proper operation. Also check dust filters periodically.
- Have waste buckets or some other method for collecting liquid waste remaining in transfer hoses after chemical transfer to prevent as much chemical as possible from getting on the ground.
- Double-check all bulk transfer connections for tightness.
- Monitor the level measurement equipment in the bulk storage tanks carefully during chemical transfer to avoid overfilling the tanks.
- Periodically check that tank vents are clear and unobstructed during liquid unloading operations.
- Coordinate with the chemical supplier to provide hydraulic lift gates for offloading of pallets or bags. Many plants may not have proper equipment to offload directly from the truck bed.
- Obtain proper weight tickets from the transportation company to verify the actual weight of chemical received to pay for only the quantity of chemical received. Check the accuracy of the weight tickets by comparison with the volume of chemical placed into the bulk storage tanks by noting the chemical level in the bulk storage tanks immediately before and after the chemical delivery.
- Verify with the transportation company that the trucks are equipped with the proper pressure-relief systems.
- Check bags delivered for tears, dampness, and other deformations and/or damage. Check drums received for leaks, dents, and other deformations and/or damage.
- Provide positive secondary containment for all chemicals.
- Check piping and vents for obstructions in liquid storage tanks.
- Periodically check for liquid leakage at storage (and day) tanks and associated containment area(s).

- Keep spill cleanup supplies, neutralizers, etc., fully stocked and accessible in the event of a minor leak.
- Periodically clean and calibrate level measurement and indication instrumentation in liquid and dry storage tanks.
- Periodically check alarm interlocks for low and high levels in tanks.
- Equip tanks with drain connections and isolation valves. Use of lockable drain valves is recommended.
- Equip tanks for OSHA-approved access (ladders, platforms, etc.) to monitor and maintain level instruments, vents, dust collectors, etc.
- Humidity control is critical for dry bag storage areas. Purchasing bagged chemicals with interior plastic liners is recommended.
- Exercise care when "cracking" drum bungs in the event of excess pressure.
- Periodically check and exercise chlorine (and sulfur dioxide) emergency gas scrubbing equipment, including but not limited to fans, controls, and chemical neutralizers.
- Use eductors for dry chemical makeup.
- Confirm adequate makeup water pressure and capacity.
- Confirm mixing requirements with the chemical supplier (i.e., slow speed mixing for polymer is generally required; however, the mixer must be able to generate sufficient torque to handle the higher viscosity).
- Use the appropriate respiratory protection equipment, as required, for chemical makeup to provide protection from dusting, acid flumes, etc.
- Equip mix tanks with drain connections and isolation valves.
- Inspect and clean mixing equipment and level instrumentation for buildups. This is very important for chemicals such as lime.
- Install calibration columns to verify feed rate accuracy from metering pump equipment.
- Provide isolation valves and drain valves, such as at the pump suction, for ease of maintenance and equipment removal.
- Inspect the condition of foot valve operators and suction piping. Excessive wear, corrosion, etc., may cause chemical metering pump systems to lose prime and not function properly.
- Minimize the length of suction and discharge piping when feeding lime slurry. Calcium carbonate buildup is a significant issue and a significant maintenance problem.
- Provide flush connections for cleaning and maintaining water slurry feed piping systems for chemical such as lime.
- Locate the chemical-feed system as close as possible to the feed application point.

- As a good operating practice, consider developing a spill prevention and countermeasures control plan (SPCC) for all chemicals even though federal regulations currently require a SPCC for petroleum and petroleum-derivatives only.
- Verify chemical compatibility with the materials of construction for pumps, piping, fittings, valves, tubing, gaskets, seals, etc. Consult the chemical supplier for guidance associated with proper material selection.
- Label, in accordance with federal and state regulations, all chemical storage tanks for hazard identification by plant personnel and emergency response personnel (fire department, hazardous material team, etc.).

CHEMICAL DOSAGE CALCULATIONS

Presented below are several examples of chemical dosage calculations, each based on the following equation:

$$\text{Dosage, ppm} = \frac{\text{(kg chemical/d [lb/d])}}{\text{(mil. kg wastewater treated/d [lb/d])}} \tag{9.1}$$

The alternate form of the above equation is

$$\text{kg chemical/d (lb/d)} = \text{(dosage, ppm)} \times \text{(mil. kg wastewater treated/d [lb/d])} \tag{9.2}$$

This calculation method applies to any chemical measured in kilograms per day (pounds per day).

Example 9.1. Calculate the chlorine dosage in ppm.

Given:

Average daily wastewater flow treated = 1890 m^3/d (0.5 mgd)

Average daily chlorine use = 6.80 kg/d (15 lb/d)

Solution:

In metric units

$$\begin{aligned}\text{Dosage, ppm} &= \frac{\text{(kg chemical/d)}}{\text{(mil. kg wastewater treated/d)}} \\ &= \frac{(6.80\ \text{kg/d})}{(1890\ \text{m}^3/\text{d} \times 0.001\ \text{mil. kg/m}^3)} \\ &= \frac{(6.80\ \text{kg/d})}{(1.89\ \text{mil. kg/d})} = 3.6\ \text{ppm}\end{aligned}$$

In U.S. customary units

$$\text{Dosage, ppm} = \frac{\text{(lb chemical/d)}}{\text{(mil. lb wastewater treated/d)}}$$
$$= \frac{\text{(15 lb/d)}}{\text{(0.5 mgd} \times \text{8.34 lb/gal)}}$$
$$= \frac{\text{(15 lb/d)}}{\text{(4.17 mil. lb/d)}} = 3.6 \text{ ppm}$$

Example 9.2. Calculate the dosage of ferric chloride used as a coagulant for primary clarification.

Given:

Average daily flow rate = 21 200 m^3/d (5.6 mgd)
Ferric chloride use = 151.4 L of 40% by weight solution/d (40 gal of 40% by weight solution/d)
1 L (gal) of 40% solution = 1.33 kg (11.1 lb)

Solution:

In metric units

$$\text{Dosage, ppm} = \frac{\text{(kg chemical/d)}}{\text{(mil. kg wastewater treated/d)}}$$
$$= \frac{\text{151.4 L/d} \times \text{1.33 kg/L} \times (40\%/100)}{(\text{21200 m}^3\text{/d} \times \text{0.001 mil. kg/m}^3)}$$
$$= \frac{\text{(80.5 kg/d)}}{\text{(21.2 mil. kg/d)}} = 3.8 \text{ ppm}$$

In U.S. customary units

$$\text{Dosage, ppm} = \frac{\text{(lb chemical/d)}}{\text{(mil. lb wastewater treated/d)}}$$
$$= \frac{\text{40 gal} \times \text{11.1 lb/gal} \times (40\%/100)}{(\text{5.6 mgd} \times \text{8.34 lb/gal})}$$
$$= \frac{\text{177.6 lb/d}}{\text{46.7 mil. lb/d}} = 3.8 \text{ ppm}$$

Example 9.3. If the 3.8-ppm dosage were increased to 6 ppm with the same wastewater flow, how many liters per day (gallons per day) of ferric chloride would be needed?

Solution:

In metric units

$$\text{Liters of chemical needed} = \frac{6 \text{ ppm}}{3.8 \text{ ppm}} \times 151.4 \text{ L/d} = 239 \text{ L/d}$$

In U.S. customary units

$$\text{Gallons of chemical needed} = \frac{6.0 \text{ ppm} \times 40 \text{ gal}}{3.8 \text{ ppm}} = 63.2 \text{ gal}$$

Example 9.4. Calculate the concentration percentage (strength) of a diluted polymer batch.

Given:

Polymer used = 68 L/d (18 gal)
kg polymer/L (lb polymer/gal) = 1.25 (10.4)
Water used = 7570 L/d (2000 gal)

Solution:

In metric units

$$\begin{aligned}
\text{Batch concentration, } \% &= \frac{\text{kg polymer}}{\text{kg polymer} + \text{kg water}} \times 100 \\
&= \frac{68 \text{ L/d} \times 1.25 \text{ kg/L}}{(68 \text{ L/d} \times 1.25 \text{ kg/L}) + (7570 \text{ L/d} \times 1 \text{ kg/L})} \times 100 \\
&= \frac{85 \text{ kg/d}}{85 \text{ kg/d} + 7570 \text{ kg/d}} \times 100 \\
&= \frac{85 \text{ kg/d}}{7655 \text{ kg/d}} \times 100 \\
&= 1.1\%
\end{aligned}$$

In U.S. customary units

$$\text{Batch concentration, } \% = \frac{\text{lb polymer} \times 100}{\text{lb polymer} + \text{lb water}}$$
$$= \frac{18 \text{ gal} \times 10.4 \text{ lb/gal} \times 100}{(18 \text{ gal} \times 10.4 \text{ lb/gal}) + (2000 \text{ gal} \times 8.34 \text{ lb/ gal})}$$
$$= \frac{187.2 \text{ lb} \times 100}{187.2 \text{ lb} + 16\,680 \text{ lb}}$$
$$= 1.1\%$$

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Chapter 10

Electrical Distribution Systems

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INTRODUCTION

The electrical distribution system has three major functions. First, the system transfers power from the transmission system to the distribution system. Second, the system reduces the voltage to a value suitable for connection to local loads. Lastly, the electrical distribution system protects the entire network by isolating electrical faults.

This chapter first provides basic terminology and concepts, followed by a discussion of typical electrical distribution systems and typical distribution-system components. Basic maintenance and troubleshooting are also covered.

Relay coordination and harmonics are covered in the next two sections. Staffing and training and high-voltage safety are also discussed. Related topics, such as utility metering/billing, energy-cost reduction, energy audits, and power-factor correction, are

also presented in this chapter. Cogeneration, which is being used at many wastewater facilities, is also covered in this chapter.

BASIC TERMINOLOGY AND CONCEPTS

DIRECT CURRENT. The two basic forms of electric current are *direct current* and *alternating current*. For direct current, the driving force (voltage) across any electrical load remains nearly constant and electricity, measured in amperes, flows in one direction. Batteries and direct-current generators provide direct current. Although direct current is typically not a major power source in wastewater treatment plants (WWTPs), it may nonetheless be used for charging batteries, certain instrumentation, breaker tripping power, or, in some cases, operating direct-current machinery. In some instances, direct-current power provides excitation current for synchronous motors or generators. One common application in wastewater treatment plants (WWTPs) is the use of direct-current power to operate chemical metering pumps.

ALTERNATING CURRENT. *Alternating current*, the most common commercial source of electricity, flows first in one direction and then in the opposite direction. Alternating-current voltage follows the patterns illustrated in Figure 10.1 (Jackson, 1989). The frequency of alternation in the United States is practically universal at 60 cycles/sec or 60 Hz. The alternating-current voltage across an electrical load increases to a maximum value. It then passes through zero to the same maximum value in the opposite direction. In theory, current-flow changes follow a sine wave (shaped by the sine of an angle as the angle increases from 0 to 360 degrees). In practice, the wave form may deviate slightly from a true sine wave.

PHASED POWER. Almost without exception, utilities deliver power as three-phase alternating current. *Three-phase power* involves three hot conductors, with voltage in each conductor 120 degrees out of phase with the other two. Although two-phase and other phase systems are possible, they are rarely used industrially. Single-phase current flows between one phase and another and between any phase and the ground. Where single-phase current is selected (e.g., lighting), circuits are designed to balance the loads (i.e., equal amperage among phases).

POWER FACTOR. *True electrical power*, typically expressed in watts (W) or kilowatts (kW), delivered to a circuit represents the actual power (as indicated by a watt meter) being consumed (Figure 10.2). Apparent power always exceeds the actual power in a circuit containing inductance or capacitance. *Apparent power*, typically

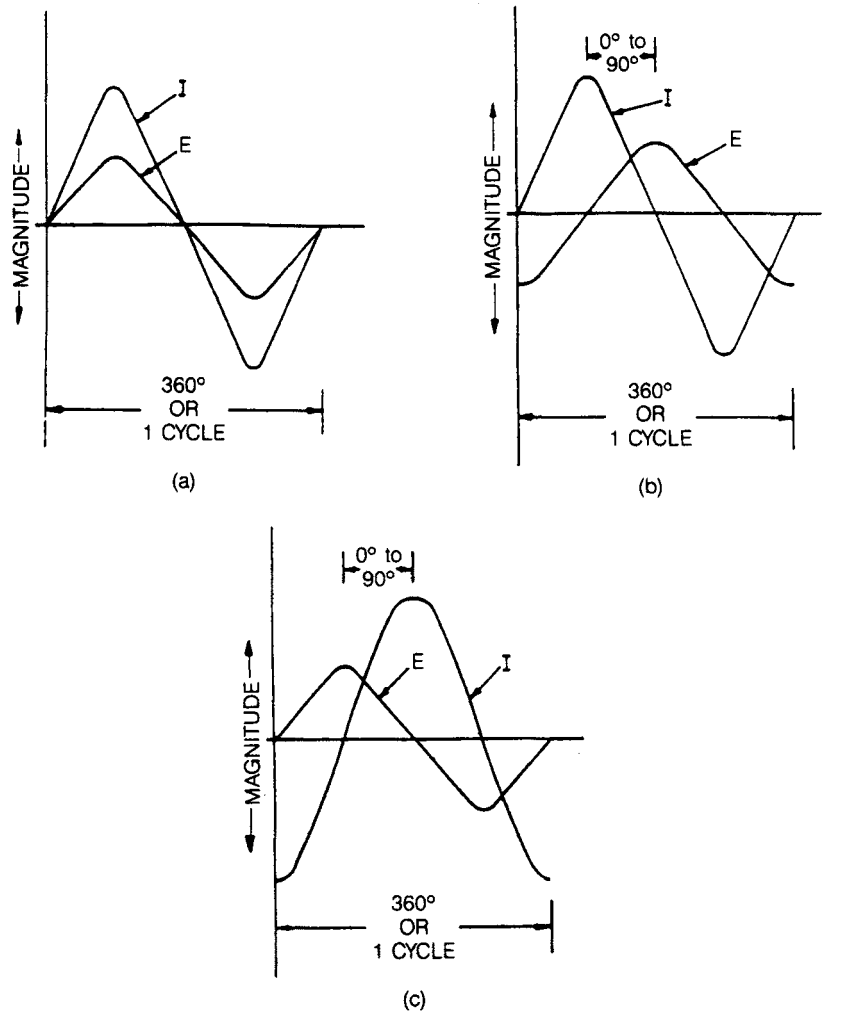


FIGURE 10.1 Alternating current patterns: (a) circuit with coinciding voltage and current waveforms, (b) current waveform leading voltage waveform, and (c) current waveform lagging voltage.

expressed in kilovolt-amperes (kVA), is the product of the effective voltage on the load (as measured with a voltmeter) and the effective current in the circuit (as measured with an ammeter). The ratio of the true power to apparent power, called the "*power factor*" (cosine of the phase angle), can represent a measure of energy efficiency. An ideal power factor would be 1.0 (100%), but the power factor for typical plant

systems ranges from 0.8 to 0.85 (80 to 85%) lagging. The power factor (PF) is calculated as follows:

$$\text{PF} = \frac{\text{kW}}{\text{kVA}} = \text{cosine} \varnothing \tag{10.1}$$

For example, if a boring mill operated at 100 kW and the apparent power was 125 kVA, then

$$\frac{(100 \text{ kW})}{(125 \text{ kVA})} = (\text{PF}) = 0.80$$

It is important to note that the power factor in a nonlinear environment does not follow these formulas or tables without filters or chokes installed on the harmonic generators.

TRANSFORMERS. There are two types of transformers used to decrease or increase voltage: step-down or step-up. A *transformer* consists of a set of windings around a core (coil), with a primary side that receives power and a secondary side that releases power.

A three-phase transformer containing three sets of coils may be connected in either a delta form or a Y form. In a delta form, each phase connects to another phase

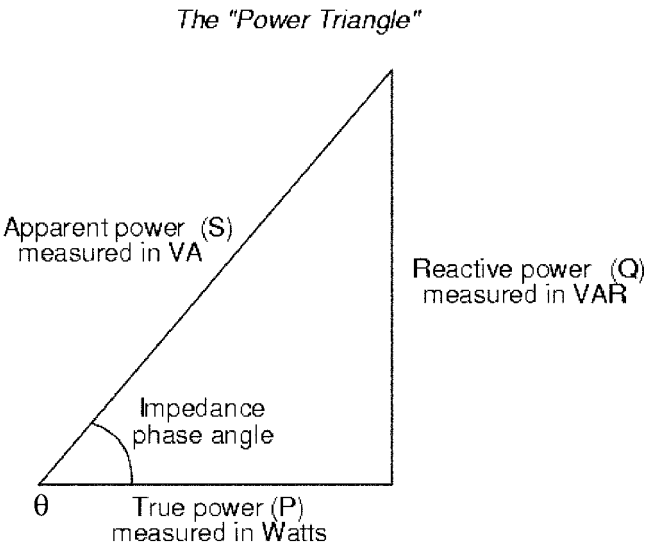


FIGURE 10.2 An example of the "Power Triangle" (Kuphaldt, 2007).

through a winding. In a Y form, each phase connects through a winding to a common point that is grounded as a safety feature. The primary and secondary connections are not necessarily the same. For example, the most common industrial step-down transformer includes a delta connection on the primary side and a Y connection on the secondary side.

Because power represents voltage times amperage, the higher the voltage delivered to a plant for a given power supply, the lower the amperage. In turn, the amperage squared multiplied by the resistance equals the power loss in wiring. As a result, the power company distributes power at the highest practical voltage to allow use of lower amperage and smaller wire.

High voltages in a plant increase the hazard of working with electricity and require more expensive insulated equipment. Therefore, a step-down transformer near the plant boundary will reduce the delivery voltage to a level usable in the plant. The most common form of power used in small plants comes from the Y winding on a transformer secondary, yielding 480 V between phases and 277 V to the ground. Higher voltages may be used within a plant to ease power distribution or to operate large motors. Typically, more than 373-kW (500-hp) systems or distribution systems as large as 4160 V (5 kV) can serve large plants.

RELAY COORDINATION. A *coordination study* is the process of determining the optimum characteristics, ratings, and settings of the power system's protective devices. The optimum settings are focused on providing systematic isolation of the faulted section of the system, leaving the remaining system in operation.

HARMONICS. *Harmonics* represent one of the component frequencies of a wave or alternating current, which is an integral multiple of the fundamental frequency. Based on a 60-cycle system, a third harmonics would have a frequency of 180 cycles. A harmonic analysis evaluates the steady-state effects of nonsinusoidal voltages and currents on the power system and its components. Some of the sources of these waveshape disturbances are direct-current rectifiers, adjustable-speed drives (ASDs), arc furnaces, welding machines, static power converters of all kinds, and transformer saturation.

BASIC ELECTRICAL FORMULAS. The relationships among current (I), voltage (E), and resistance (R) in a direct-current circuit are given as follows:

$$E = I \times R \tag{10.2}$$

For example, calculate the voltage if the amps are 2.0 and the resistance is 5 ohms.

Volts = 2.0 amps × 5 ohms
Volts = 10.0

Power consumed by a load in a direct-current circuit is expressed as follows:

$$P = I^2 \times R \tag{10.3}$$

For example, calculate the power if the amps are 2.0 and the resistance is 5 ohms.

Power = $2^2 \times 5$
Power = 20 watts

In an alternating-current circuit (single-phase, assuming the circuit only contains resistance), power is expressed as follows:

$$P = E \times I \tag{10.4}$$

For example, what is the power for a single-phase circuit if the volts are 10 and the amps are 2.0?

Power = 10 volts × 2.0 amps
Power = 20 watts

With a balanced three-phase system, the expression for power is

$$P = E \times I \times \text{Power Factor} \times 1.732 \tag{10.5}$$

For example, what is the power if the voltage is 240 across a three-phase motor, the current draw in any leg is 5 amps, and the power factor is 0.8?

Power = 240 volts × 5 amps × 0.8 × 1.732
Power = 1663 watts

TYPICAL ELECTRICAL DISTRIBUTION SYSTEMS

INTRODUCTION. The input for a distribution substation is typically at least two transmission or subtransmission lines to provide redundancy. Input voltage may be 115 kV, for example, or whatever is common in the area. The output represents a number of feeders. Distribution voltages are typically medium voltage (between

2.4 and 33 kV) depending on the size of the area served and the practices of the local utility. System safety and reliability are paramount. For this reason, there is substantial redundancy in most distribution systems.

TYPICAL LAYOUT. The electrical-distribution system for any plant can be shown on the single-line distribution diagrams for that particular plant. These diagrams show power sources for all of the units drawing power and all feeders consuming power. Figure 10.3 shows a diagram of a hypothetical plant distribution system in block form, and Figure 10.4 shows the same system in electrical engineering format. Table 10.1 lists symbols used on the diagram, as well as other commonly used symbols.

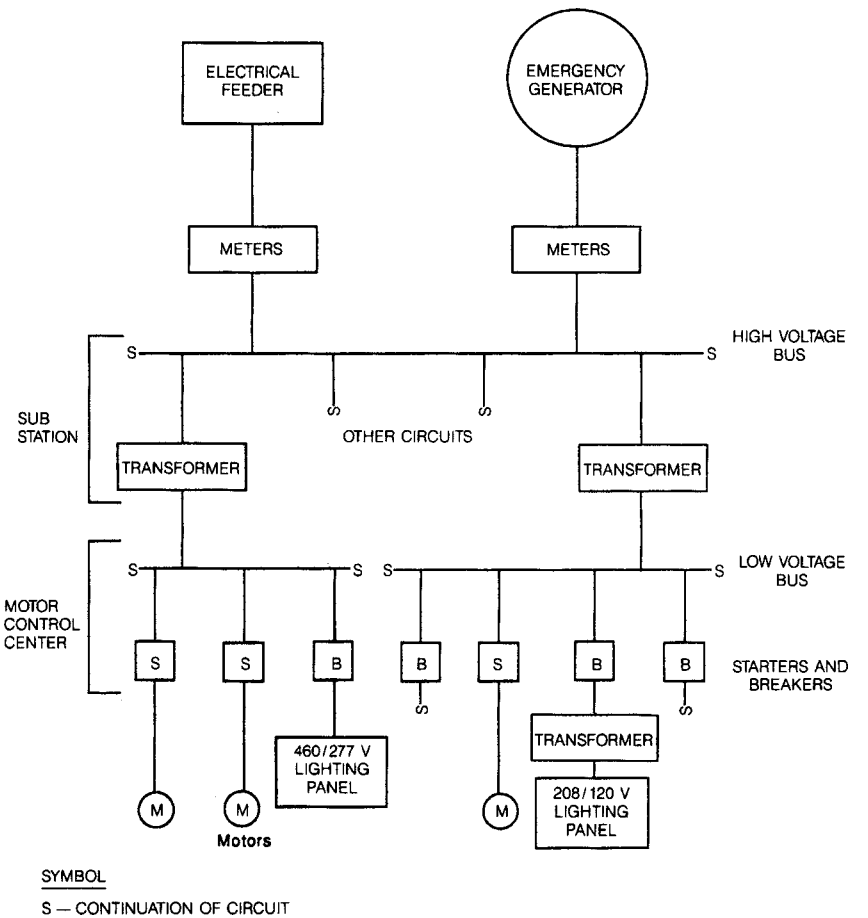


FIGURE 10.3 Block diagram of an electrical distribution system.

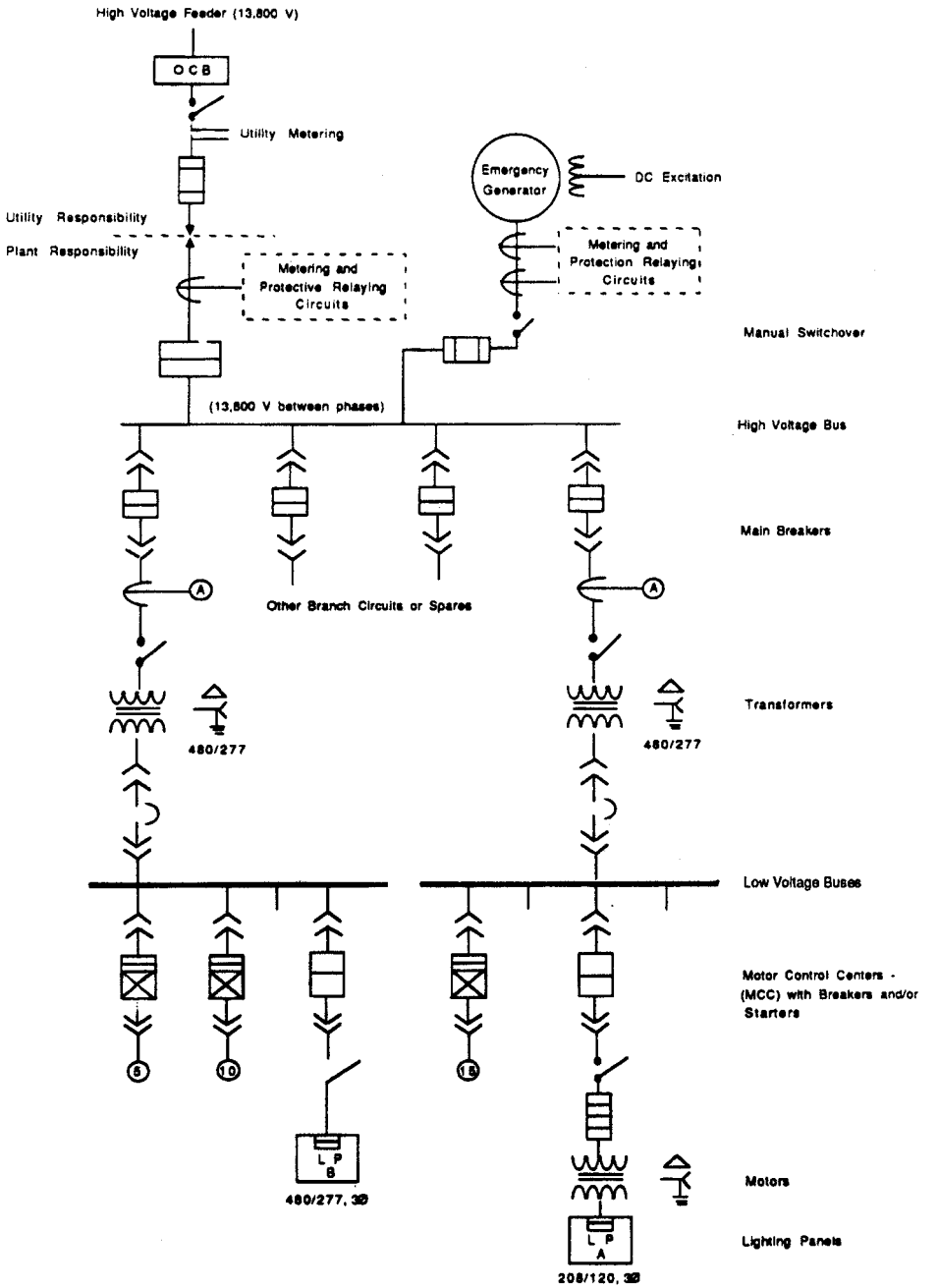
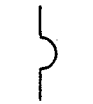
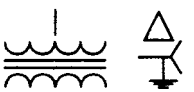
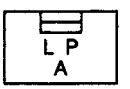


FIGURE 10.4 Abbreviated typical electrical distribution system (metering and protective equipment omitted).

TABLE 10.1 Typical electrical symbols.

OCS	Oil circuit breaker
100 50	Circuit breaker—air, three pole Top—frame number, Bottom—tripsetting
	Air circuit breaker
	Drawcut contacts (unit can be plugged in)
	Magnetic breaker
	Fuse
	Pothead (connection underground to overhead wire)
	Open switch—nonfusible
	Current transformer
A	Meter—type indicated in center (ammeter in this example)
 480 - 120/208 V	three-phase power transformer three-wire delta Wye, grounded neutral
	Magnetic starter/circuit breaker
 L P A 3Ø -4 wire 120/208 V	Lighting panel (protective device shown "A" designates panel identification)
3Ø	Phase indication
5	Squirrel-cage induction motor (horsepower indicated in circle)

In the example shown, the plant provides a transformer to change the voltage of its delivered power to a lower voltage for plant distribution. In many cases, however, the utility may provide the transformer, thereby supplying the plant with the normal distribution voltage for plant use.

In the diagram shown, the utility's high-voltage feeder and the plant's transformer deliver power to the plant. The utility provides its own metering and certain protective devices. The utility maintains the equipment it supplies, while the plant maintains all other equipment. For the case shown, the high-voltage power comes to a high-voltage bus. The plant's emergency generator also feeds the high-voltage bus in this example. Additionally, there can be other feeders operating either simultaneously, in parallel, or with a manual or automatic switchover.

In the largest stations, all the incoming lines have a disconnect switch and a circuit breaker. In some cases, the lines will not have both (i.e., only a switch or a circuit breaker is needed). Typically, these will also have a current transformer to measure the current coming in or going out on a given line.

Once past the switching components, the lines of a given voltage all tie in to a common bus. This is a number of thick metal bus bars (almost always three bars) because three-phase current is almost universal.

The most sophisticated substations have a double bus, in which the entire bus system is duplicated. Most substations, however, will not have a double bus because it is typically used for ultrahigh reliability in a substation whose failure could bring down the entire system.

Once buses are established for the various voltage levels, transformers may be connected between the voltage levels. These will again have a circuit breaker, much like transmission lines, in case a transformer has a fault (commonly referred to as a "short circuit").

Additionally, a substation always has the control circuitry and protective devices needed to command the various breakers to open in case some component fails.

A typical electrical-distribution system in smaller plants is 480/277 V (Y system). This system, with the neutral connection (a common connection in Y), economically supplies lighting loads at the 277-V level.

COMPONENTS OF A DISTRIBUTION SYSTEM

FEEDERS. Electricity is transmitted over large areas using ultrahigh voltage and low currents to limit voltage drop. This typically occurs through overhead lines that are protected with lightning arresters. Once delivered to substations, the voltage is

stepped down to the delivered voltage, which is typically 480 V-alternating current (V-ac). Once in the plant, engineers design a distribution system to power all the equipment in the plant. In an effort to create a high-reliability design, engineers will protect the transmission media by adding redundancy, breakers, lightning arresters, buried cable, emergency generators, and uninterruptible power systems (UPSs).

AUTOMATIC TRANSFER SWITCH. The automatic transfer switch (ATS) ensures system reliability by providing a continuous supply of power. An ATS can automatically sense the best source of power from two feeds and then direct appropriate opening and closing of motor-driven disconnect switches (circuit breakers) to connect that source to the load.

The primary purpose of the ATS system is to automatically sense loss or decrease of voltage, determine that an acceptable alternate source of voltage exists, and switch the load to that alternate source. A voltage of 120 V-ac obtained from potential transformers in preferred and alternate sources is continuously sampled to determine which source should feed the load. Should a fault current be detected in either the preferred or alternate source at the time of closure, the ATS will prevent the potentially damaging action.

SWITCHING FUNCTION. An important function performed by a substation is *switching*, which refers to the connection and disconnection of transmission lines or other components to and from the system. Switching events may be "planned" or "unplanned". A transmission line or other component may need to be de-energized for maintenance or for new construction (e.g., adding or removing a transmission line or a transformer).

To maintain reliability of supply, no company ever brings down its whole system for maintenance. All work that needs to be performed—from routine testing to adding entirely new substations—must be done while keeping the whole system running.

More importantly, perhaps, a fault may develop in a transmission line or any other component. Examples of this include a line that is hit by lightning and develops an arc, or a tower that is blown down by high winds. The job of substations is to isolate the faulted portion of the system. There are two main reasons for this. First, a fault tends to cause equipment damage and, second, it tends to destabilize the entire system. For example, a transmission line left in a faulted condition will eventually burn down. A transformer left in a faulted condition will eventually blow up. While these events are happening, the power drain makes the system more unstable. Disconnecting and isolating the faulted component quickly tends to minimize both problems.

SERVICE TRANSFORMERS. Service transformers "step down" the voltage from ultrahigh voltage to usable voltage. Many plants' equipment run on 480 V-ac and then have a local transformer to step the voltage down to 120 V-ac to power lighting panels. The primary side of the step-down transformer is the high-voltage side, and the secondary side is the customer load side. Typically, there is a main breaker that protects the transformer from the utility grid and can isolate the plant for load testing of generators. A power company typically will have a complex series of system monitors and breakers to prevent any one system from disrupting other clients on the distribution network. The secondary side will typically have disconnect switches and breakers to cut the power on demand or when a short is detected on the load side.

Service transformers typically step down the voltage from 26 400, 13 200, or 4160. These transformers are typically owned and maintained by the utility company. In some cases, the customer may elect to own and maintain the transformer. Typically, customer ownership is chosen when an attractive high-tension rate is offered. The customer must weigh the reduced energy costs against ownership and maintenance expenses.

TIE BREAKER. A tie breaker is used to connect two discrete sections of a unit substation or motor control center, which operate independently. Tie breakers are typically open. Usually, a Kirk Key (Kirk Key Interlock Company, Massillon, Ohio) interlock system is used to allow only two of the existing three breakers (two mains and a tie) to be operated at any one time.

PROTECTIVE RELAYS. Protective relays monitor and disconnect loads from the power source if protective-device parameters are exceeded. The main types of protective relays are overcurrent, feeder, voltage frequency, and motor and programmable logic controllers (PLCs).

STANDBY OR EMERGENCY POWER SUPPLY. Standby or emergency power can be supplied either through an "in-house" generator or a separate feeder from the utility. The standby or emergency generator shown in Figure 10.3 has a manual switchover system, an arrangement obviating the need for complex equipment that increases the installation cost and could malfunction. If the plant cannot withstand even a short period without power or if the plant is unattended during certain periods, then the switchover device should be automatic.

To avoid the cost of owning and maintaining an emergency generator, a WWTP may receive power from a separate utility-owned line, preferably a power line not fed from the same feeder or substation. Although switchover can be automatic, it is

typically manual, again to protect the utility. Depending on a plant's agreement with the utility, either the plant or the utility may control switchovers.

SWITCHGEAR. The term "switchgear", which is typically used in association with the electric power system, or grid, refers to the combination of electrical disconnects and/or circuit breakers used to isolate electrical equipment. Switchgear is used both to de-energize equipment to allow work to be done and to clear faults downstream. Switchgear is located anywhere that isolation and protection may be required (e.g., generators, motors, transformers, and substations). Although switchgear can be installed in any area protected from the weather, an enclosed, indoor location is preferable. While some outdoor installations are insulated by air, this requires a large amount of space.

SUBSTATIONS. The substation includes a main circuit breaker, the high-voltage bus, and several feeder breakers (called *circuit breakers*) supplying power to motor control centers (MCCs) and other electrical facilities. In some cases, the substation also includes a transformer.

Figure 10.5 shows a main step-down transformer in a large [more than 380 000-m^3/d (100-mgd)] WWTP. It is a delta/Y-type with 67 000 V on the primary side and 13 800-V

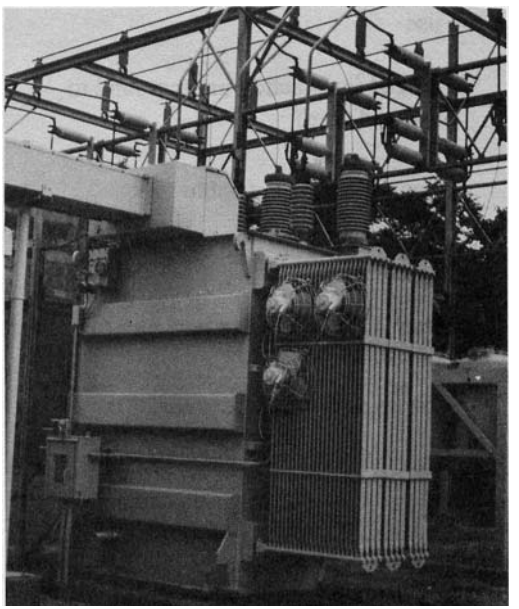


FIGURE 10.5 High-voltage transformer.

phase-to-phase on the secondary. High-voltage power comes in through insulated terminals on the top, and low-voltage power goes out through cables in the top duct to the substation bus. The transformer shown is cooled by oil, which circulates through an exterior cooling section. At another substation in the same plant (Figure 10.6), there are transformers that reduce voltage from 13 800 to 4160 V.

Figure 10.7 shows a 13 800-V breaker in the substation connected to the main transformer in Figure 10.5. The breaker is in the panel on the right (door open), and various meters and protective devices are shown to the left.

MOTOR CONTROL CENTER. The motor control center includes a series of steel cabinets that contain motor starters and breakers for other services. Typically, these devices are installed under cover because general-purpose enclosures are cheaper and easier to maintain. Power is distributed from the MCCs to motors and lighting panels. Typically, a transformer feeds one or more MCCs that are located near the units served. The MCCs, purchased as packaged units, include buses into which starters can be plugged. The MCCs can also accommodate special devices, such as PLCs, adjustable-frequency drives, and reduced-voltage starters.

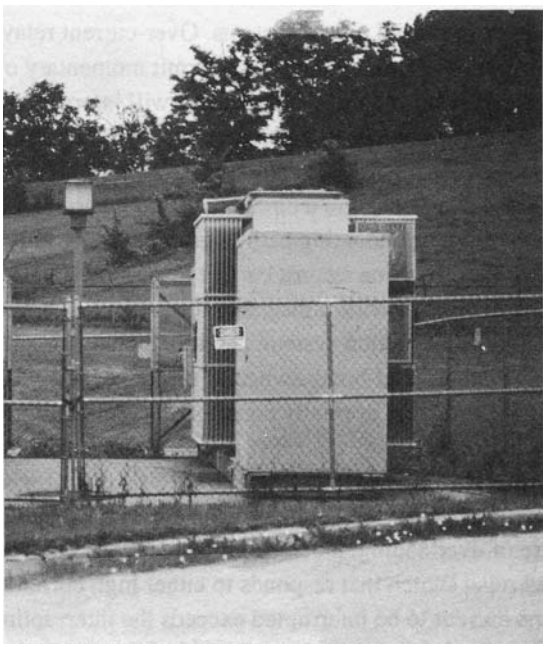


FIGURE 10.6 Intermediate-voltage transformer.

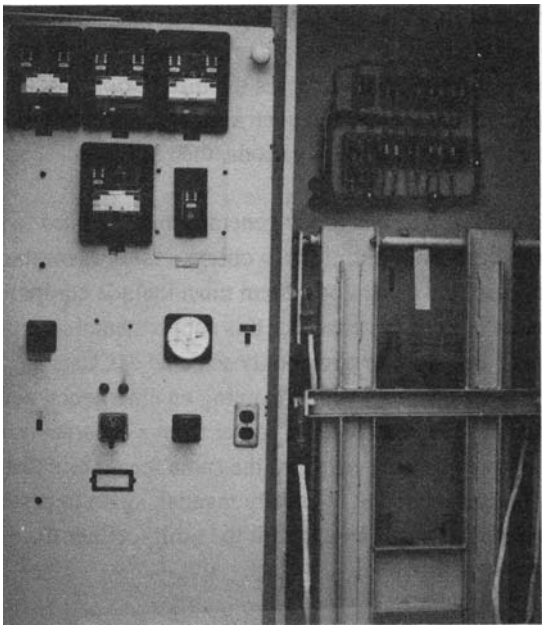


FIGURE 10.7 High-voltage circuit breaker.

The *starter*, a device that connects power to an electric motor, allows the motor to start. Motor starters contain coils, contacts, overload heaters, and springs. All these components can be replaced and/or repaired. Motor starters operate when the coil energizes. The starter controls the opening and closing of contacts that allow the flow of electrical power to the motor. Starters with built-in overload relays help protect the electric motor when the load becomes too great and threatens to overload and possibly damage the motor. In an overload situation, this type of protection can shut down the motor, thereby preventing it from overheating. Figure 10.8 shows an MCC in a WWTP. This motor control center has various cubicles that house starters with different capacity ratings.

MOTORS. While electric motors are only one component of an electrical drive, they are one of the most important. To obtain maximum efficiency and reliability from electric motors, considerable care must be given to their application, control, and protection. Industrial motor standards are published by the Institute of Electrical and Electronic Engineers (Piscataway, New Jersey), the American National Standards

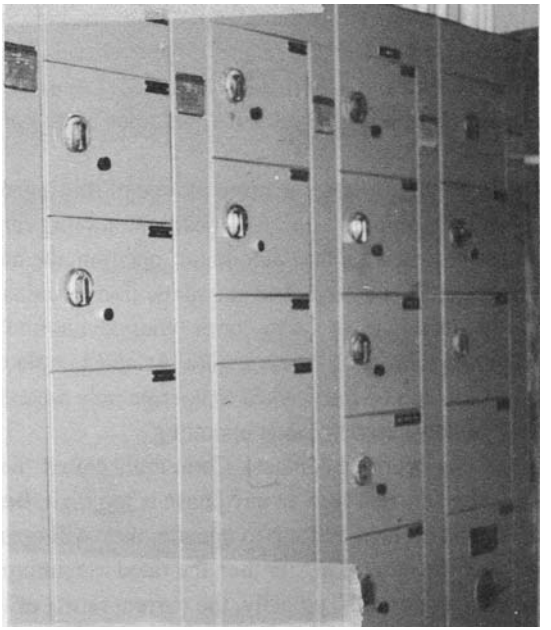


FIGURE 10.8 Motor control center.

Institute (Washington, D.C.), the National Electrical Manufacturers Association (NEMA) (Rossyln, Virginia), and Underwriters Laboratories Inc. (Northbrook, Illinois). These standards are continually improved and updated. Motors are rated by horsepower and duty cycle; it is important to know the load that will be driven and the torque requirements when selecting an electric motor. Motors can be either direct current or alternating current. Direct-current motors are suitable in load applications supplying large torque, while alternating-current motors, either synchronous or induction, are used more extensively commercially. The squirrel-cage-induction alternating-current motor is the most common, with a characteristic speed–torque relationship determined by its construction.

ADJUSTABLE-SPEED DRIVES. The following five types of ASDs are available:

- *Variable-frequency drives* are electronic devices that control the speed of the motor by controlling the frequency of the voltage at the motor. These devices are used in a wide range of applications and can provide constant-torque and

variable-torque operation. They are most efficient where the flow rates, speed, torque, etc. are not constant (e.g., wastewater pumping, aeration blower operation, or sludge handling). These units also affect power quality by producing harmonics in the system; such conditions can be corrected by line filters designed for the application. While ASDs save energy, they are complex electronic devices that require trained repair experts.

- *Direct-current ASDs* are electronic devices that control direct-current motors by changing the voltage applied to the motor. Direct-current ASDs are a traditional ASD device and are used almost exclusively for constant load (e.g., cranes, elevators, and hoists) and close-speed control.
- *Eddy-current drives* are electrical devices that use an electro-magnetic coil on one side of coupling to induce a magnetic field across a gap, creating an adjustable coupling. Eddy-current drives have been in wide use for more than 50 years in variable-torque, rough-duty, and high-starting torque applications. They are found in material-handling conveyors; heating, ventilating, and air conditioning (HVAC) pumps; and fans.
- *Hydraulic drives* are devices operating much like an automotive hydraulic transmission. Typical applications are found in constant-torque situations, difficult environments, and rough-duty applications. Hydraulic drives are found driving large pumps and conveyors.
- Mechanical devices can be used to control speed. Mechanical speed-control products include gearing, mechanical transmissions, and belt drives with variable-pitch pulleys.

BRANCH POWER PANEL. Branch power panels are supplied with power from a bucket of a MCC, which is transformed to low voltage (120 V-ac single-phase power) to supply circuit-breaker protection for building small power (e.g., lighting, receptacles, small fans, and motors).

LIGHTING PANELS. There are two basic types of lighting panels. Power comes to one unit as 480/277 V three-phase; the lighting operates at 277 V. This panel is used mostly for yard lighting, as well as lighting the larger process buildings. The other type of lighting panel serves a building, laboratory, or other facility with a number of convenient outlets for operating small equipment and power tools. A transformer precedes such a lighting panel to reduce the voltage to 120/208 V three-phase or 120/240 V single-phase.

LIGHTING CONTROLS. Lights can be turned on and off with simple manual switches, photoelectric cells, time clocks, motion detectors, and timers. Photocells, frequently used for outside lighting, require cleaning or replacement every 2 or 3 years. This task may be cumbersome because the photocells are typically in areas with difficult access and often require special equipment and cleaning. Accordingly, astrological time clocks are becoming popular. They run on an annual basis with the "power-on" time for night use increasing as winter approaches. The obvious disadvantage of such units is the need for clock resetting after a power outage.

Motion detectors conserve energy because the lights turn off when the space is vacant. Nonetheless, motion detectors are seldom used industrially. Simple timers that can be installed in a switch box operate more reliably than motion detectors. The timers can be set for the area's expected period of use. If a plant has a process computer, it can be used to turn lights on and off according to preprogrammed instructions. In all cases, override switches should be provided to accommodate access during emergency operation procedures.

LIGHTING. ***Lighting Intensity.*** Adequate lighting is needed for safety, efficient operation, and security at night. Individual efficiency has been shown to drop drastically when lighting levels are reduced at workstations.

The measure of lighting intensity on a surface is known as a lux (lx), or foot-candle (ft-c). In general, office and laboratory areas require lighting ranging from 345 to 1075 lx (32 to 100 ft-c). Reading and close work require higher ratings up to 1075 lx. Shops require 538 to 1615 lx (50 to 150 ft-c), with localized spotlighting requiring higher values. Outside areas, such as parking lots, require from 11 to 215 lx (1 to 20 ft-c), depending on the expected levels of activity. Because all lighting diminishes with dirt buildup on the fixtures and filament deterioration, measurements should follow a few months of usage to determine the adequacy of the actual lighting level. Recommended lighting levels for various work functions can be obtained from any manufacturer of lighting equipment.

Incandescent Lights. The types of lights most commonly used in WWTPs are incandescent, fluorescent, and high-intensity discharge (HID). Incandescent light, the oldest form of lighting, uses the most energy per lux and has the shortest life. Incandescent bulbs operating at a lower voltage than rated last longer, but their efficiency is lower. Because incandescent fixtures are more compact and less expensive, incandescent lights are often used for spotlighting and lighting closets and other areas that require lighting for only short periods. Additionally, because of their lower cost,

incandescent lights with a heavy enclosure are often used in areas where explosive vapors may be present.

Fluorescent Lights. Fluorescent lighting is typically provided via long tubes. These tubes are more expensive than the simple electric light bulb, and fluorescent fixtures typically cost more than incandescent fixtures. Nevertheless, fluorescent lighting is typically more economical than incandescent lighting because it uses power more efficiently; in addition, a tube lasts as much as eight times longer than an incandescent bulb.

Fluorescent lighting provides good color, similar to that of incandescent lighting. Its uses include illuminating WWTP offices and laboratory areas. Some fluorescent lights require a short time for the arc to be struck; however, most industrial lights have instant-start capability.

High-Intensity Discharge Lights. Three common types of HID units are mercury vapor, high-pressure sodium vapor, and metal halide. All of these types require a few minutes before reaching full intensity because they incorporate a circuit to heat and vaporize the metal or compound used in the lamp. Mercury vapor lamps have a long life and are cheaper than other HID units. Metal halide lamps are more efficient than mercury vapor lamps, but they cost more and typically are unavailable in small sizes. Although metal halide or mercury vapor lights may be needed in rare cases where color rendition is required, high-pressure sodium vapor units are typically best for HID lighting applications because of their low cost, long life, and efficient power use.

Although low-pressure sodium vapor units, which are more efficient than the other types discussed, still exist, they are cumbersome and have a much shorter life than the high-pressure sodium type. Most HID lights are used in areas that must remain illuminated for a long period of time (e.g., yard lighting required for the entire night and lighting in work or process areas where it is impractical to turn the lights on and off frequently). In such areas as pump rooms and switch-gear rooms, where lights can be turned off periodically to save energy, the fluorescent light is preferred because of the time required by HID lights to reach full intensity. In the past, HID lights, because of their brilliance, were not recommended where the luminaire would be close to a person's eyes. However, recently developed luminaires allow use of HID lights in areas with low ceilings.

Emergency Lighting. Emergency lighting is required for illuminating critical control areas and for allowing egress from an area if the normal lights go out. An emergency generator that starts automatically with a power failure is wired separately to turn on emergency lights in critical areas. Instead of an emergency generator, battery packs are

often used for evacuation. Sometimes the lights are attached to the battery unit. Battery packs are trickle charged using an alternating-current source and a built-in rectifier. They are connected to the same alternating-current circuit that supplies the normal lighting and thereby sense the loss of alternating current power.

CONTROL CIRCUITRY. Plant supervisors should understand the control diagrams for the equipment installed in their plant; therefore, they should request complete legends for the control-circuit diagrams.

Control circuitry for starters, shown on ladder diagrams, provides for control power as single-phase, with one side as ground and the other side as potential. Control diagrams for two hypothetical circuits are shown in Figure 10.9.

In the case of Circuit A, pressure on the start button allows current to flow through the stop circuit and closed switches [limit switch (LS) and time switch (TS)] to the main coil in the starter (M) and then through the closed overload contacts—one for each phase. As the main coil becomes energized, it pulls the three-phase contactor for the motor or other devices into the closed position, allowing the unit to start. Simultaneously, contacts labeled "MA" are opened or closed, depending on their original state. Contact MA, shown below the start button, allows the main coil to stay energized, even after the release of the start button. When the stop button is pushed, or the limit switch, the time switch, or an overload opens, the coil is de-energized and the motor stops. For example, the limit switch, external to the unit, may open on a high-liquid level. The time switch will open after a preprogrammed period elapses.

The circuit (Figure 10.9) illustrates a different type of starting switch, such as a level switch. With the switch in the off position, nothing runs. In the hand position, the motor runs. In the automatic position, the motor only runs if the remote limit switch is closed. The automatic line contains an interlock from Circuit A. This means the motor or other device for Circuit A must be energized before Circuit B can operate. For example, a vacuum filter can be interlocked to operate only when the conveyor that removes the dewatered solids is operating.

Both diagrams include overload contacts, which are actuated by overload heaters that sense motor current. Because the overload contacts depend on heat buildup to operate, they will open if a high current flows briefly or if a current higher than the rated maximum motor current continues for a longer period. Typically, the current rating of the overload contacts can be changed by replacement with a different size, or, in some cases, they can be manually adjusted.

Operators must learn why an overload occurred and correct the abnormal condition before restarting a tripped unit. Restarting a tripped unit two or more times within a short period may cause the motor or another electrical component to overheat and fail.

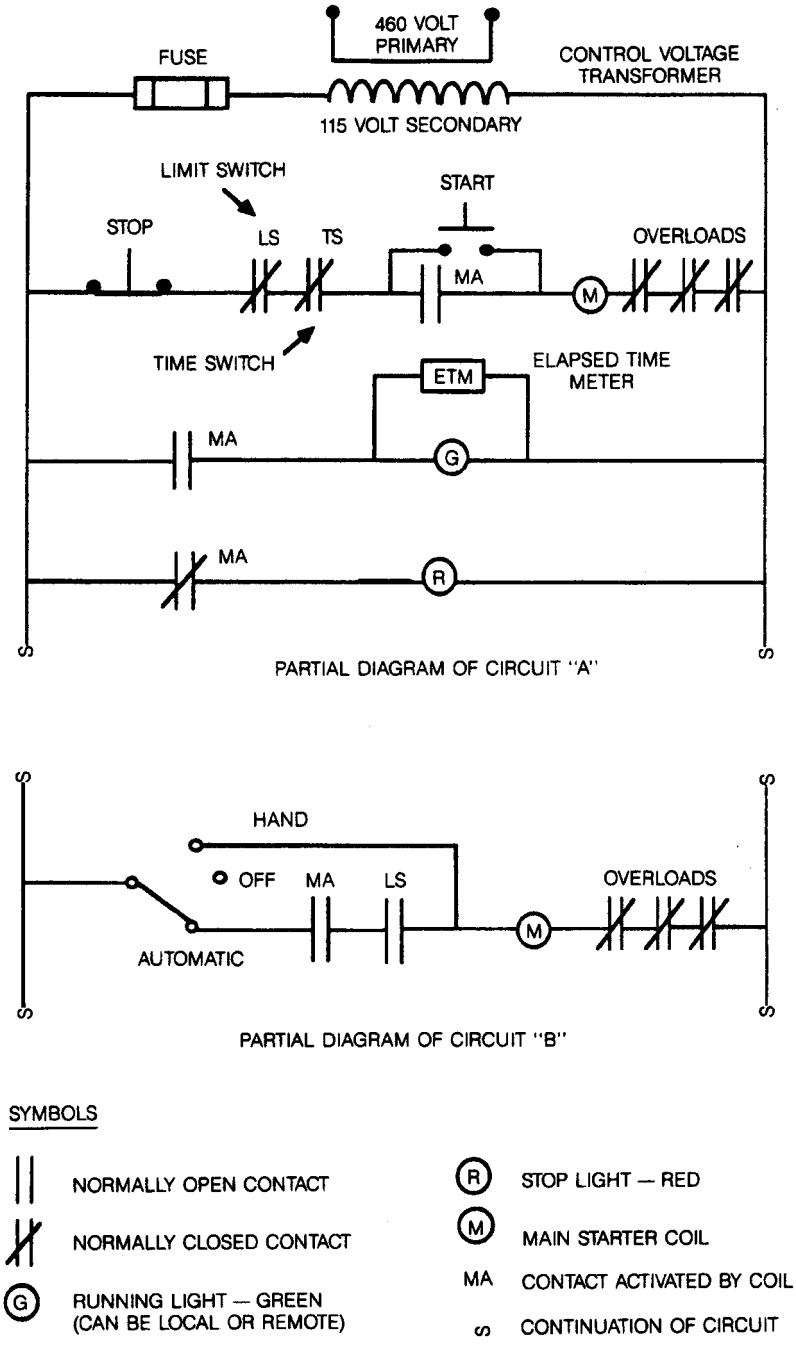


FIGURE 10.9 Circuit control diagrams.

The best means of motor protection is to apply the type of start switch used in Circuit A. However, a disadvantage of Circuit A is that it deactivates on power failure; the motor must then be restarted manually when power returns. Conversely, the motor in Circuit B, with its hand-off-automatic switch, will start when power returns and the other switches are closed. A disadvantage of Circuit B is that the motor is not adequately protected from overload. If an overload occurs, the heater will restore contact after it cools. Then, the motor will attempt to start, and the heater will kick it out again. After three or more start–stop cycles, the motor may burn up. To prevent such multiple starts, additional protection can be installed.

If a motor coil develops an open circuit, the motor will still run, but in a single-phase mode; thus, it will eventually burn out. To protect the motor from an open circuit, a phase-failure relay will trip the starter. Various other types of timers and interlocks can be incorporated into starter circuits. Good maintenance practice includes having spare contacts for a starter to allow the addition of other functions in the future.

PROGRAMMABLE LOGIC CONTROLLERS. Programmable logic controllers are solid-state devices (a member of the computer family) that incorporate most of the control features of hard-wired relays. However, PLCs offer the advantage of being readily changed. They are capable of storing instructions to directly control such functions as sequencing, timing, counting, arithmetic, data manipulation, and communication for process control. A programmable controller has two basic sections: a central processing unit and an input–output interface system to field devices. Incoming signals from such devices as limit switches, analog sensors, selector switches, etc. are wired to the input interfaces; devices to be controlled (e.g., motor starters, solenoid valves, pilot lights, etc.) are connected to the output interfaces. The central processing unit accepts input data, executes the stored control program, and updates the output devices.

Programmable logic controllers can monitor electrical distribution systems and make critical decisions in milliseconds to maintain the health of the system. They can reallocate loads, start and stop emergency generators, and alert operators to potential problems.

UNINTERRUPTIBLE POWER SYSTEMS. Critical equipment should be protected from power losses with UPSs. They ensure continuity of power. Alternating-current power is supplied to a battery/charger system. The output of the battery is then connected to an inverter, which converts direct-current power to alternating-current power at 60 cycles. In the event of an alternating-current power failure, the battery maintains power to the system via the inverter. The input voltage to the UPS

depends on the load served. Typically, the input voltage is 120-V single-phase or 480-V three-phase. The device is powered from a branch power circuit. Uninterruptible power systems are used to power computers, paging systems, and alarm systems.

INSTRUMENTATION AND CONTROL POWER. Critical instruments and PLCs can be powered by UPS systems. Most of the remote instrumentation in a plant is powered without UPS. In these cases, power comes from a branch power circuit.

Typical instrumentation and control power is either 120 V-ac or 24 V-direct current (V-dc) power. In some cases, the instrument is loop-powered, which means that the power to run the instrument comes from the 24 V-dc power supply within the PLC input/output card.

CAPACITORS. The concept of a capacitor as a kilovar generator is helpful in understanding its use for power factor improvement. A capacitor may be considered a kilovar generator because it supplies the magnetizing requirements (kilovars) of induction motors.

This action may be explained in terms of the energy stored in capacitors and induction devices. As the voltage in alternating-current circuits varies sinusoidaly, it alternately passes through zero voltage points. As the voltage passes through zero voltage and starts toward maximum voltage, the capacitor stores energy in its electrostatic field, and the induction device gives up energy from the electromagnetic field. As the voltage passes through a maximum point and starts to decrease, the capacitor gives up energy and the induction device stores energy. Thus, when a capacitor and an induction device are installed in the same circuit, there will be an interchange of magnetizing current between them. The leading current taken by the capacitor neutralizes the lagging current taken by the induction device. Because the capacitor relieves the supply line of supplying magnetizing current to the induction device, the capacitor may be considered to be a kilovar generator because it actually supplies the magnetizing requirements of the induction device.

Power-factor correction capacitors are installed in either of two locations: (1) at a MCC to correct for the total load on the MCC, which is a compromise because all of the connected loads are not energized at the same time; and (2) directly, at all motors that are 19 kW (25 hp) and larger. The latter method then corrects the power factor of the load to which it is connected when energized.

CONDUIT AND WIRING CONSIDERATIONS. For safety and mechanical protection, most wiring in WWTPs is enclosed in rigid or flexible conduit. Open-tray

wiring is typically restricted to large cables or to shops where wiring changes are frequent and the atmosphere is not detrimental to the conductor installation.

Wiring can be either copper or aluminum. With aluminum wiring, copper-to-aluminum junctions require careful construction. When copper prices drop, the incentive to use aluminum is reduced.

Insulation ratings are typically higher than the voltages being used. For example, 460-V systems typically have 600-V insulation. Special insulation is available to accommodate high or low temperatures or corrosive conditions.

The National Electrical Code Handbook (2005) specifies the minimum allowable wire and conduit sizes, number of wires of each size in a conduit of a given size, wire junctions, and many other aspects of wiring. Local jurisdictions may impose more rigorous standards; many local power companies also have their own rules for distribution-system wiring. Any changes or additions to electrical equipment must conform to the latest edition of the National Electrical Code or other applicable standards. Electrical installations typically require inspection to ensure that they comply with local and federal rules.

Stress cones prevent insulation failure at the termination of a shielded cable. This is caused by the high concentration of flux and the high potential gradient that would otherwise exist between the shield termination and the cable conductor. Precautions must be taken to ensure that the termination is free of dirt and foreign matter, and insulating compounds and tapes must be applied in a prescribed manner. A typical use for stress cones would be in pad-mounted transformers, switchgear, high-voltage motor installations, or in most applications where shielded cable is being terminated. Typically, stress cones are not provided by the motor manufacturer, but are made by the motor installer.

GROUNDING. The main reason why grounding is used in electrical-distribution networks is safety. Indeed, when all metallic parts in electrical equipment are grounded, there are no dangerous voltages present in the equipment case if the insulation inside the equipment fails. If a live wire touches the grounded case, then the circuit is effectively shorted, and the fuse or circuit breaker will isolate the circuit. When the fuse is blown, the dangerous voltages are safely dissipated.

Safety is the primary function of grounding, and grounding systems are designed to provide the necessary safety functions. Although grounding also has other functions in some applications, safety should not be compromised in any case. Grounding is often used to provide common ground reference potential for all equipment, but the existing building grounding systems might not provide good enough ground potential for all equipment, which could lead to potential ground difference and ground-loop problems that are common in computer networks and audio/video systems.

PROTECTIVE DEVICES. Overcurrent relays are the most typically used devices for short-circuit (direct-connection, phase-to-phase, or phase-to-ground) protection of industrial power systems. Overcurrent relays have adjustable current settings. Time-delay relays permit momentary overcurrent without opening the breaker. A phase failure relay will interrupt power to equipment with either current loss in a phase or severe imbalance among the power-line phases.

If lightning causes overvoltage in a circuit, a lightning arrestor limits the overvoltage by providing a conducting path to the ground of low impedance. Many other devices for protection against current disruption are also available.

Circuit-opening devices provide a means of disconnecting a faulty circuit or equipment from the distribution system. Devices include circuit breakers, fuses, interrupter switches, load-break switches, disconnect switches, and contactors. Distribution protection typically consists of either equipment or circuit protection.

Protection devices that are not limited to the specific circuit with the fault protect the rest of the system from the faulty element. For example, if a motor overheats because of overloading, it can be protected by a *contactor*—a magnetically operated relay switch that responds to either high current or high temperature. If the current to be interrupted exceeds the interrupting capacity of the contactors, a circuit breaker or fuse should be installed in the circuit.

MAINTENANCE AND TROUBLESHOOTING

GENERAL. The vast majority of electrical maintenance should be predictive or preventive. This section focuses exclusively on these activities. There are four cardinal rules to follow in any maintenance program: (1) keep it clean, (2) keep it dry, (3) keep it tight, and (4) keep it frictionless.

In general, the most probable cause of electrical equipment failure is foreign contamination (e.g., dust particles, lint, or powdered chemicals). Dirt buildup on moving parts will cause slow operation, arcing, and subsequent burning. Moreover, coils can short-circuit. Dirt will always impede airflow and result in elevated operating temperatures.

Electrical equipment always operates best in a dry atmosphere, where corrosion is eliminated. Moisture-related grounds and short circuits are also eliminated. Liquids other than water (e.g., oil) can cause insulation failures or increase dirt and dust buildup.

Most electrical equipment operates at a high speed or is subjected to vibration. The term "tightness" is not a contest of human strength; rather, it must always be a calculated or specified value and be obtained with a torque wrench. When aluminum con-

ductors are used, each mechanical junction should be made with a specific torque. Insufficient torque will result in localized heat at the joint and, ultimately, failure. Excessive torque will result in deformation.

Any piece of equipment or machinery is designed to operate with minimum friction. Dirt, corrosion, or excessive torque will often cause excessive friction.

Of the four cardinal rules, none is essentially electrical in nature. The failure of a bearing in a motor can lead to an ultimate motor winding failure that is electrical, but the root cause of the failure could have been mechanical.

The goal of any electrical preventive maintenance program is to minimize electrical outages and ensure continuity of operation. The bulk of the program centers on proactive tasks. A successful program includes not only these proactive tasks with appropriate documentation, but also a consistent commitment to obtain reliable equipment that has been properly installed. This commitment should be evident in any design construction upgrade or replacement work. It is extremely difficult to maintain equipment that has not been soundly engineered or that has become outmoded, obsolete, or overloaded during plant growth. Because a program is implemented by personnel, not computers, qualified field personnel are required for a successful program.

PREVENTIVE AND PREDICTIVE MAINTENANCE SPECIFICS. A good preventive maintenance program includes checking MCCs annually. The time interval between inspections can vary depending on area cleanliness, atmosphere, operating temperatures, vibration, and overall operating conditions. Maintenance involves cleaning the equipment and checking for obvious defects (e.g., burned relays, damaged insulation, fire, ant infestation, unsealed conduits entering boxes, and loose leads). The maintenance crew should inspect relays for loosened terminals and lock screws; examine the coils, resistors, wiring, toggles, and holding devices; and look for dirty or burned contacts, dirty or worn bearings, and foreign material in magnetic air gaps. Power should be turned off during the work. However, if power shutdown is impossible, a vacuum cleaner with a plastic tip can be used. Other specific maintenance instructions are contained in the *Switch Gear and Control Handbook* (Smeaton, 1998).

All mechanisms at unit substations should be checked using the manufacturer's recommended schedule and procedure. Breakers should be drawn out and checked for signs of arcing. Additionally, all appropriate components should be cleaned, and adjustments should be made to the mechanisms as required.

Every 2 to 3 years, the overload devices should also be checked. Although equipment can be purchased if the plant performs this work, contracting the work typically is more practical. Many major equipment manufacturers can provide this service.

For oil-filled transformers, the oil level and temperature should be checked in accordance with manufacturer's recommendations. At least every 3 years, the oil should be sampled and replaced or re-refined. The oil should also be checked for moisture and alkaline content. Electrical service companies can perform the sampling, even while the transformer remains in service. Transformer cooling fans should be checked periodically (follow the operations and maintenance manual guidelines). Transformer top bushings should be checked for contamination at intervals recommended by the manufacturer. Some transformers have a nitrogen blanket that eliminates moisture buildup in the oil. The nitrogen gas bottle should also be checked at intervals recommended by the manufacturer.

Standby generators should be exercised with load monthly. Testing should allow the generator to reach its operating temperature. The inspection should include a check of the starter batteries or compressed air starter.

Critical motors should be tested for integrity of insulation; additionally, every 5 to 6 years they should be sent out for testing of the windings, bearing inspection, cleaning, re-varnishing, and baking. Table 10.2 provides a preventive maintenance checklist for capacitors.

TABLE 10.2 Capacitor preventive-maintenance annual checklist.

Component	Condition	Result
Case	Physical damage Overheating Discoloration Leaks, puncture	Replace. Check with U.S. Environmental Protection Agency authority for polychlorinated biphenyl-filled apparatus.
Structure	Ventilation	Area kept clean
Site	Safety	Isolation, fenced enclosure
	Rust peeling	Refurbish, paint
	Identification	Engraved nameplates
Fuses	Continuity	Self-indicating fuses, check with ohmmeter
Bleeder-resistor		Check with manufacturer for resistor values
Nominal operating conditions	Operating voltage and currents	7-day profile with recording meters (±10% of rated values) 7-day temperature profile (50 to 90 °C if indoors) Calculate kilovolt-amperes and compare to nameplate values
Insulation	Breakage, cracks	Replace damaged housing Megger from bushings to case, 1000 megohms minimum

Cables carrying 600 V or more should be tested for insulation integrity at intervals recommended by the manufacturer. The voltage should be slowly raised while reading the microamps. The plot (microamps versus voltage) should be a straight line. A rapid change of slope is indicative of failure. If the cable has a minor failure, going immediately to full load can blow the cable. Therefore, it is important to inspect cables for signs of corona (a white powdery residue). This residue can perpetuate and cause cable insulation failure; so, all residue should be cleaned and neutralized. Most electrical service contractors will use direct current to check the cable.

A frequently overlooked aspect of preventive maintenance is checking electrical grounds. Electrical grounds of machinery, equipment, and buildings should be checked every 2 to 3 years and corrected as necessary.

Emergency lights should be checked at least quarterly. Battery-powered lights should preferably be self-diagnostic (i.e., they should have devices to indicate when a fault exists). At least once each quarter, emergency lights should be turned on for at least 30 minutes. If this procedure is not followed, the battery will deteriorate.

Lighting fixtures should be cleaned annually or more often if recommended by the manufacturer. For fluorescent fixtures, both the diffuser (outer cover) and reflector should be cleaned. When one tube burns out in a fluorescent fixture, all of the tubes should be replaced because of the expected short remaining lives of the others. Where there are large groups of fixtures in a given area, the most economical approach is to relamp all fixtures after a period of time somewhat shorter than their rated life, or, if a light meter is available, when brightness diminishes to a predetermined level.

The following is a supplemental list of preventive and predictive maintenance activities for various electrical components (refer to manufacturer recommendations for task frequency):

Liquid-filled transformers

- Verify oil type and level
- Check top bushings for contamination
- If applicable, inspect nitrogen supply system
- Cycle fans to ensure proper operation
- Verify grounding
- Conduct Doble power-factor test
- Perform Doble excitation test
- Conduct insulation resistance test
- Perform dielectric fluid quality test
- Analyze dissolved gas

Dry transformers (more than 1000 kVA)

- Doble power-factor test (medium-voltage units)
- Doble tip-up test (medium-voltage units)
- Doble excitation test (medium-voltage units)
- Insulation resistance test
- Turn-to-turn ratio test
- Core, coil, and vent cleaning and vacuuming

Oil-filled circuit breakers

- Doble power-factor test
- Insulation resistance test
- Breaker cleaning and lubrication
- Mechanical and electrical function check
- Oil integrity test

Medium-voltage circuit breakers

- Doble power-factor test
- Insulation resistance test
- Breaker cleaning and lubrication
- Mechanical and electrical function check
- Contact resistance test

Medium-voltage cables

- Direct-current high-potential test
- Doble power-factor test
- Doble tip-up test
- Connection inspection and tightening
- Terminal inspection

Medium-voltage, metal-enclosed switches

- Insulation resistance test
- Contact resistance test
- Connection cleaning, inspection, and tightening
- Proper operation of space heater
- Mechanical operation test

Medium-voltage starters

- Insulation resistance test
- Contact resistance test
- Connection cleaning, inspection, and tightening
- Proper operation of space heater
- Mechanical/electrical operation tests

Medium-voltage motors

- Polarization index test
- Winding resistance test
- Insulation resistance test

Arresters

- Doble power-factor test
- Porcelain/polymer surface cleaning
- Connection tightening

Substation batteries and chargers

- Specific gravity test
- Battery load test
- Connection cleaning and inspection
- Battery-charger operational test

Capacitor banks

- Connection cleaning and inspection
- Porcelain surface inspection and cleaning
- Fuse and fuse-holder cleaning and inspection
- Operational checks

Ground resistance

- Three-point fall-of-potential test
- Ground connection inspection

Protective relays

- Relay cleaning and inspection
- Connection tightening
- Contact cleaning and inspection
- Injection test and calibration

Indicating meters—voltage/current

- Meter cleaning and inspection
- Connection tightening
- Injection test and calibration

Watt-hour meters

- Meter cleaning and inspection
- Connection tightening
- Injection test
- Calibration

Low-voltage power circuit breakers

- Primary/secondary current injection test
- Contact resistance test
- Insulation resistance test
- Contact assembly cleaning and inspection
- Mechanical component cleaning, inspection, and lubrication

Low-voltage, molded-case, bolted-in circuit breakers

- Visual inspection
- Cleaning, inspection, and exercise

Low-voltage switchgear

- Insulation resistance test
- Cleaning and visual inspection
- Bolted connection inspection (check for signs of overheating)
- Verification of operational functions
- Indicating-lamp check

Low-voltage switches

- Contact resistance test
- Insulation resistance test
- Connection cleaning, inspection, and tightening
- Mechanical operation test

Low-voltage MCCs

- Insulation resistance test
- Cleaning and visual inspection
- Bolted connection inspection (check for signs of overheating)
- Verification of operational functions
- Indicating-lamp check

Aerial switches

- Porcelain surface cleaning and inspection
- Connection cleaning and inspection
- Contact surface cleaning and inspection
- Mechanical operation tests
- Inspection via binoculars

Aerial buswork

- Porcelain surface cleaning and inspection
- Bus connection cleaning and inspection
- Fuse holder cleaning and inspection

Power distribution system

- Thermographic infrared inspection while system is energized and under full load

TROUBLESHOOTING. Troubleshooting requires a good quality volt-ohmmeter and the usual mechanic's tools. With the volt-ohmmeter, a mechanic can determine whether wiring is grounded and whether insulation is in good condition. On submersible pumps, for example, phase-to-ground can be checked periodically. A resistance reading that drops below previous readings may indicate the beginning of leakage into the windings, requiring overhaul of the pump seal.

If a motor starter trips a motor, leads can be disconnected and the windings checked, reading each phase-to-ground. If the volt-ohmmeter shows a low ohm reading, the phase is grounded. Even if checking the motor phase-to-ground reveals no short, the motor may still have failed phase-to-phase. This possibility cannot be checked routinely, unless the resistance of each winding is known. If the phase-to-ground check does not indicate a defective motor, then further checking must begin with the starter. The staff electrician disconnects motor wires from the starter and again checks phase-to-ground on the motor leads. Bad wiring may be indicated; however, if that is not the case, the motor leads should be disconnected and the starter energized. If the starter holds, then a phase-to-phase breakdown may exist, possibly requiring motor rewind or replacement. Table 10.3 (WPCF, 1984) provides a comprehensive troubleshooting guide for electric motors.

A review of the manufacturer's operations and maintenance manuals for the plant's equipment may disclose other electrical maintenance tasks that can be accomplished by a capable general maintenance person. Unless the facility has a well-trained electrician, complex electrical troubleshooting, particularly for high-voltage equipment, should be contracted. The plant supervisor should arrange for one or more electrical contractors to provide 24-hour service.

RELAY COORDINATION

A coordination study is the process of determining the optimum characteristics, ratings, and settings of the power system's protective devices. The optimum settings are focused on providing systematic interruptions to the selected power system segments during fault conditions.

Coordination means that downstream devices (breakers/fuses) should activate before upstream devices. This minimizes the portion of the system affected by a fault or other disturbance. At the substation level, feeder breakers should trip before the main. Likewise, downstream panel breakers should trip before the substation feeder supplying the panel.

A protective device coordination study is performed to select proper protective devices (e.g., relays, circuit breakers, and fuses) and to calculate protective relays and circuit-breaker trip unit settings.

A protective device coordination study is performed either during the design phase of a new system to verify that protective devices will operate correctly in an existing system, or when the protective devices are not operating correctly. It is important to note that utility companies can change to a higher level of fault current, which would necessitate changing relay settings.

TABLE 10.3 Troubleshooting guide for electric motors.

Symptoms	Cause	Result*	Remedy
1. Motor does not start. (Switch is on and not defective.)	a. Incorrectly connected.	a. Burnout	a. Connect correctly per diagram on motor.
	b. Incorrect power supply	b. Burnout	b. Use only with correctly rated power supply.
	c. Fuse out, loose or open connection.	c. Burnout	c. Correct open circuit condition.
	d. Rotating parts of motor may be jammed mechanically.	d. Burnout	d. Check and correct: 1. Bent shaft 2. Broken housing 3. Damaged bearing 4. Foreign material in motor.
	e. Driven machine may be jammed.	e. Burnout	e. Correct jammed condition.
	f. No power supply.	f. None	f. Check for voltage at motor and work back to power supply.
	g. Internal circuitry open.	g. Burnout	g. Correct open circuit condition.
2. Motor starts but does not come up to speed.	a. Same as 1-a, b, c above.	a. Burnout	a. Same as 1-a, b, c above.
	b. Overload.	b. Burnout	b. Reduce load to bring current to rated limit. Use proper fuses and overload protection.
	c. One or more phases out on a three-phase motor.	c. Burnout	c. Look for open circuits.
3. Motor noisy (electrically).	a. Same as 1-a, b, c above.	a. Burnout	a. Same as 1-a, b, c above.

TABLE 10.3 Troubleshooting guide for electric motors (*continued*).

Symptoms	Cause	Result*	Remedy
4. Motor runs hot (exceeds rating)	a. Same as 1-a, b, c above.	a. Burnout	a. Same as 1-a, b, c above.
	b. Overload	b. Burnout	b. Reduce load.
	c. Impaired ventilation.	c. Burnout	c. Remove obstruction.
	d. Frequent start or stop.	d. Burnout	d. 1. Reduce number of starts or reversals. 2. Secure proper motor for this duty.
	e. Misalignment between rotor and stator laminations.	e. Burnout	e. Realign.
5. Noisy (mechanically)	a. Misalignment of coupling or sprocket.	a. Bearing failure, broken shaft, stator burnout due to motor drag.	a. Correct misalignment.
	b. Mechanical imbalance of rotating parts.	b. Same as 5-a.	b. Find imbalanced part, then balance.
	c. Lack of or improper lubricant.	c. Bearing failure.	c. Use correct lubricant, replace parts as necessary.
	d. Foreign material in lubricant.	d. Same as 5-c.	d. Clean out and replace bearings.
	e. Overload.	e. Same as 5-c.	e. Remove overload condition. Replace damaged parts.
	f. Shock loading.	f. Same as 5-c.	f. Correct causes and replace damaged parts.
	g. Mounting acts as amplifier of normal noise.	g. Annoying.	g. Isolate motor from base.
	h. Rotor dragging due to worn bearings, shaft, or bracket.	h. Burnout	h. Replace bearings, shaft, or bracket as needed.
6. Bearing failure	a. Same as 5-a, b, c, d, e	a. Burnout, damaged shaft, damaged housing.	a. Replace bearings and follow 5-a, b, c, d, e.
	b. Entry of water or foreign material into bearing housing.	b. Same as 6-a.	b. Replace bearings and seals, and shield against entry of foreign material (water, dust, etc.). Use proper motor.

*Many of these conditions should trip protective devices rather than burnout motors.

TABLE 10.3 Troubleshooting guide for electric motors (*continued*).

Symptom	Caused by	Appearance
1. Shorted motor winding	a. Moisture, chemicals, foreign material in motor, damaged winding.	a. Black or burned coil with remainder of winding good.
2. All windings completely burned	a. Overload. b. Stalled. c. Impaired ventilation. d. Frequent reversal or starting. e. Incorrect power.	a. Burned equally all around winding b. Burned equally all around winding c. Burned equally all around winding d. Burned equally all around winding e. Burned equally all around winding
3. Single-phase condition.	a. Open circuit in one line. The most common causes are loose connection, one fuse out, loose contact in switch.	a. If 1800-rpm motor—four equally burned groups at 90° intervals. b. If 1200-rpm motor—six equally burned groups at 60° intervals. c. If 3600-rpm motor—two equally burned groups at 180°. NOTE: If Y connected, each burned group will consist of two adjacent phase groups. If delta connected, each burned group will consist of one phase group.
4. Other	a. Improper connection. b. Ground	a. Irregularly burned groups or spot burns.

Many burnouts occur shortly after motor is started up. This does not necessarily indicate that the motor was defective, but typically is due to one or more of the above mentioned causes. The most common of these are improper connections, open circuits in one line, incorrect power supply, or overload.

HARMONICS

A harmonic analysis evaluates the steady-state effects of nonsinusoidal voltages and currents on the power system and its components. These harmonic currents create heat, which, over time, will raise the temperature of the neutral conductor, causing nuisance tripping of circuit breakers, overvoltage problems, blinking of incandescent lights, computer malfunctions, etc.

Among the electrical devices that appear to cause harmonics are personal computers, dimmers, laser printers, electronic ballasts, stereos, radios, televisions, fax machines, and any other equipment powered by switched-mode power supply equipment. This is not to say that harmonics will cause all these problems, only that it is possible.

These problems can be prevented somewhat by using a dedicated circuit for electronic equipment. Also, on a branch circuit, an isolated ground wire should be used for sensitive electronic and computer equipment. A more expensive alternative is to rectify and filter the mains, thereby effectively removing all low-frequency harmonics, including the fundamental. Oversized neutrals represent another possible means to prevent overheating of this wire. In power-distribution systems, electricians are typically interested in measuring the current; thus, a "true-root mean square" current measuring clamp-on meter is typically used.

STAFFING AND TRAINING

Electrical staff duties include all aspects of maintenance (preventive, predictive, corrective, and emergency). It is rare that a facility or district will have plant personnel who possess the ability and knowledge to service, renew, and overhaul each piece of equipment presently in use or projected to be used in the plant. Supplementing the staff's skill base with outside specialists and maintenance contractors is a normal practice.

In a small facility, some electrical work may be done by the operator. In many small facilities, the operator also serves as the mechanic, the electrician, and the instrument technician. In larger facilities, specialization typically prevails, and there are a variety of titles that are used in the electrical trades. However, whether the facility is small or large, it is essential that only qualified, well-trained personnel work on instrument or electrical equipment.

At least one journeyman electrician is typically employed in medium-to-large facilities. Facilities of this size range may employ various levels of electricians (e.g., an electrician's helper, an electrician, a high-voltage electrician, an instrument technician helper, and an instrument technician).

An electrician's helper works under the supervision of an experienced electrician. Often, the helper is in an apprentice program. An electrician is certified by the state

and/or the municipality. A first-level electrician would work on lower voltages (120 to 600 V). The 600-V threshold is not rigid; it depends on the municipality or state. A high-voltage electrician works on systems in excess of 600 V.

Like an electrician's helper, an instrument-technician helper works under the supervision of an experienced instrument technician. Often, the helper is in an apprentice program. The instrument technician has typically completed an apprenticeship program and provides on-the-job training for assigned helpers.

Sometimes, job classifications are established for the major divisions of electrical specialties. These categories are solid-state controls and drives; lighting; and switchgear (e.g., high-, medium-, and low-voltage motors and motor control circuits).

Normally, electricians handle 120 V and above, and instrument technicians handle below 120 V. Instrument technicians routinely work on the following systems: phone, intercom, alarm, security, and computers.

Most electricians learn their trade through apprenticeship programs. These programs combine on-the-job training with related classroom instruction. Apprenticeship programs may be sponsored by joint training committees made up of local unions of the International Brotherhood of Electrical Workers (Washington, D.C.) and local chapters of the National Electrical Contractors Association (Bethesda, Maryland); company management committees of individual electrical contracting companies; or local chapters of the Associated Builders and Contractors (Arlington, Virginia) and the Independent Electrical Contractors Association (Alexandria, Virginia). Because of the comprehensive training received, those who complete apprenticeship programs qualify to do both maintenance and construction work.

Apprenticeship programs typically last 4 years, and include at least 144 hours of classroom instruction and 2000 hours of on-the-job training each year. In the classroom, apprentices learn electrical theory as well as installation and maintenance of electrical systems. On the job, apprentices work under the supervision of experienced electricians. To complete the apprenticeship and become electricians, apprentices must demonstrate mastery of the electrician's work.

Most localities require electricians to be licensed. Although licensing requirements vary from area to area, electricians typically must pass an examination that tests their knowledge of electrical theory, the National Electrical Code, and local electric and building codes. Training, however, does not end once an employee attains journeyman status. Mandated by the certifying state, training typically consists of a 15-hour electrical code update course and 6 hours of electrical electives every 3 years. This continuing education effort is typically supplemented with other internal courses. Continued training of 40 hours per year for electrical trades is not uncommon. Examples of this include vendor training for newly installed equipment and new safety procedures.

HIGH-VOLTAGE SAFETY

If not handled properly, electricity—particularly high-voltage electricity—can be extremely dangerous. The following basic suggestions should be followed by everyone working with or near high-voltage circuits:

- **Consider the result of each act.** There is absolutely no reason to take chances that will endanger your life or the lives of others. Always consider what you are going to do and how it might affect you and others around you.
- **Keep away from live circuits.** Do not change parts or make adjustments inside machinery or equipment when high voltage is energized. Always de-energize the system.
- **Do not service high-voltage electrical equipment alone.** Another person should be present when high-voltage equipment is being serviced. This person should be capable of rendering first aid in the event of an emergency.
- **Do not tamper with interlocks.** Do not depend on interlocks for protection; always shut down the equipment or de-energize the electrical system. Never remove, short-circuit, or tamper with interlocks except to repair the switch.
- **Do not ground yourself.** Make sure you are not grounded when adjusting equipment or using measuring equipment. When servicing energized equipment, use only one hand and keep the other hand behind you.
- **Do not energize equipment if there is any evidence of water leakage.** Repair the leak and wipe up the water before energizing.
- **If work is required on energized circuits, the following practical safety rules should apply:**
  - Only authorized and experienced personnel should work on energized electrical systems. If you don't know about electricity, you could be playing a deadly game.
  - Ample lighting is an absolute necessity when working around high-voltage electrical current that is energized.
  - The employee doing the work should be insulated from the ground with some suitable nonconducting material (e.g., dry wood or a rubber mat of approved construction).
  - The employee doing the work should, if at all possible, use only one hand in accomplishing the necessary repairs.
  - Identify all circuit breakers to indicate which equipment or branch outlets they control so the system or equipment can be de-energized immediately in case of an emergency.

  - A person qualified in first aid for electric shock should be near the work area during the entire repair period.
- **Wear all recommended personal protective equipment, including flash protective attire and equipment.**

UTILITY METERING AND BILLING

Next to labor, electricity is typically one of the most costly items in the operation of a WWTP. There are many ways to lower electrical costs without compromising service or water quality. Understanding how the local electric utility computes your bill is the first step in controlling energy costs.

BILLING FORMAT. Utility rate structures are proposed by utilities and accepted or modified by a public service commission in the state where the utility is located. Plant supervisors should become familiar with schedules for their facilities and be sure that the plant is charged for electricity at the most economical rate schedule available. Schedule information will also help the supervisor avoid operations that unnecessarily increase costs. To determine whether the rate structure being applied is the most economical available, plant supervisors should discuss alternatives with the utility concerned or employ a rate consultant.

Most utilities submit bills to their customers on a monthly basis. As meter reading follows a Monday through Friday schedule, a bill might not cover the normal calendar month because the number of weekends included in the monthly billing period will vary. The average bill typically contains two basic charges: an energy charge and a demand charge. A flat fee may also be part of the bill, although it typically represents a minor portion of the total bill and is the same for each customer in a specific classification.

ENERGY CHARGES. The energy charge is based on the quantity of electricity supplied and is typically a rate of a given number of dollars per kilowatt hours ($/kWh) of power use.

Most public service commissions also allow a utility to apply a fuel adjustment charge (typically $0.01 to $0.05 in the United States), which can be either a credit or an additional charge reflecting changes in the cost of fuel. This charge varies from month to month. Use of the fuel adjustment charge permits the utility to continually recover changing fuel costs without seeking rate adjustments from the public service commission.

DEMAND CHARGES. Demand, measured in kilowatts, is the maximum rate at which electricity is used. Demand represents the maximum number of kilowatts drawn, typically measured in 15- to 30-minute intervals within a monthly billing cycle. Summation of customer demands indicates the total generation and distribution capacity that the electrical utility must maintain. Thus, the demand charge, based on the plant's measured demand, compensates the utility for its incremental investment in the additional generation and distribution capacity necessary to meet its theoretical maximum load.

The utility company's demand meter measures the WWTP's demand. Most utilities record the demand for each 15 to 30 minutes electronically on tapes and transcribe the tapes at their offices. Although the utility does not routinely furnish the demand information to its customers, it will provide printouts, if requested, for a monthly or annual fee. This information also may be obtained from the utility account representative.

The customer is charged for the highest demand recorded during the billing period. Some utilities apply a "ratchet" to demand. This means that the demand charge or a certain percentage of the demand in any billing period will be applied as the minimum demand for calculating demand charges during the following year (11 months maximum or summer months high) if actual demand is lower during any of those months.

POWER FACTOR CHARGES. Because a poor power factor requires utilities to install larger generating equipment and increases their line losses, utilities frequently apply a penalty for a poor power factor and sometimes allow a credit for a high power factor. The penalty or credit typically is a certain percentage adjustment for each one-tenth of a point that the power factor drops or rises above the established figure. Power factor adjustment can be applied either to the energy and demand or to the demand only.

OTHER RATE FEATURES. Frequently, utilities set a summer use rate that differs from their winter rate. Utilities with a heavy air-conditioning load, for example, may have their peak electrical demand loads during the summer. They will, therefore, establish a higher summer rate. Conversely, utilities that experience high heating loads and peak demands during the winter will charge more then.

Another frequently applied adjustment, time-of-day rates, imposes higher energy and demand charges to that period of the day when the utility experiences the highest average demand. The utility may divide the day into two to five periods. To charge based on time-of-day rates, the utility must install metering to record the consump-

tion during each period. To reduce time-of-day charges, the operator may, if practical, postpone some operations (e.g., pumping or solids handling) until the peak periods have passed.

As mentioned, rate structures are based on a customer's type of load and the delivered voltage. Typically, higher delivered voltages will result in a lower rate. In this case, the customer must furnish transformers to reduce the voltage in the plant.

Utilities may offer special services (e.g., yard lighting and spare feeders). Special services and charges, therefore, must either be standardized and approved by the public service commission or be included in special contractual arrangements between the utility and the customer.

ENERGY COST REDUCTION

GENERAL. Elements in reducing energy costs include rates and riders, demand control, and efficiency. First, know your rate structure and take full advantage of any cost savings without sacrificing your process. Second, learn about all applicable rate structures and riders offered by your utility. Some utilities may allow for more cost-effective operation.

For example, higher delivered voltages will typically result in a lower rate. This lower rate can be obtained by furnishing transformers to reduce the voltage in the plant.

Additionally, utilities sometimes use another system to reduce their total demand. The alternate system entails granting a credit or a preferred rate to customers who agree to reduce electrical consumption immediately upon the utility's request. Typically, the utility allows the customer a reasonable period after notification to make the necessary adjustments. In a WWTP, few if any processes can be stopped to reduce demand. If the plant's emergency generator has the appropriate air pollution permits, it can be used to lower the power consumption from the utility.

If a facility's rate structure has a demand charge, the use of demand control can reduce energy costs. Minor changes in operational procedures can reduce demand charges. For example, if spare equipment is to enter service, the equipment being shut down should be turned off first to avoid running both motors at the same time. Demand meters should be installed and trends studied. An operator should also review the feasibility of modifying an operation to minimize demand. Where practical, a demand control system should be installed that monitors demands and either alerts the operator to forecasted demand exceedances or adjusts certain predefined equipment to ensure that demand limits are not exceeded.

MOTORS. Replacement of existing motors with high-efficiency motors has significant potential for energy savings; the average savings on these energy-efficient motors ranges from 3 to 5%. The payback period also depends on the service conditions and running time of the motor. Incremental savings are greatest on smaller motors or motors that have to be rewound. Overall savings on larger motors [more than 75 kW (100 hp)] are smaller on a percentage basis because of the high replacement cost; payback periods on the replacement of standard motors vary from 2 to 10 years. High-efficiency motors have more copper for lower loss in the windings, better design to reduce no-load loss, and better bearings and aerodynamics to reduce friction and windage loss.

The Energy Policy Act of 1992, a federal statute, requires that certain types of new motors sold in the United States as of October 24, 1997, must meet or exceed specified efficiency ratings. Table 10.4 provides a comparison between standard- and premium-efficiency motors. The efficiency of the motor is highest when they are operated close to 100% of their load.

TRANSFORMERS. Energy-efficient transformers should be used, especially in the case of dry transformers. However, efficiency is seldom specified when buying transformers. Values of 95% or higher are typical, and differences between high- and low-efficiency units are only 1 to 2%, with a significant first-cost premium for more efficient units. Complete life-cycle costs must be carefully examined, along with the economics of high-efficiency, dry-type transformers.

Transformers can be expected to operate 20 to 30 years or more and, as such, buying a unit based only on its initial cost is uneconomical. Transformer life-cycle cost (also called "total owning cost") takes into account not only the initial transformer

TABLE 10.4 A comparison between standard- and premium-efficiency motors.

Hp	**Standard-efficiency motors** Average efficiency at 100% load	**EPA energy-efficient motors** Minimum nominal efficiency at 100% load	**NEMA premium motors** Minimum nominal efficiency at 100% load
5	83.3	87.5	89.5
10	85.7	89.5	91.7
20	88.5	91.0	93.0
25	89.3	92.4	93.6
50	91.3	93.0	94.5
100	92.3	94.5	95.4
200	93.5	95.0	96.2

EPA = Energy Policy Act of 1992.

cost, but also the cost to operate and maintain the transformer over its life. This requires that the total owning cost (TOC) be calculated over the lifespan of the transformer, as follows:

$$\text{TOC} = \text{initial cost of transformer} + \text{cost of the no-load losses} + \text{cost of the load losses} \tag{10.6}$$

Lastly, transformers should be sized to match the load as closely as possible to reduce the no-load component of the total loss.

ENERGY EFFICIENT LIGHTING. Energy can be saved by using lights only when needed, selecting the correct type of lighting, and properly maintaining the lighting system. During plant or office operation, certain areas are unoccupied for varying periods of time. If the lamps are turned off as people leave the area during these various periods, there will be lower energy consumption than if the lamps were left on. The length of time the lamps are off and the type of light source should affect the decision as to whether these lamps should be left burning or turned off. More importantly, however, is the type of lamp involved. Whether savings can be achieved by turning lamps off can only be determined by evaluating the energy savings against the increased costs of lamp replacement. Any evaluation must consider the inconvenience and cost of turning lamps on and off, possible costs for installing switching devices, and the waiting time required for restarting lamps.

Incandescent lamps should be turned off when not needed. Energy will be conserved and electrical costs will be reduced without shortening the life of the lamp. High-intensity lamps typically are not turned off during short unoccupied periods because a 3- to 15-minute warm-up time is required during starting. They should be switched off only when the subsequent startup can be pre-planned so as not to interfere with work assignments. Although each HID lamp has a long life, frequent starting (less than 5 burning hours per start) will reduce lamp life by as much as 30%.

Fluorescent lamps are often turned off to reduce electrical energy consumption and will most often produce savings in energy costs that more than offset the increased costs of lamps and lamp-replacement labor. The life of these lamps depends on the number of hours the lamps operate per each start. "Life" is rated by the industry on a 3-hour burning cycle. The more hours that a lamp is on per start, the more its life is increased. The average life is the point at which 50% of the lamps survive. Table 10.5 depicts the average life of several types of fluorescent lamps per burning hours.

Whenever a new facility will be constructed or an existing facility revamped, an opportunity exists to select the most efficient lighting scheme. First, match the function

TABLE 10.5 Relative life of fluorescent lamps at various burning hours (burning hours per start).

Lamp	3	6	10	12	18	Cont
40 white rapid start	18 000	22 000	25 000	26 000	28 000	34 000
High output	12 000	14 000	17 000	18 000	20 000	22 500
Very high output	9000	11 300	13 500	14 400	16 200	22 500
Slimline	12 000	14 000	17 000	18 000	20 000	22 500

of the room to the required lighting needs and ensure that the new room finishes (walls and ceilings) are reflective to maximize available light. Second, where feasible, take advantage of natural light. Next, select the most cost-effective lighting system (first and second cost) for the defined requirements. Include programmable timers, override switches, and motion detectors in the design control systems to further attain cost-effective operations.

There are a variety of lighting systems available. Some general information relative to energy efficiency for incandescent lamps, fluorescent lamps, and HID lights is provided herein.

In terms of incandescent lamps, higher wattage general-service lamps are more efficient than lower wattage lamps. Using fewer high-wattage lamps in a given area will save energy. For example, one 100-W general-service lamp produces 1750 lumens, or two 60-W general-service lamps produce 860 lumens each or 1720 lumens total. For the same wattage, general-service lamps are more efficient than extended-service lamps, although the extended-service lamp's life is longer than the general-service lamp (100-W general service lamp/750- to 100-hour life/17.5 lumens/watt 100-W extended-service lamp/2500-hour lamp life/14.8 lumens/watt).

To obtain equal lighting, approximately 18% more lamps and energy are required when using extended-service lamps. Because of their low efficiency, extended-service lamps are recommended only where maintenance labor costs are higher or lamps are difficult to replace.

Fluorescent lamps have three to five times the efficiency of incandescent lamps and compare favorably to most HID sources. Fluorescent-lamp efficiencies vary depending on lamp length, lamp loading, and lamp phosphor.

Three common types of HID units are mercury vapor, high-pressure sodium vapor, and metal halide. Mercury-vapor lamps have a long life and are cheaper than other HID units. Although metal halide lamps are more efficient than mercury-vapor

lamps, they cost more and typically are unavailable in small sizes. High-pressure sodium vapor units are typically best for HID lighting applications because of their low cost, long life, and efficient power use.

A good lighting system that is well-maintained will provide the visual conditions for maximum performance to maintain lighting levels for which the system was originally designed. The major lighting system maintenance activities are cleaning and relamping.

Proper cleaning schedules will maximize light for the same level of energy expended. Dirt can account for light losses from 30 to 50%. Therefore, fixtures and lamps should be washed regularly using the proper cleaning solution. Cleaning frequency will depend on the amount and type of dirt in the air and whether the fixture is the ventilated or nonventilated type. Wall and ceiling cleaning and repainting are also techniques to maximize light output for the same power expenditure.

ENERGY AUDITS

Plants can do much to improve energy usage via better energy management, better instrumentation and control systems, and energy-efficient equipment. In addition to facility-initiated measures, incentive and special rate programs may be available from the local utility.

An energy audit typically starts with creating an energy audit team consisting of plant personnel, an electrical utility representative, and possibly an outside process or energy expert. After reviewing the plant energy bills and collecting plant energy and operating data, the team should conduct a detailed field investigation of plant processes and equipment to find out the amount of energy used and the "when and how" of energy demand. The field investigation includes lighting, HVAC, pumping, and unit processes.

The team should then review outside institutional programs. Many electrical utilities and government entities have rebates, grants, or loan programs that should be considered when prioritizing payback on projects.

The next team task is to use the collected information to develop energy-conservation measures and implementation strategies. The team must look at capital and operating costs, cost-to-benefit ratios, energy savings, process requirements and complexity, and effluent quality. The most essential parts of such a program are the energy audit follow-up activities to ensure that the measures or projects are implemented and the savings achieved. Utilities, government, and associations are a good source of sample audit templates.

POWER FACTOR CORRECTION

When an electric load has a power factor lower than unity, the apparent power delivered to the load is greater than the real power that the load consumes. Only the real power is capable of doing work, but the apparent power determines the amount of current that flows into the load for a given load voltage.

Energy losses in transmission lines increase with increasing current. Therefore, power companies require that customers, especially those with large loads, maintain the power factors of their respective loads within specified limits or be subject to additional charges. Engineers are often interested in the power factor of a load as one of the factors that affects power-transmission efficiency.

For a linear circuit operating from a sinusoidal voltage, the current must be a sinusoid at the same frequency. When the current is exactly in phase with the voltage, the power factor is 1. This corresponds to a purely resistive load. A toaster is an example of an approximately linear device; an electric motor is not. For a nonlinear circuit (e.g., a switchmode power supply), the current is not necessarily sinusoidal. In that case, there is current at harmonics of the voltage frequency.

Power-factor correction returns the power factor of an electric alternating current power transmission system to very near unity by switching in or out banks of capacitors or inductors that cancel the inductive or capacitive effects of the load. For example, the inductive effect of motor loads may be offset by locally connected capacitors. It is also possible to effect power-factor correction with an unloaded synchronous motor connected across the supply. The power factor of the motor is varied by adjusting the field excitation and can be made to behave like a capacitor when overexcited.

COGENERATION

If a plant needs constant heating or mechanical energy, cogeneration of electricity should be evaluated. Indeed, large potential savings are available for facilities capable of producing onsite power and heat. Such systems require a protective relaying system that meets all the utility company requirements to protect the system. Cogeneration in wastewater plants typically involves the burning of digester gas to generate electricity and produce heat for processes or buildings. Cogeneration systems are typically installed in larger [more than 132-L/s (3-mgd)] plants, and require detailed investigation.

In most cogeneration and trigeneration power and energy systems, the exhaust gas from electric-generation equipment is ducted to a heat exchanger to recover the thermal energy in the gas. These exchangers are air-to-water heat exchangers, in which the exhaust gas flows over some form of tube and fin heat-exchange surface and the heat from the exhaust gas is transferred to make hot water or steam. The hot water or

TABLE 10.6 Cogeneration and trigeneration power and energy technology.

Technology	Operating history	Nitrogen oxide emissions	Size (kWh)	Gas cleaning requirements
Internal combustion engines	Common	Common in last few years	250–2500	Moderate
Microturbines	Recent applications	Low	30–250	Extensive
Gas turbines	Common	Low	>3000	Extensive
Fuel cells	New	None	200–1000	Extreme
Stirling engines	New	Very low	55	None

steam is then used to provide hot water or steam heating and/or to operate thermally activated equipment (e.g., an absorption chiller for cooling or a desiccant dehumidifier for dehumidification). Current technologies used include internal combustion engines, microturbines, gas turbines, fuel cells, and stirling engines. Table 10.6 provides further details about these technologies.

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Chapter 11

Utilities

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INTRODUCTION

In-plant utilities perform a vital support role in the operation of wastewater treatment facilities. Some utilities assist with equipment and process operations, and others support the safety and welfare of plant personnel. Utilities such as water supplies, compressed air, communications systems, heating, ventilating, and air conditioning systems, fuel supply systems, and roadways continuously serve as an integral part of the plant's daily functions. Others, such as fire protection, storm drainage, and flood protection, serve on an occasional, seasonal, or emergency basis. Loss of any of these services can impair operations, cause facility failure, or impose risks and discomfort on plant staff.

MAINTENANCE

Routine and regular maintenance of utilities helps ensure long-term and trouble-free operation. Good maintenance practices include the items and frequencies listed in the tables in this chapter. More frequent maintenance may be necessary if indicated by operating experience or if specified by the equipment manufacturer.

The operator should observe appropriate safety precautions and practices when operating and maintaining rotating or electrical equipment (see Chapter 5). Adequate space, lighting, and ventilation are necessary for proper and safe inspection and efficient operation of equipment. The operator should use effective ear protection for extended exposure to equipment with high noise levels. More complete and detailed descriptions of proper operating and maintenance procedures are available in the manufacturer's instruction book furnished with the equipment. Instruction manuals should be in the hands of those responsible for performing the maintenance.

WATER SYSTEMS

Two types of water—potable and nonpotable—are used in wastewater treatment operations. Potable water (water suitable for drinking) is used for showers, hot-water heaters, water coolers, water closets, urinals, lavatories, washing machines, kitchen sinks, safety showers, mop sinks, fire hydrants, and laboratory sinks with vacuum breakers. Hot water for any of the above units is not drawn from boilers used for supplying hot water to a sludge heat exchanger, sludge heating coils, or other devices where sludge or other contaminants may be present. Nonpotable water (water not ensured to be suitable for drinking) may be used for flushing or filling idle tanks, fire protection, toilet flushing in some states, or for other purposes with limited human contact.

The plant's files should include the water source and name of the supplier. Locations of pipelines, hydrants, booster pumps, and shutoff valves should be noted. Each item should be tagged for emergency use. The different water supplies should be clearly labeled. If special wrenches or tools are required to open or close these valves, the tools should be identified and mounted in a nearby location.

Drinking water supplies must be separate from all other water sources. Interconnections between potable and nonpotable water sources are strictly prohibited, and cross-connections must be prevented. Hose outlets using drinking water service need antisiphon devices to prevent accidental back siphoning or contamination of the drinking water supply. The operator should avoid attaching hoses directly to fire hydrants when flushing tanks if the fire hydrants are supplied with potable water.

Most states require measures to prevent potable water contamination, such as an air-gap tank or backflow preventer for water from a public water supply as it enters the plant site. In addition, protective measures must be taken to supply potable water for service water for wastewater equipment cleaning or any other purpose involving water contact with a contaminant. Air-gap tanks and backflow preventers need regular service and inspection to ensure proper operation.

Sources of nonpotable water include treated wastewater effluent and potable water after it has passed through a break tank with an air-gap inlet or an approved backflow preventer. Nonpotable water is used for seals, scrubbers, backflushing, tank flushing, cooling towers, boilers, digester heating, chlorine solution, irrigation, chemical and polymer dilution, and various other in-plant demands. Although the equipment and distribution systems that provide nonpotable water vary, they always include pumps, piping, valves, and controls. Such systems may also include accessories such as strainers, receiving tanks, flow meters, hydrants, water treatment facilities, and hydropneumatic tanks.

Every hose bib, faucet, hydrant, and sill cock in the treatment plant requires clearly and permanently posted nonpotable water signs to indicate that the water is not safe to drink. Personnel need instructions to prevent accidental consumption of nonpotable water.

Seal water, used for cooling, flushing, and sealing the stuffing boxes of rotating equipment, typically comes from bladder tanks, hydropneumatic systems, or direct pressure systems. Bladder tanks consist of a receiving vessel fitted with a flexible internal membrane (bladder) that separates the nonpotable water supply from the air cushion above. Hydropneumatic tanks, connected to a nonpotable water supply, are pressurized with compressed air. Controls allow for regulation of the compressed air and water that enter the hydropneumatic tank so the necessary capacity and pressure can be maintained. Direct-pressure systems include a pump to draw water from a break

tank that feeds the seal water system. A pressure relief valve and bypass line recirculate unused water to the break tank. This method is less energy efficient than the systems discussed above.

Monitoring and recording water usage regularly on a plant-wide basis for each of the several process systems and for other major water-using equipment will signal water-use changes that may require corrective action.

In general, all buried piping will have some type of cathodic protection to prevent corrosion. Inspection and maintenance frequencies for the cathodic protection system and of water system components are shown in Table 11.1. Where possible, the water system should be laid out in a loop with frequent isolation valves so repairs can be conducted without disrupting large sections of the plant.

DRAINAGE SYSTEMS

Two types of drains are often used in wastewater treatment facilities: plant drains and storm drains. It is important to keep these two systems separate to prevent contamination of surface waters and to reduce the likelihood of being required to have a National Pollutant Discharge Elimination System (NPDES) permit for the storm drainage discharge. Plant drains for dewatering tanks and equipment convey the fluids elsewhere in the plant for appropriate treatment. Operational considerations include the rate and duration of dewatering and their effects on plant processes. Portable pumps may be required to completely dewater tankage. Plant drainage systems should include properly located cleanouts or manholes that are checked and cleaned regularly to avoid debris accumulations that restrict the capacity of the drains. For the same reasons, drains need regular flushing.

TABLE 11.1 Water system inspection and maintenance.

Inspection and maintenance tasks	Suggested frequency[a]
Backflow prevention device	M
Calibrate meter pump(s)	A
Inspect hydropneumatic tank and equipment	W
Clean strainers	W/R
Operate hydrants	A
Operate valves	A
Test cathodic protection system	S
Monitor water usage	D

[a]D = Daily; W = weekly; M = monthly; S = semiannually; A = annually; and R = as required.

Where groundwater-pumping systems exist to prevent flotation of structures and tankage, the operator should check the water level at each of the groundwater-monitoring stations. If any water level is above the bottom of the tank or structure, or if the system lacks a monitoring station, the operator should pump the groundwater sump or well dry before dewatering the tank. Failure to follow these procedures can cause structural failures and broken connecting services. If the tankage has hydrostatic relief devices, these units should be checked each time the tank is empty to ensure proper seating and free operation of the units.

Sanitary drainage from building showers, lavatories, floor drains, toilets, and other plumbing fixtures is collected and discharged at the plant headworks for treatment. Floor drains should be flushed weekly to ensure unrestricted drainage through the system and to fill traps to prevent sewer gases from entering the buildings.

Sump pump systems, composed of a pit, pump, and liquid-level controls, help remove collected water and wastes from structures. These systems may have either submersible or vertical centrifugal pumps driven by externally mounted motors. Duplex pump systems are often provided in critical areas. In the sump pits, high water level alarms are necessary to alert personnel of sump pump failure. Routine operation and maintenance includes weekly to monthly flushing of the sumps and checking of the floats and controls.

Stormwater drainage systems convey surface runoff away from building tanks, walks, and roadways to an off-site drainage course or storm sewer. Collection inlets, area drains, culverts, storm sewers, swales, ditches, roof drains, gutters, and downspouts should be kept free of debris. Stormwater ponding should be avoided unless the pond is designed to control stormwater release to the conveyance systems.

FUEL SYSTEMS

Several fuels provide the energy needed for plant operation, vehicles, and emergency power. These include fuel oil, natural gas, liquid propane gas, digester gas, gasoline, and diesel. Most of these fuels, except natural gas and perhaps digester gas, require a suitably sized storage vessel that may be installed either above or beneath the ground. Underground storage tank systems normally include product distribution piping and associated equipment for filling, vertical, and level indication.

Underground storage tanks for petroleum products must comply with strict federal and state regulations. These regulations, administered by the county health officer, are intended to prevent leaking tanks that can cause groundwater contamination, endanger lives, increase fuel usage, and require expensive cleanup procedures. Since

1946, all underground tank owners have been required to obtain permits to install and operate tanks with hazardous petrochemical products. Notification and permitting also apply to existing tanks that have been taken out of service since January 1, 1974, but have not been removed from the ground.

As of May 8, 1986, all underground storage systems must meet stringent secondary containment requirements, must have proper corrosion protection to prevent releases, and must be continuously monitored for leakage failure of tank or pipelines for the operational life of the tank system. Fuel delivery systems must conform with state and U.S. Department of Transportation rules and regulations, local agency rules for air emissions, and supplier requirements.

Natural gas is generally supplied by pressurized pipelines. Any natural gas leak is readily detected by its characteristic odor. If the odor is detected, the operator should determine the source, and if severe, evacuate the area immediately, notify the local utility and the fire department to isolate the supply to the area, and turn off electrical power to avoid any source of ignition.

Methane generated by the decomposition of solids in the absence of oxygen can be used to fire boilers, heaters, incinerators, or engines. Excess gas can be stored for sale, burned to power equipment or heating, or burned by special gas flaring systems.

Both natural gas and methane (digester) gas are highly toxic and can produce explosive conditions in contained areas; areas where digester gas may collect require combustible gas analyzers and alarms. If gas is detected, the operator should evacuate the area immediately, turn off power at a remote switch or breaker, and ventilate the area. Only personnel equipped with a self-contained breathing apparatus, consistent with the confined-space entry protocol (see Chapter 5), are allowed to enter the area until gas analyzers indicate that safe conditions have been restored. In no case should any other personnel be allowed in an explosive atmosphere.

Safety controls on fuel systems include pressure regulators, flame traps, automatic shutoff valves, pressure-vacuum release valves, and antisiphon valves. Semiannual inspection and maintenance of each item is necessary to ensure its proper operation.

COMPRESSED AIR

Compressors are machines designed to deliver air or gases at a pressure higher than their normal pressure. Under controlled conditions, air is compressed to provide a power source for operating pneumatic equipment, pumps, and tools. Compressors furnish instrument air supplies, air jets for cleaning equipment, purge air, and air for wastewater ejectors, as well as pressurizing gases for transport and distribution.

TYPES OF COMPRESSORS. Compressor types are typically classified as displacement or dynamic. The displacement type can be subdivided into reciprocating positive displacement or rotary positive displacement types (Figure 11.1).

Displacement compressors use pistons, vanes, or other pumping mechanisms to draw air or gases into the unit, increase pressure by reducing the volume, and discharge the air into a receiver. An air receiver stores air under pressure and dampens the pressure pulsations in the air system. By storing air, the receiver reduces the frequency of loading and unloading, or starting and stopping the compressor. Since receivers collect oil and water from the compressed air, they need regular draining.

Portable compressors are self-contained, with drive and air receivers mounted on the unit. Vacuum pumps withdraw air from a tank or pipeline to reduce its air pressure below atmospheric and discharge it to the atmosphere. In principle, vacuum pumps reverse the operation of a compressor.

Accessories and protective devices in compressor systems prevent system and equipment damage, control flow and pressure, remove oil contamination, dry the air (for instrumentation and other uses), reduce noise, separate moisture, and serve other

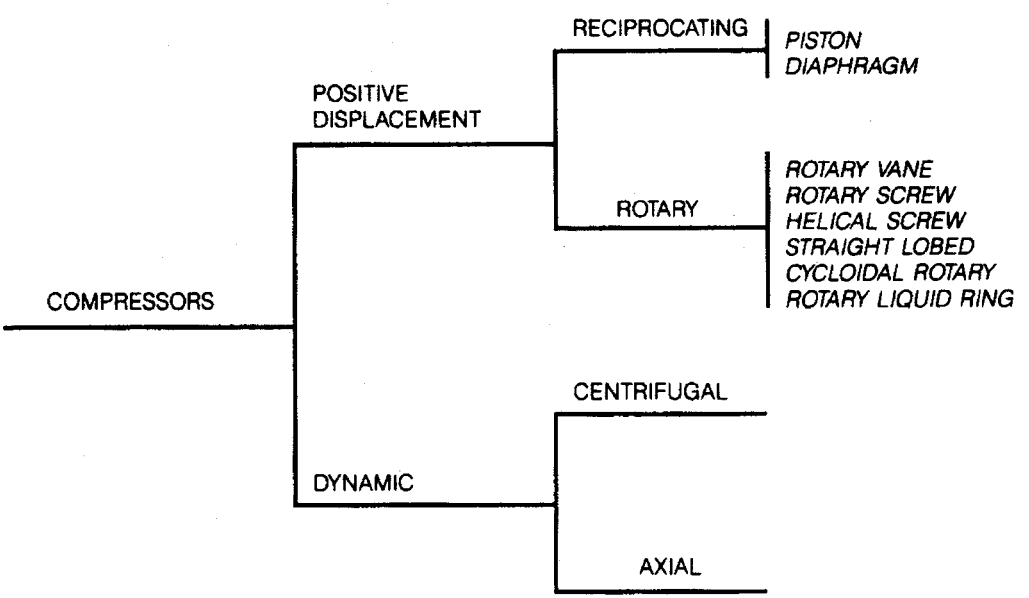


FIGURE 11.1 Types of air compressors.

functions. A simple compressor system may include an intake filter, intake silencer, compressor, discharge silencer, intercooler or aftercooler, moisture-oil separator, air receiver, safety relief valve, pressure relief valve or pressure regulator, and pressure switches for compressor on-off control (Figure 11.2). Control systems may include elements for monitoring and sequencing in addition to protective devices for the equipment.

COMPRESSOR MAINTENANCE. Regular compressor maintenance helps ensure long-term and trouble-free operation. Good maintenance practices include the items and frequencies listed in Table 11.2. More frequent maintenance may be necessary if indicated by operating experience or specified by the equipment manufacturer.

The operator should observe appropriate safety precautions and practices when operating and maintaining rotating or electrical equipment (see Chapter 5). Adequate space, lighting, and ventilation are necessary for proper and safe inspection and efficient operation of the units. Operators should use effective ear protection for extended exposure to equipment with high noise levels. More complete and detailed descriptions of proper operation and maintenance (O&M) procedures are available in the manufacturer's instruction book furnished with the equipment. Instruction manuals should be in the hands of those responsible for the inspection and continuing service of the units.

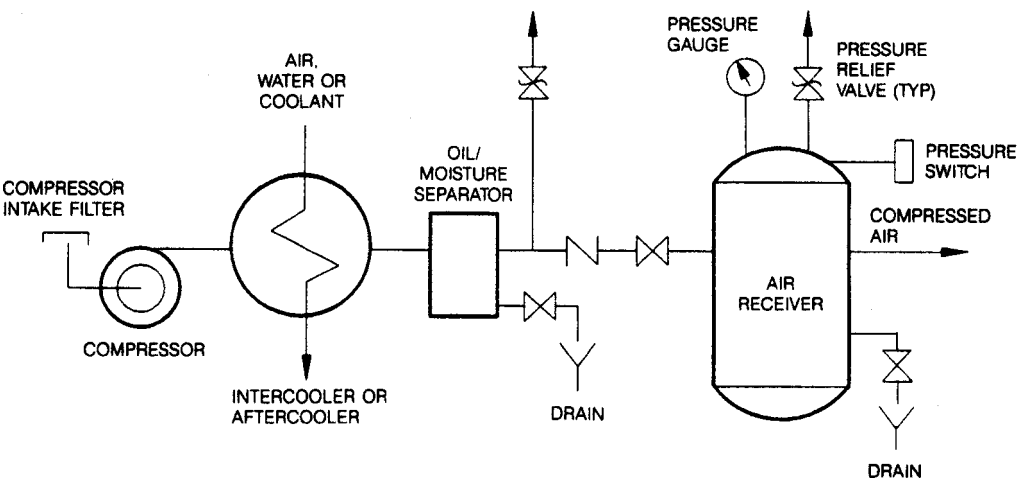


FIGURE 11.2 Typical compressed air system.

TABLE 11.2 Compressor inspection and maintenance chart.

Inspection and maintenance tasks	Suggested frequency[a]
Check for unusual noise and vibration	S
Tighten bolts, belt drives, and chains (see Chapter 12)	R
Check, clean, or replace dirty air filters	Q
Drain air receivers, intercoolers, separators	Q
Check crankcase and drive oil and grease levels; do not overlubricate	M
Operate safety valves and regulators manually	S
Clear dust, dirt, and debris from compressor and drive external surfaces	S
Check all condensate traps	S
Check time to pressurize the system	S
Check pressure switch and pressure settings	S
Inspect piping, valves, unloaders, belt alignment, and electrical connections	S
Log temperature, pressure, cooling water, temperature and flow, lubrication use, pressure, vibration, running time, and service repairs	M
Check electric motor operation (see Chapter 12)	R

[a]M = monthly; Q = quarterly; S = semiannually; and R = as required.

AIR DRYERS. Air dryers, often included with compressed air systems to remove moisture (dry air) for services such as pneumatic instrument control, usually use one of three common drying methods:

- Refrigeration,
- Regenerative desiccant (heat or heatless), and
- Deliquescent.

Refrigeration dryers cool the compressed air to condense the water vapor and drain off the resulting liquid.

Regenerative desiccant (water-absorbing substances) dryers use a moisture-adsorption medium and a dual-tower arrangement with automatic valving and control circuits. As the active tower removes moisture from the air, the other tower undergoes a purge cycle to remove the moisture from the adsorption media. After completion of the purge cycle, the towers switch, with the previously active tower entering a purge sequence. Heatless types of these dryers require 10 to 15% of the air to purge the adsorption media in the inactive tower. Heater types require 1% of the air for purging the adsorption media in the inactive tower, together with activation of heating elements.

Deliquescent dryers are large vessels containing patented pellet desiccants. Compressed air passes over and through the desiccant where the water vapor is adsorbed.

These units require periodic replacement of the desiccant and removal of accumulated water. As a signal for replacement, some desiccants are designed to change color when they become exhausted.

A typical air-dryer arrangement is presented in Figure 11.3. Normally, each air-dryer system requires a prefilter. Most units have monitors that indicate failure of the units to supply dry air. Regular inspection and maintenance, such as replacement of exhausted desiccants or checking the air temperature on refrigeration dryers, are essential for proper performance of the dryers.

FIRE PROTECTION SYSTEMS

For any fire, no matter how small, the operator should call the local fire department immediately. Fire extinguishers, fire hoses, sprinkler systems, and fire hydrants should be available to put out fires. Special portable fire extinguishers must be used for electrical and chemical fires. The first five minutes constitute the most critical period for controlling a fire; if appropriate, plant staff should try to extinguish or control small fires until firefighters arrive. It may not be appropriate or advisable for plant staff to try to extinguish small fires in small facilities with limited staff on shift. After their arrival, only firefighters should remain in the area. In case of a major fire, the area must be evacuated immediately.

The National Fire Protection Association (NFPA) classifies fires as Class A, B, C, or D. Class A fires (ordinary combustibles) burn wood, paper, textiles, or trash. Class B

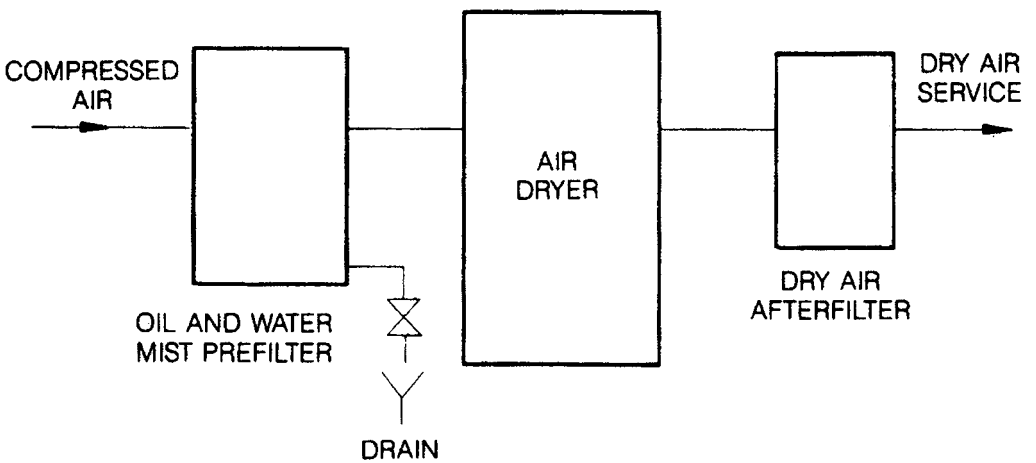


FIGURE 11.3 Air-dryer system.

fires (flammable liquids) burn flammable liquids such as gasoline, paint, solvents, grease, and oils. Class C fires (electrical equipment) are those in or near electrical equipment. Class D fires (combustible metal) burn combustible metals such as sodium, titanium, uranium, zirconium, lithium, magnesium, and sodium-potassium alloys.

Water from hose connections or Class A fire extinguishers is appropriate for Class A fires. Fire extinguishers with special solutions or dry chemicals are required to extinguish the other classes of fires (Figure 11.4). Portable fire extinguishers of the appropriate class must be placed in strategic areas to extinguish the type of fire that may occur in each area. The proper type of fire extinguisher for Class A, B, C, or D fires must be present, fully charged, and in good working condition.

Fire protection emphasizes yearly inspection of fire extinguishers for corrosion, damage, loss of charge, repair, or placement of the units as necessary. Spare units should be on hand. Tags stating the most recent maintenance and recharge data must be attached to each unit.

Plant staff must be informed that fighting fires is serious business. They must be instructed in proper use of fire extinguishers and warned that using fire extinguishers in poorly ventilated areas without proper safety equipment can cause asphyxiation. The operator must ensure that smoke detection sensors, thermal sensors (where applicable), and appropriate alarms are strategically placed to alert plant staff of danger and the need for corrective actions. Signs prohibiting smoking and open flames must be clearly posted in areas where combustible materials are stored or where flammable gases may accumulate.

Fire hydrants, located throughout a plant for fire department use, must remain unobstructed and easily identifiable. Other special fire protection equipment at the plant site may include sprinkler systems, deluge systems, fire pumps, standpipes, hose cabinets, and hose reels. Maintenance requirements for each system need regular review to ensure that alarms function and equipment is ready for operation. Automatic sprinklers and fire-hose systems must remain fully pressurized at all times.

The local fire department should inspect the plant yearly to review fire protection equipment and evaluate fire prevention procedures. The operator should consult the local fire department to resolve any questions related to fire control, prevention, or protection. Fire department telephone numbers should be prominently posted at each plant telephone.

HEATING, VENTILATING, AND AIR CONDITIONING

The air within the plant's buildings is handled by heating, ventilating, and air-conditioning (HVAC) systems ranging from simple to complex. Air-handling systems can

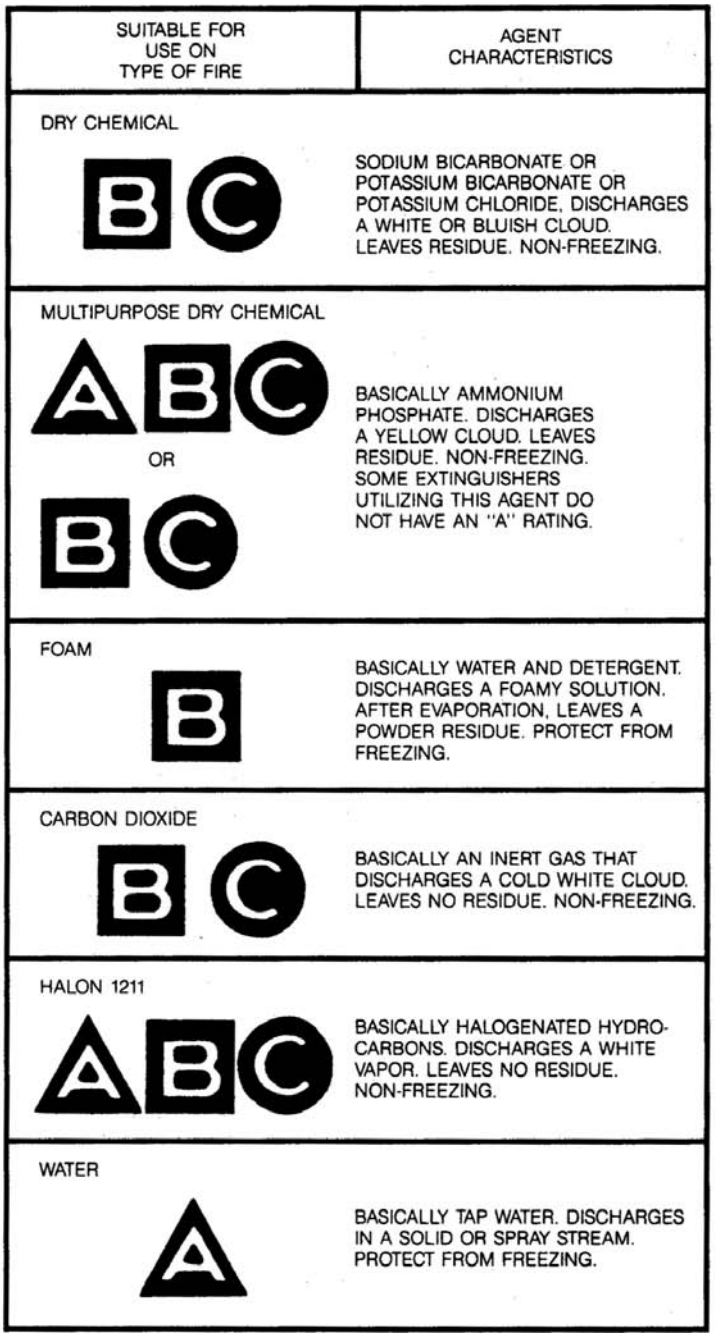


FIGURE 11.4 Types of fire extinguishers.

include only ventilating units that supply unheated or uncooled outside air; heating and ventilating units that supply heated air as needed; and HVAC units that provide heated or mechanically cooled air, as necessary.

Ventilation air supports life, prevents accumulation of explosive gases, reduces heat buildup, and helps maintain safe working conditions. During hot weather, air movement helps cool the body by evaporating perspiration. In buildings, ventilation air eventually reduces temperatures and humidity as hot, indoor air is exchanged for cooler, outside air. Heat supplied through heating coils, ducts, tubes, or elements comes from sources such as boilers, hot-air furnaces, electric elements, heat pumps, or heat-recovery devices. Mechanical air-conditioning systems are designed to provide comfort for employees and visitors or controlled environments for systems, products, or equipment. Air-conditioning systems cool, dehumidify, filter, and circulate room air. Dehumidifiers are either mechanically refrigerated appliances or devices containing chemical absorbents that remove moisture from the air. The reduction of air moisture by air conditioning or dehumidification helps to enhance human comfort and prevent rust, rot, mold, and mildew.

VENTILATING. Fans, sometimes with renewable filters, provide ventilation air. Ventilation may be provided by supply fans, exhaust fans, or both. Operation of ventilation equipment may be continuous or intermittent. Intermittent systems are often interconnected with lighting systems so that they activate automatically when personnel enter the area and switch on the lights. Likewise, the fans deactivate when the lights are shut off. Two other fan-control systems include a timer and a thermostat. The timer is often used where a remote station is not visited frequently or is operated seasonally.

Many areas must be ventilated independently to avoid the problem of exhausting obnoxious or hazardous gases from one space into another. For example, pumping station wet wells that contain screens, mechanical devices, and other equipment needing maintenance or inspection require a ventilation system separate from that ventilating the dry wells. Also, laboratory facilities and fume hoods must have separate ventilation systems to prevent distribution of odors or obnoxious gases to other areas within the building.

Ventilation rates for each structure are based on its use and occupancy (WEF, 1992). In all areas, adequate ventilation must be provided to ensure safe working conditions for plant personnel. Personnel must not enter screen rooms or wet wells unless the mechanical ventilation equipment is functioning properly.

Some conditions require high rates of ventilation. For wet wells, forced air must enter the space at a rate of at least 12 air changes/hour and, if ventilation is intermittent, the rate must be at least 30 air changes/hour (WEF, 1994). One air change equals

the total volume of air in the ventilated space. Dry wells require at least 6 air changes/hour or, if ventilation is intermittent, at least 30 air changes/hour.

If ventilation systems fail in confined spaces where a hazardous atmosphere may develop, the operator should exercise extreme caution. A hazardous atmosphere may develop wherever hazardous or explosive gases such as hydrogen sulfide, methane, gasoline, oils, solvents, or other hydrocarbons are present or may enter; where toxic gases such as hydrogen sulfide or methane may accumulate; or where oxygen may be depleted.

The operator should not attempt to enter these areas without testing the atmosphere for toxic or combustible gases and oxygen deficiency. If it is necessary to enter a space where asphyxiation or exposure to explosive or toxic gases might occur, operators should follow the protocol for entry to confined spaces as described in Chapter 5. Following the safety rules can save the life of the operator and those of fellow workers.

HEATING. In general, there are three types of heating for buildings or process equipment: hot water, steam, and hot air. In addition, infrared systems are used to heat small areas and some special processes. The most common energy sources for heating are coal, oil, gas, and electricity. Steam or hot-water boilers require special handling to ensure proper operation. Burner controls for boilers are equipped with flame safeguard systems that prevent explosive conditions. Only trained staff or knowledgeable equipment mechanics should service and maintain these units. Steam and hot-water systems are normally used when there is a high heating load. Electrical and infrared heating are used for lower heating loads and special situations.

Some large process equipment units and drives produce excess heat, which, if properly reclaimed, can be used to supplement heating of building spaces during cold weather. To conserve energy, heat-recovery equipment should be considered where heating and ventilation systems are required to use more than 50% outdoor air; that is, the rate of supply is one-half the rate of exhaust. Heat-recovery systems reclaim heat in exhaust air streams and use the reclaimed heat to preheat outside ventilation air. Similarly, heat-recovery systems serving air-conditioned spaces use the cooler exhaust air to precool ventilation air. Types of heat-recovery systems include air-to-water coil, heat pipe, and rotary heat-exchanger wheel.

An air-to-water coil system transfers heat from the exhaust air to the outside air as it enters and passes through the system. The system consists of a water-filled coil in the exhaust fan system connected by piping to a similar coil in the supply fan system. A circulation pump, valving, and temperature controls are required to operate the system.

A heat-pipe system is an air-to-air heat-transfer device consisting of a bank of refrigerant-filled tubes that transfer heat from one end of the tube bank to the other. Warm

air heats the refrigerant, which vaporizes and moves to the opposite end of the tubes located in the outside airstream. Heat transfers to the incoming outside air from the refrigerant vapor as it condenses. The condensate then flows back to the exhaust side of the tube. Rotary heat-exchanger wheel systems consist of a desiccant-impregnated wheel that rotates slowly between the incoming, outside airstream and the exhaust air. The wheel transfers heat from the warm exhaust air to the cooler outside air being drawn into the system.

AIR CONDITIONING. Air conditioning is based on a simple law of gases—when a gas is compressed, it heats; conversely, when a gas expands, it cools. A condenser-compressor unit circulates refrigerant through piping, valves, condensing coil, and cooling coil (evaporator). Within the cooling coil, a liquid refrigerant absorbs heat as it evaporates, thereby chilling the surrounding air. A blower draws warm air through a filter and across the cooling coil and then forces the cooled air into the room. Air conditioning serves to dehumidify and cool the air.

Dehumidifiers draw moisture-laden air over refrigerated coils to condense the water vapor and then drain off the condensate. A water-absorption medium, periodically replaced or regenerated, can also remove moisture from air. Fans draw humid air through the dehumidifier and return dry air to the room.

AIR MONITORING. Sensors are used to detect smoke or heat, temperature, combustible hydrocarbons (methane or gasoline), hydrogen sulfide, carbon monoxide, sulfur dioxide, ammonia, ozone, and chlorine. Detection equipment may be interconnected with the heating and ventilating equipment. Safe plant operation requires maintenance of all sensors to keep them in perfect operating condition.

To conserve energy, HVAC systems can be equipped with automatic setback systems. In all cases, the thermostats should be set as high as practical in summer and as low as reasonable in winter. Many plants maintain temperatures in areas not continually occupied as low as 10 to 13 °C (50 to 55 °F) during the winter and as high as 38 °C (100 °F) during the summer.

Computer rooms require special control of temperature, humidity, and air purification. Other areas with electrical or electronic equipment may also require dehumidification or air conditioning.

Exhaust from some ventilated spaces may require odor treatment before release to the atmosphere. Several odor treatment systems can be used, ranging from scrubbing towers with chemicals to fume incinerators. Each type of system requires special attention to ensure effective operation (see Chapter 13).

HEATING, VENTILATING, AND AIR CONDITIONING MAINTENANCE. Table 11.3 lists several of the important maintenance tasks required for HVAC equipment. More detailed and specific O&M information is available from the manufacturer's instruction guides. Maintenance frequencies should at least equal those indicated, but should be higher if specified by the equipment manufacturer or suggested by operating experience. The operator should observe all safety precautions and practices recommended by the manufacturer when operating and maintaining rotating, electrical, or fuel-system equipment.

COMMUNICATION SYSTEMS

Reliable communication systems are vital during normal plant operations and during emergencies. The telephone offers the principal mode of communication between wastewater treatment personnel and others outside the plant. Local telephone service companies provide the communication links, and plants can purchase or lease their own telephones. Sophisticated telephone systems can restrict certain telephone units to local calls while allowing unrestricted access from other units. Cellular telephones can also be a vital communication function for facilities.

Communication systems within a plant generally include several telephones, including a few with paging speaker systems. These systems may also have such items as portable beepers, pagers, or two-way radio communicators. Special telephones, required for hazardous areas, may be owned and maintained by the plant or may be leased from others. Battery recharge systems are required to keep the portable units operative. The radio communication system serves as an effective backup system when normal telephones are out of service.

LIGHTNING PROTECTION

Many parts of the country experience frequent lightning strikes. Large arrestors are applied to electrical systems to protect the apparatus from the effect of overvoltages. Lightning rods are used to protect buildings and other property.

ROADWAYS

Plant roadways provide cars, trucks, and other vehicles with access to the plant's buildings, structures, and equipment. The roadways must have stable, all-weather surfaces on base courses strong enough to bear truckloads and withstand frost action, if necessary. Roadway surfaces may be asphalt pavement, concrete, macadam, crushed

TABLE 11.3 Heating, ventilating, and air conditioning inspection and maintenance.

Inspection and maintenance tasks	Suggested frequency[a]
Fuel oil pumps	
Check pump seals; adjust or replace as required (see Chapter 12)	R
Check clearances within pump for free turning without appreciable end play	A
Remove exterior dirt and foreign materials from pump fittings	A
Inspect parts for wear; replace worn parts	A
Check strainers and water separators; clean regularly	M
Heating coils	
Tighten loose nuts, bolts, and screws	R
Check crank arm pivots and damper rods for wear; replace if necessary	S
Flush strainers, dirt pockets, and drip legs	M
Purge air from coil through vent	S
Unit heaters	
Clean casing, fan blades, fan guard, and diffuser	A
Tighten fan guard, motor frame, and fan bolts	R
Check fan clearances; maintain free rotation	A
Air-handling units and fans	
Check filters; clean or replace as necessary	S
Check for unusual noise and excessive vibration; perform during all other inspection and maintenance work	R
Inspect fan wheels, shafts, housing scroll, and side liners for corrosion or abrasive wear; replace as necessary	A
Tighten bolts and connections	R
Clean housing, wheels, louvers, and inlet and outlet ductwork	A
Check condition and tension of belts; replace cracked, frayed, or worn belts (see Chapter 12)	R
Check alignment of system components	A
Clean dampers and check linkage for freedom of movement, corrosion, and abrasion	A

[a]D = daily; W = weekly; M = monthly; S = semi-annually; A = annually; and R = as required.

stone, compacted gravel, soil cement, or other suitable surfaces. Roadways are crowned and sloped to shed water and may include curbs and gutters to control and direct runoff. Grades, vertical clearances, and curve radii must accommodate delivery trucks and maintenance equipment.

Any potholes, cracks, settlements, depressions, raveling, warping, scaling, or other damage needs prompt repair. Maintenance may take the form of patching, sealing, dragging, or resurfacing. Asphalt pavements and concrete repair areas must be clean and dry before patching, sealing, or resurfacing to ensure a good, tight bond. Maintenance

includes keeping roadways clear of debris and litter and trimming or removing trees, shrubs, and other obstructions to ensure a clear line of sight at intersections. A seal coat should be applied to asphalt pavement approximately every 5 years.

Signs are necessary to indicate speed limits, no-parking areas, fire zones, delivery zones, crosswalks, visitor parking, and other traffic-control directions. Paved roads need stripes and other pavement markings for traffic safety and control. Guardrails, bollards, or other traffic barriers need periodic inspection and repair.

In northern climates, maintaining safe year-round access to the plant facilities requires snow removal and deicing of roadways. The operator should avoid using salt on concrete roads or walks because chlorides in the salt eventually deteriorate the concrete. Snow fencing along some roads may be necessary to prevent snowdrifts. Good maintenance includes checking the plows, snowblowers, and deicer inventory before each winter season.

FLOOD PROTECTION

Most wastewater facilities are located at low elevations within watersheds and many exist within floodplains. Without adequate protection, floods may cause loss of life, injuries, and heavy damages, including loss of equipment, severed transportation lines, and cut communication links. Appropriate flood-protection facilities should keep treatment plants fully operational and accessible during a 25-year flood (a flood having one chance in 25 of being equalled or exceeded during any year). Plant facilities should be protected against a 100-year flood (a flood having one chance in 100 of being equalled or exceeded during any year).

All buildings and structures susceptible to flood damage need protection by either a levee or some other form of floodproofing. Floodproofing, temporary or permanent, involves keeping water out as well as reducing the effects of water entry. Sandbags to build temporary dams are one form of temporary floodproofing.

Protection from floods may best be achieved by permanent dikes, levees, or flood walls. Each system provides a barrier to prevent floodwaters from entering a protected area. Drains or conduits through the barriers must have gates or valves to prevent backflow to the dry side, and interior drainage must be pumped over the barrier during floods when the valves on the drainage conduits are closed to prevent backflow.

An alternative method of floodproofing includes closures, panels, and seals on doors, windows, and other openings to prevent water from entering buildings. Floodproofing with closures and seals, if applied to unsound structures, might result in more damage than might occur without floodproofing. Proper design of the closure must ensure sufficient structural capacity to withstand imposed hydrostatic forces. In addi-

tion, the building or structure must be evaluated for stability to resist overturning, sliding, or flotation.

A less desirable method of reducing flood damage is to intentionally flood the structure to balance the internal and external hydrostatic pressures. With this method, a flood-protected drainage system is needed to ensure positive drainage of the spaces after the flood.

Main power service to the wastewater treatment facilities should be located above the high-water mark for the plant protection design flood (typically the 100-year flood). If floods prevent direct access to buildings or structures except by boat, the power company should provide a remote main-power disconnect in an accessible area.

Sump pumps used to drain areas within the structures need to include auxiliary, independent alarms to warn personnel of high water. The sump pumps need to be connected with flood-protected, standby electrical generating equipment.

Plant management responsibilities include development of standard operating procedures for carrying out flood-protection measures. These procedures should specify tasks, sequences, and personnel assignments. Yearly inspections of flood preparations and drills to execute the flood-protection plan are essential parts of a good maintenance program. Summaries of flood-protection procedures should be prominently posted.

Plant management needs advance information from flood forecasting and warning sources as early as possible to carry out the flood-protection plan (WPCF, 1986). Established lines of communication and control are necessary for executing the plan, accounting for vacations, holidays, weekends, and sick leaves. Systems and equipment necessary for the flood-protection plan must be kept in a state of readiness at all times. Inadequate planning or equipment may result in a disaster when a flood does occur.

SOLID WASTE DISPOSAL

A wastewater treatment facility generates solid waste other than treatment sludges and residues. Paper, cans, cardboard, bottles, rags, kitchen waste, yard waste, bags, pails, and pallets represent a partial list of plant solid wastes requiring disposal or recycling. Good housekeeping is the first step in solid waste management.

Solid waste is normally removed by a service company or plant personnel who collect and haul the solid waste to landfills or recycling centers. In general, open fires for on-site solid waste disposal are prohibited. Solid waste must be stored on-site in appropriate containers to reduce the risk of fires and vermin infestations.

Plant staff should review the types of waste generated and encourage recycling or the use of returnable bulk containers. Some communities have programs to collect

aluminum, glass, paper, and yard waste. Participation in these programs conserves resources and promotes community goodwill. With some investigation, the operator may find that some chemicals, solutions, or other items can be obtained in returnable containers. This will reduce the volume of solid waste handled. In addition, many wastewater treatment facilities generate waste oil and hazardous waste that require special handling; regulations vary from state to state. The plant safety officer should review the applicable state laws and develop a hazardous waste management plan that complies with the state's requirements.

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INTRODUCTION

The purpose of this chapter is to provide basic information on current best practices for maintenance organizations. Libraries could be filled with the wealth of information published over the last decade on efficient maintenance practices. This chapter attempts to reduce the oceans of information into a concise summary, with numerous references and suggested readings at the end of the chapter for those interested in further reading.

BACKGROUND

The face of maintenance, the way world-class industries approach the basic repair function, has changed prolifically during the past 30 years. From the 1960s, through most of the 1980s, progressive companies practiced time-based preventive maintenance techniques under the premise that a correlation exists between equipment age and failure rate and that the probability of failure can be determined statistically. The first studies aimed at challenging this traditional approach came from the airline industry. In the early 1960s, airline maintenance practices of inspections and complete overhauls accounted for 30% of all operating costs. Forthcoming studies revealed that nearly 90% of all component failures were random, making scheduled replacements ineffective for prolonging life. By 1965, traditional overhauls requiring complete disassembly and remanufacture were replaced with "conditional overhauls" that focused on correcting only the immediate cause of failure. In 1968, the introduction of the Boeing 747 was accompanied by the first attempt at reliability-centered maintenance. By 1972, the practice of scheduled overhaul was discontinued entirely. From this need to make maintenance decisions independent of equipment age, condition-monitoring technologies emerged.

Further evidence that machine component failures have no correlation to age is shown in Figure 12.1. This graph shows how the life distribution of 30 identical 6309 deep-groove ball bearings installed on bearing test machines and run to failure results in large variations and supports abandonment of time-based maintenance strategies for increasing bearing life.

MAINTENANCE BEST PRACTICES

By definition, "best practices" are those methods that represent the best way to accomplish work and lead to superior performance. Maintenance strategies fall into one of four categories

- Run-to-failure,
- Preventive (time-based),

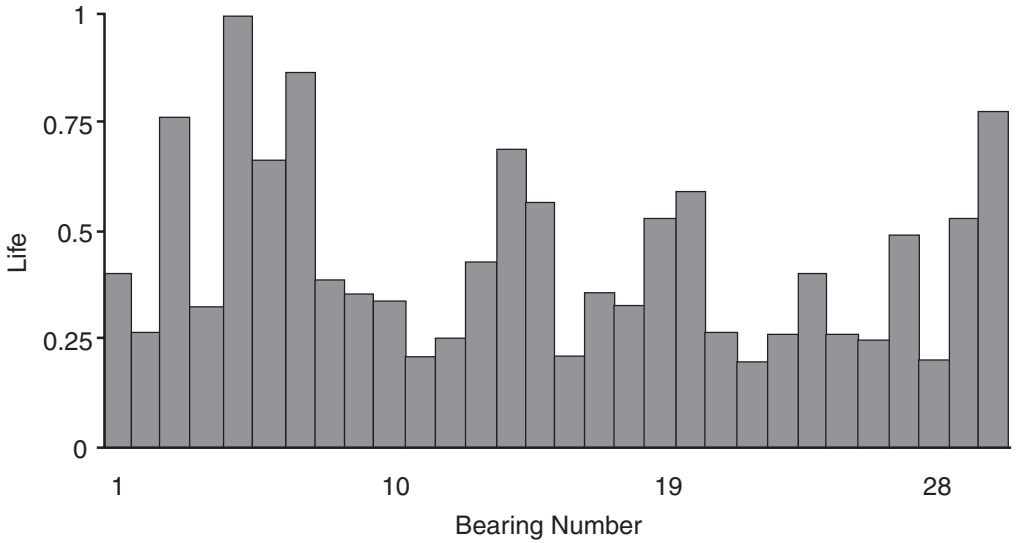


FIGURE 12.1 Bearing life scatter diagram (adapted from NASA, 2000).

- Condition-based, and
- Proactive.

Best-in-class maintenance organizations will use a mix of all of these strategies. Equipment criticality, process redundancy, and life-cycle cost analysis guides proper selection. As equipment history is gathered and reviewed, appropriate strategies evolve accordingly. As organizations move from run-to-failure towards condition-based and proactive maintenance, maintenance costs are typically reduced to one-third of original levels. The key element of a proactive program is root-cause failure analysis.

FAILURE ANALYSIS

Root-cause failure analysis (RCFA) is essential when trying to eliminate problems and failures from repeatedly occurring. Unfortunately, maintenance departments are often judged by how quickly a unit is returned to service and end up reinstalling conditions that lead to failure. Rarely are machine breakdowns attributable to a single cause. With in-depth analysis, multiple significant contributors can be identified. The roots of failure are

- Physical roots,
- Human roots, or
- Management system (latent) roots.

Preserving failure data is essential in an RCFA. For example, before replacing a failed pump, some of the items to record include operating data before the incident (pressure, temperature, flowrate, level, etc.), coupling condition, shaft alignment as found at failure, shaft runout, and anchor bolt condition. Sampling oil and grease from the failed unit and having lubrication analysis conducted is also useful. The physical examination of a failed component can help identify the failure mechanism, such as fatigue, wear, corrosion, or overload. This is the physical root of the failure. If needed, most manufacturers offer failure diagnostic services. An in-depth gear analysis would include visual inspection noting tooth wear patterns, the measurement of tooth pitch and lead error, quantitative chemical analysis of the material, and testing of the material tensile strength and hardness.

The physical reasons why a component failed, as well as the human errors of omission or action that resulted in the physical root, are more easily identified than a latent root. For example, a failed bearing (physical root) is found to have a damaged cage from inadequate lubrication. The mechanic who delayed greasing (human root) was reassigned to emergency repairs that preempted planned maintenance on the bearing (latent root). A management philosophy that does not allow "system" weaknesses to exist or go unchecked can eliminate huge groups of problems.

MACHINE INSTALLATION FUNDAMENTALS

The first step in any condition-monitoring program starts before any real-time operating data are collected. Pumps need to be sized for operation at or near the best efficiency point, dynamically balanced, mounted on stable foundations, coupled using precision shaft alignment tolerances, checked for pipe strain, and receive proper lubrication if they are expected to achieve run times of 5 years or more. Ideally, condition monitoring is not needed because machine assembly and installation practices are of such high quality. Of course, this is rarely the case. Bearings are not pressed on shafts properly, housing clearances are too large, and bracket sag goes unaccounted for during alignment. These are but a few of the problems that a good condition-monitoring program will detect.

SHAFT ALIGNMENT. Essential and fundamentally sound precision alignment of coupled shafts will increase the reliability of rotating equipment. Recall that bearing life is exponentially (a cubic function) related to force, making small misalignments a much larger problem than one would think. A practical benchmark for shaft alignment tolerances can be found in *Shaft Alignment Handbook* (Piotrowski, 1995; page 145).

Remember that shaft alignments are typically performed with the machine at rest, in a nonoperating state. While running under load, a machine will grow thermally and deflect according to foundation strength, pipe strain, and shaft speed. For the vast majority of equipment in a treatment plant, offline alignment is acceptable. For process critical equipment, or shaft speeds exceeding 1800 rpm, monitoring offline to running condition position changes may be worthwhile. Typically accomplished using an optical jig transit or proximity probes, recorded shaft positions at running speed can be compared to offline starting points and adjustments can be made as needed. Possible applications would be an aeration blower or a biogas compressor. Lockheed Martin (1997a) provides a detailed discussion of "offline to running condition" alignment techniques.

Finally, note that any alignment tolerances provided by a coupling manufacturer are absolutely not transferable to the driven shafts. Couplings do not correct, absorb, dampen, or otherwise fix in any way, shaft misalignment. Allowable coupling misalignment (provided by the coupling manufacturer) has nothing to do with the survivability of the pump system. The system includes not only the coupling, but also shafts, seals, and bearings. The misalignment tolerances shown on page 145 of *Shaft Alignment Handbook* (Piotrowski, 1995) are guidelines for a complete system and are more useful than component specifications. Note that the allowable misalignment is expressed in units of mils per inch, with the denominator representing the distance between the coupling flex points or points of power transmission.

BALANCING. Proper balancing of components and assembled rotating equipment is essential for long life. An unbalanced impeller creates a force on machine bearings according to the following:

$$F = 1.77 \times W \times R \times \left(\frac{\text{rpm}}{1000}\right)^2 \tag{12.1}$$

Where

F = force (lbf),
W = unbalance weight (oz),
R = radius of unbalance weight (in.), and
rpm = rotating speed (revolutions per minute).

Note: lbf $\times$ 4.448 = N.

As the shaft speed goes up, the resulting force increases as a square function, making balancing important for high-speed equipment. For example, a centrifuge oper-

ating at 2600 rpm with an 8-oz imbalance at a 15-in. radius results in the following force:

$$F = 1.77 \times 8 \times 15 \times \left(\frac{2600}{1000}\right)^2 = 1436 \text{ lbf} \tag{12.2}$$

Note: lbf × 4.448 = N.

The additional load produced by this force reduces expected bearing life. Formulas for calculating bearing life are as follows:

$$L_{10} = \frac{1000\,000}{(\text{rpm} \times 60)} \times \left(\frac{C}{P}\right)^a \tag{12.3}$$

Where

L_{10} = minimum life (hour),
rpm = rotating speed (revolutions per minute),
C = published basic dynamic load rating (lbf),
P = radial load on bearing (lbf), and
a = 3 (ball bearings), 3.33 (roller bearings).

The unbalance force (F) is added to (P) in eq 12.3, and the exponential relationship (a cubic function) magnifies small balance problems into large ones. Detailed discussions of the above parameters as well as procedures for calculating radial loading (P) can be found in most bearing manufacturer catalogs. For an example, assume a spherical roller bearing is rotating at 500 rpm under a radial load (P) of 33 000 lbf. The catalog value of the basic dynamic load rating (C) is 254 000 lbf and the bearing life is calculated as follows:

$$L_{10} = \frac{1000\,000}{(500 \times 60)} \times \left(\frac{254\,000}{33\,000}\right)^{3.33} = 29\,807 \text{ h} \tag{12.4}$$

Often, unbalance is reported in displacement units of mils (1 mil = 0.001 in.). This is a measure of the vibration response to the unbalance force. Representing the actual unbalance quantity, in units of ounce-inches, is done by relating the two measurements. Testing the residual unbalance by placing a known weight at a known radius and measuring the displacement allows the unbalance to be expressed either way. Shop balancing is done at speeds usually ranging from 250 to 500 rpm, as unbalance is the same at all speeds. The resulting force caused by the unbalance increases with speed, making proper balancing critical at higher operating speeds.

Commonly used balance tolerances are presented below. Which one to use is application-dependent.

Centrifugal Force <10% Static Journal Load. This specification states that the force resulting from unbalance must be less than 10% of the weight supported at each bearing. Typically, it is assumed that the total rotor weight is supported equally by two bearings and that the weight supported at each bearing is the total rotor weight divided by two.

MIL-STD-167-1 (U.S. Navy). This tolerance came from the military (1974), needing operating machinery quiet enough to avoid sonar detection. For rotors operating at more than 1000 rpm, the permissible unbalance is

$$U_{\text{per}} = \frac{4W}{N} \tag{12.5}$$

Where

U_{per} = permissible unbalance (oz-in.),
W = total rotor weight (lbm), and
N = rotating speed (rpm).
Note: oz × 28.349 = g; in. × 25.4 = mm.

This is an empirical formula, requiring data to be entered in the units shown for a correct solution. For a 1000-lbm rotor operating at 3600 rpm, the allowable residual unbalance is

$$U_{\text{per}} = \frac{4 \times 1000}{3600} = 1.11 \text{ oz - in. / plane} \tag{12.6}$$

Note: oz × 28.349 = g; in. × 25.4 = mm.

American Petroleum Institute. The American Petroleum Institute standard is, in effect, one-half of the MIL-STD. The formulas are identical except for the method of calculating the rotor weight (W). Here the total rotor weight is assumed to be supported by two journals; hence one-half the total rotor weight is used in the calculation.

ISO 1940-1 (International Organization for Standardization). This standard refers to balance quality of rotating rigid bodies and classifies rotor types by assigning them a

balance quality grade, referred to as a "*G*" number. Grades are separated by a factor of 2.5, as shown in the abbreviated listings of Table 12.1. American National Standards Institute (ANSI) has also adopted this standard as ANSI S2.19-1999. Permissible unbalance is calculated from the following:

$$U_{per} = \frac{G \times 6.015 \times \frac{W}{2}}{N} \tag{12.7}$$

Where

U_{per} = permissible unbalance (oz-in.),
G = balance quality grade number,
W = total rotor weight (lb), and
N = rotating speed (rpm).

Note: oz × 28.349 = g; in. × 25.4 = mm.

TABLE 12.1 International Organization for Standardization balance quality grades for rigid rotors.

Rotor classification (balance quality)	Rotor description (general machinery types)
G 40	Car wheels, wheel rims, drive shafts.
G 16	Automotive drive shafts, parts of crushing and agricultural machinery.
G 6.3	Parts or process plant machines. Marine main turbine gears. Centrifuge drums, fans, and assembled aircraft gas turbine rotors. Paper and print machine rolls. Flywheels, pump impellers, general machinery, and machine tool parts. Standard electric motor armatures.
G 2.5	Gas and steam turbines, blowers, rigid turbine-generator rotors, turbo-compressors, machine tool drives, computer memory drums, and discs. Medium and large electric motor armatures with special requirements. Armatures of fractional horsepower motors and turbine-driven pumps.
G 1.0 Precision balancing	Jet engine and charger rotors and tape recorder and phonograph drives. Grinding machine drives and small electrical armatures with specific requirements.
G 0.4	Spindles, discs, and armatures of precision grinders. Gyroscopes.

This also is an empirical formula, requiring data to be entered in the units shown for a correct solution. The standard suggests a balance quality grade of 6.3 for pump impellers. For a 1000-lb rotor operating at 3600 rpm, the allowable residual unbalance is

$$U_{per} = \frac{6.3 \times 6.015 \times \left(\frac{1000}{2}\right)}{3600} = 5.26 \text{ oz - in. / plane} \qquad 12.8$$

Note: oz × 28.349 = g; in. × 25.4 = mm.

PERIPHERALS AND MISCELLANEOUS PRINCIPLES. Rotor balancing and proper shaft alignment are important for long machine life. Many other factors play a significant role. Properly designed machine foundations will support applied loads without settlement or crushing, maintain true alignment conditions, and absorb and dampen unwanted vibrations. Useful guidelines for a good foundation include

1. The concrete foundation mass should be 5 to 10 times the mass of supported equipment (the density of concrete is roughly 2400 kg/m^3 [150 lb/cu ft]).
2. Imaginary lines drawn downward 30 deg from the shaft centerline should pass through the bottom of the foundation (not the sides).
3. The foundation should be 76 mm (3 in.) wider than the baseplate, 152-mm (6 in.) for pumps greater than 373 kW (500 hp).
4. Use concrete with compressive strength between 20 685 and 27 580 kPa (3000 and 4000 psi).
5. Let newly poured foundations cure 6 to 8 days; this allows concrete compressive strengths to attain 70 to 80% of their final value.

Piping strain in excessive amounts can make a precision balance and shaft alignment job pointless. Pump flanges are fluid connections and never should be used as pipe anchor points. To check for piping strain, place dial indicators on both shafts of the piped system and loosen the foot bolts. No more than 2 mils (0.002 in.) movement should result. Table 12.2 shows practical benchmarks to help aid in evaluating a piping stress measurement.

Additionally, piping configuration can influence long-term reliability. Centrifugal pumps, in particular, are susceptible to turbulent flows and high fluid velocities at the suction point. Generally, suction piping should be at least 1.5 times the pump's inlet

TABLE 12.2 Piping strain guidelines.

Total indicator runout (in.*)	Significance
<0.002	Ideal condition
0.002–0.005	Acceptable
>0.005	Provide needed piping supports
0.020	Refabricate piping

*in. × 25.4 = mm.

diameter. Use eccentric reducers with the straight side on top to transition to the pump inlet, and try to provide a straight run of six times the pump inlet diameter.

Shaft runout, or total indicator runout, should always be measured before installing any rotating piece of equipment. Both face and radial runout is measured using dial indicators and measures the eccentricity and perpendicularity of a shaft with respect to the centerline of rotation. Guidelines for acceptable shaft runout are linked to rotating speed, with higher revolutions per minute needing more precision. Table 12.3 shows practical guidelines for shaft runout.

Soft foot conditions exist when the mounting feet of a machine and the mating baseplate do not make full surface contact. Many problems can be traced to soft foot conditions as they can offset the centerline of shaft rotation, warp machine casings, and reduce internal component clearances. Soft foot is measured by placing dial indicators at the machine feet, loosening the hold-down bolts, and checking for movement. More than 2 to 3 mils of movement indicates a soft foot condition that should be corrected. Be sure to use shims that provide full footprint support across the face, and do not use more than four to five shims in a stack. Either of these conditions can make shaft alignment more difficult.

Often overlooked, proper bolt fastening secures the machine in place, absorbs impact forces, and prevents mechanical looseness from developing. A torque wrench is needed for good installation practices. Proper settings are dependent on the size and

TABLE 12.3 Shaft runout guidelines.

Rotating speed (rpm)	Max total indicator runout (in.*)
0–1800	0.005
1800–3600	0.002
3600 and up	<0.002

*in. × 25.4 = mm.

grade of the bolt. To approximate the wrench torque needed for proper tensioning, use the following:

$$T = 10^{b + m \log d} \tag{12.9}$$

Where

T = torque (ft-lb),
d = bolt diameter (in.), and
b, m = exponents from Table 12.4.

Note: ft × 0.3048 = m; lb × 0.4536 = kg.

Remember that these are guidelines only, for use with fasteners "as received" from the mill. In all cases, manufacturer specifications on torque settings should be followed. Also, most fasteners will retain a small quantity of oil from the manufacturing process. Applying special lubricants can reduce the amount of friction in the fastener assembly, allowing the specified torque to produce a far greater tension than desired.

CONDITION-MONITORING TECHNOLOGIES

For the vast majority of rotating equipment, integrated condition-monitoring technologies including vibration, thermography, ultrasonics, tribology, and electrical condition monitoring provide the most cost-effective strategy. All of these techniques have the common objective of showing early signs of deterioration, before failure of function. Condition monitoring will not prevent machine deterioration. It will stop unneeded repairs and allow repair before failure of function.

TABLE 12.4 Fastening guidelines[a] (adapted from Oberg et al., 1996).

SAE grade number	Tensile strength (psi[b])	Bolt diameter (in.[c])	b[d]	m[d]
2	74 000	0.25–3	2.533	2.94
5	120 000	0.25–3	2.759	2.965
7	133 000	0.25–3	2.948	3.095
8	150 000	0.25–3	2.983	3.095

[a]For standard unplated industrial fasteners. For cadmium-plated nuts and bolts, multiply by 0.8.
[b]psi × 6.895 = kPa.
[c]in. × 25.4 = mm.
[d]See eq 12.9 for explanation of exponents.

Note that preventive maintenance (calendar or time-based) is still a useful part of an overall effective maintenance program. Applications in which abrasive or corrosive wear occurs are still good candidates for time-based activities.

VIBRATION ANALYSIS

Before transistorized electronics ushered in the digital age, mechanics used to see if a coin would stand on end when placed on a machine housing. Although only a pass or fail test, it was, nonetheless, an attempt at measuring vibration levels. In the 1930s, T.C. Rathbone, an industry insurance underwriter, measured overall machinery vibration levels using an oscilloscope and calculated frequency components by hand. Vibration analyzers today are highly sophisticated and, of all available nonintrusive testing methods, provide the most information.

Vibration monitoring quantifies machine movement in response to a force. The captured time waveform can be plotted as amplitude versus time, or data can be transformed using a fast Fourier transform (FFT) and expressed as amplitude versus frequency. Any random vibration signal can be represented by a series (a Fourier series) of individual sine and cosine functions that can be summed to yield an overall vibration level. The amplitude of this vibration signal defines the severity of the problem. Plotting the amplitude versus the frequency (the Fourier spectrum) allows for identification of discrete frequencies contributing most to the overall vibration signal, commonly referred to as a "signature analysis" or a "frequency spectrum". Machine looseness, misalignment, imbalance, and soft foot conditions are all fairly easily identified in the frequency spectrum generated by an analyzer.

The instrument used for measuring vibration is a transducer, which converts a sensed mechanical motion to an electrical signal. Transducers can measure displacement (mils), velocity (in./s), and acceleration (*G*s or 32.2 in./s^2). All three measurements are describing the same thing, the amplitude of the motion. Once one value is found, the others can be mathematically calculated from the following relationships:

$$v = 2 \times \pi \times f \times d \tag{12.10}$$

$$a = 2 \times \pi \times f \times v \tag{12.11}$$

Where

d = peak displacement (mm [in.]),
f = cycles per second (Hz),
v = peak velocity (in./s), and
a = peak acceleration (in./s^2).

Recall that a Hertz is defined as a cycle per second, making 60 rpm = 1 Hz. A machine with a shaft speed of 1800 rpm (30 Hz) that measures displacement amplitude of 10 mils (0.01 in.) has velocity and acceleration of

$$v = 2 \times \pi \times 30 \times 0.01 = 1.88 \text{ in./s} \tag{12.12}$$

$$a = 2 \times \pi \times 30 \times 1.88 = 354 \text{ in./s}^2 \tag{12.13}$$

Note: in. × 25.4 = mm.

Presently, the accelerometer is the preferred transducer for machine monitoring because the frequency response is good over a broad range of operating speeds. They measure acceleration directly and are equipped with electronic integrators to give velocity and displacement. Displacement signals are emphasized, or more pronounced, at lower frequencies (<20 Hz), and acceleration emphasizes high frequency (>1000 Hz) peaks. The best indicator of overall machinery condition is velocity.

Over the past few years, the vibration industry has made great strides in detecting impending bearing failures at their onset, long before loss of function. Early surface imperfections generate short-duration, high-impact spikes of energy. Digital technology using very high sampling rates can capture the impacts. Time-domain waveforms are particularly useful in this area. By examining amplitude, symmetry, and particularly pattern recognition, time waveforms are an indicator of the true amplitude of bearing impacts (the FFT analysis will bias the amplitude low). This technique also has good application in low-speed equipment, gears, looseness, and orbit analysis of sleeve bearings. Figure 12.2 shows the time waveform, as well as the corresponding spectral plot, from a failing bearing on a primary sludge pump. Note the characteristic pattern of a large spike flowed by a "ringing down" in the time waveform and the nonsynchronous energy with a noisy floor in the spectral plot.

LUBRICATION AND WEAR PARTICLE ANALYSIS

Lubrication and wear particle analysis provides information on the condition of the lubricant itself, as well as the wear condition of the friction surfaces the lubricant is protecting. Analysis of the lubricant quantifies the chemical contamination, its molecular condition, dissolved elements, and state of additives. Common testing includes viscosity measurement, acid number, and base number. Typically, oil analysis can indicate that a problem exists but may not be able to identify the specific problem.

The amount, makeup, shape, and size of the wear particles present in the lubricant provide information about the internal machine condition and the severity of compo-

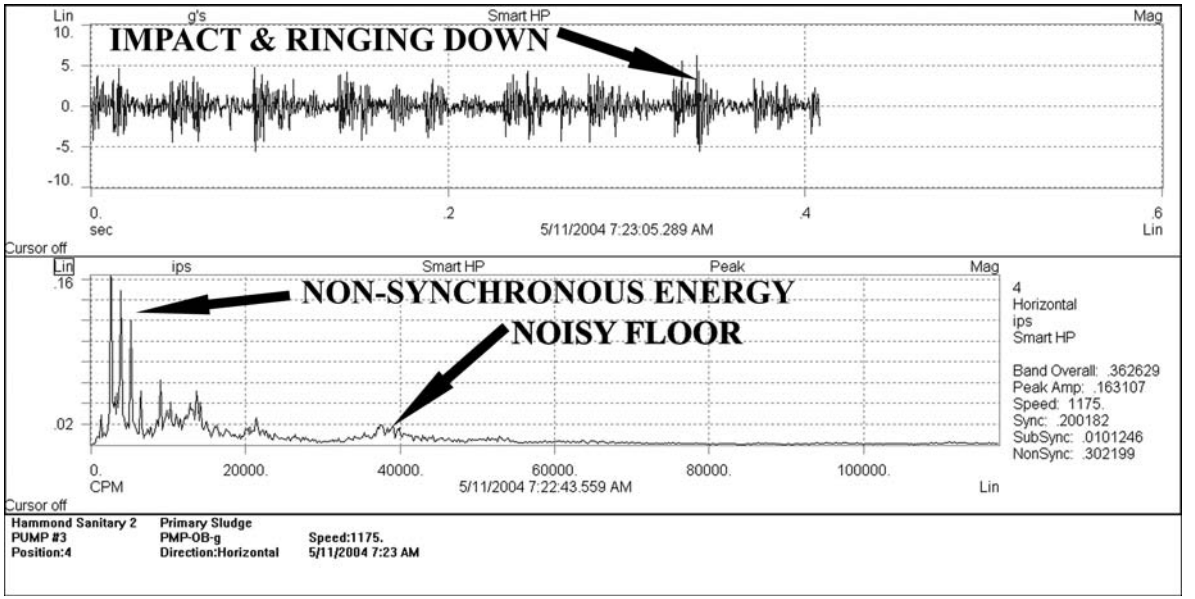


FIGURE 12.2 Failing bearing on a primary sludge pump—vibration data.

nent wear. There are several different analysis techniques. Changes in the ratio of small to large particles, the total weight of the particles, or the concentration of ferrous particles indicate that the wear process has begun. In most cases, samples drawn from active, low-pressure lines ahead of filters will yield an accurate diagnosis of the specific source, severity, and location of the problem. The importance of sampling location cannot be emphasized enough. The objective is to collect oil samples that represent what is passing through the machines bearings. Large reservoirs and downstream of filters are poor choices.

Every attempt should be made to follow lubrication specifications provided by the equipment manufacturer, particularly recommended volumes and change intervals. In some cases, too much grease will cause overheating and premature failure. Note that a sealed bearing, as supplied from the factory, will typically have the bearing cavity filled to 25 to 35% with grease. In other applications, the manufacturer requires three or four tubes of grease per bearing, but does not explain that the purpose of this volume of grease is to purge the bearing. Results of analysis on used oil or grease samples should be used to adjust the frequency of changes.

THERMOGRAPHIC ANALYSIS

Commonly identified with electrical equipment monitoring, thermograpy is also a useful tool for monitoring plant machinery. Thermography measures infrared radiation energy emissions (surface temperatures) to detect anomalies. Infrared cameras have resolution to within 0.1 °C and digitally store captured images. Both the absolute and relative temperatures can be obtained on virtually all types of electrical equipment, including switchgear, connections, distribution lines, transformers motors, generators, and buswork. Mechanically, infrared thermography applications are numerous and include all equipment with friction points such as bearings couplings, piston rings, brake drums, and heat exchangers. Like all of the other condition-monitoring technologies, data trending of equipment images will mark changes and help establish baselines. Table 12.5 provides broad guidelines for absolute temperature limits of some common mechanical components.

TABLE 12.5 Mechanical component temperature limits.

Component	Temperature (°C)
Bearings, roller element type	
Races/rolling elements	125
Retainers (plastic)	120
Cages/retainers/shields (metal)	300
Bearings, plain type	
Tin/lead-based Babbitt	149
Cadmium/tin-bronze	260
Seals (lip type)	
Nitrile rubber	100
Acrylic lip	130
Silicone/fluoric	180
PTFE*	220
Felt	100
Aluminum (laboratory)	300
Mechanical seal materials	
Glass-filled Teflon	177
Tungsten carbide	232
Stainless steel	316
Carbon	275
V-belts	60

*PTFE = polytetrafluoroethylene.

Motor ratings are established by their maximum allowable operating temperature and are a function of the insulation system. Motor life is reduced by 50% for every 10 °C rise above their rating. Temperatures on the outside of a motor will typically run 20 °C cooler than the inside. Table 12.6 provides useful information for conducting thermal analysis of motors.

ULTRASONIC ANALYSIS

Ultrasonic sound waves have frequencies above 20 kHz, the threshold at which human hearing stops. Every machine emits a unique sonic signature, which can be monitored for change by an ultrasonic detector. Detectors are typically hand-held devices that resemble a pistol and weigh approximately 0.9 kg (2 lb). Through a process called heterodyning, the ultrasonic signal is modified and processed into the audible range. Headphones allow a technician to hear the processed signal, and a meter quantifies the amplitude in decibels (dB).

A useful application of ultrasonic technology is determining when to grease bearings and how much to apply. This can be a challenging issue for technicians, as trying to determine when it was last done, how much was added, and the type of lubricant used is not always readily available, or trustworthy if it is. Once a baseline is established through historical readings, readings on similar equipment, or observations while lubricating, a change of 8 dB over normal lubricated conditions warrants attention. Deliver lubricant to the bearing until the signal returns to normal levels. Using headphones, lubricant is supplied until the sounds drop off and then begin to rise again. At this exact moment, lubricant delivery stops.

In 1972, NASA completed experiments using ultrasonics for early bearing fault detection. The technical brief (NASA, 1972), describes the experiments conducted using ball bearings and measuring the response in the 24 to 50 kHz range. In general, amplitude response increases more than 12 dB above baseline are an early indicator of

TABLE 12.6 Maximum motor temperatures (°C) at 40 °C ambient.

Class	Internal	External
A	105	85
B	130	110
F	155	135
H	180	160

deterioration. When tuned into the lower end of the ultrasound range, troubleshooting slow-speed bearings, typically fewer than 600 rpm, is possible.

Additionally, sonic signatures enable technicians to identify and locate compressed air leaks, steam trap leaks, and tank leaks. Compressed gas or fluid leaks through a small opening create turbulence on the downstream side, which can be captured by a scanning ultrasound device.

ELECTRICAL SURGE TESTING

The surge test is the cornerstone of electrical condition monitoring, providing information on the health of electrical windings. This specialized test locates weaknesses in the turn-to-turn, coil-to-coil, and phase-to-phase insulation of a motor's windings. Many electrical failures start with weakness in the turn insulation (noted at over 80% in some of the literature), and the surge test is the only test capable of identifying this deterioration. The test instrument applies energy pulses to the windings and monitors the stability of the waveform for signs of weakness. Surge comparison produces no numbers to be trended—it is a pass or fail test, requiring careful repetition to determine the location and severity of an observed fault.

Many field electricians will perform a megohm test (commonly referred to as "meggering") on a motor to check winding insulation health. This is not the same thing as a surge test. Surge testing checks for faults in the coils themselves, meggering monitors the insulation quality. It is possible for a motor to continue operating even though it is failing a surge test, but the identified problem should be addressed as appropriate.

MOTOR CURRENT SIGNATURE ANALYSIS

A nonintrusive test, motor current signature analysis, is useful in detecting mechanical and electrical problems in rotating equipment. The basis for the technology is that an electric motor driving a mechanical load acts as a transducer, varying current draw as the load changes. Analysis of these current variations may be trended over time, ultimately providing early warning of machine deterioration or process alteration.

PROCESS CONTROL MONITORING

Bear in mind that condition monitoring will not assess the operating efficiency of a pump-motor system. Often costing more than maintenance activities, inefficient pumping should be of interest to all maintenance personnel. Process parameter monitoring is a

valuable aide to condition monitoring. Parameters of interest are temperatures, line pressures, and flowrates. A useful equation for determining pump efficiency follows:

$$\text{hp} = \frac{\text{gpm} \times \text{TDH}}{3960 \times \text{efficiency}} \tag{12.14}$$

Note: hp × 0.75 = kW.

Where

gpm = gallons per minute,
TDH = total dynamic head (ft), and
efficiency = pump efficiency (%, expressed as a decimal).

Pressure gauges installed on the pump suction and discharge pipes will give the total dynamic head, and a flow meter on the discharge provides the information needed to measure pump efficiency. Using equation 12.14 in the units given, the efficiency of a pump discharging 25 000 gpm, against 17 ft-head, powered by a 150-hp motor, is 72%. The calculation follows:

$$\text{Efficiency} = \frac{25\,000 \times 17}{3960 \times 150} = 0.72$$

PREVENTIVE MAINTENANCE

Note that preventive maintenance (calendar or time-based) is still a useful part of an overall effective maintenance program. Applications in which abrasive or corrosive wear occurs are still good candidates for time-based activities. It is important to continually review a preventive maintenance program, ensuring that tasks are valid and provide measurable benefits. Equipment criticality and historical reliability should be used to eliminate unnecessary tasks and identify where to focus preventive tasks. Condition monitoring cannot replace preventive maintenance tasks. All equipment needs to be lubricated, cleaned, adjusted, and painted and have minor component replacements. The interval at which these tasks are completed can, and should, be adjusted with analysis of condition-monitoring data. Without exception, compliance with an established preventive maintenance schedule should be aggressively pursued.

RELIABILITY-CENTERED MAINTENANCE

As new monitoring programs are initiated, or existing ones are expanded, trying to decide which technology to use, the success at indicating incipient failures, and the

frequency of use can all be somewhat overwhelming. The reliability-centered maintenance (RCM) process provides a structured approach for evaluating these questions. Pioneered by Stanley Nowlan and Warren Heap while working for United Airlines, their document "Reliability Centered Maintenance", published in 1978, remains one of the most solid RCM discussions available. The authors proposed examining the consequences of failure as a starting point for maintenance decision-making and using condition-monitoring data to modify decisions as operating information develops. A basic discussion of RCM decision criteria is presented below. More detailed discussion of RCM methods can be found in the references and suggested readings provided at the end of the chapter.

Reliability-centered maintenance strategy focuses on three rules for evaluating maintenance decisions:

1. Identifying a failure mode,
2. Applicability, and
3. Effectiveness.

RULE 1—IDENTIFYING A FAILURE MODE. The intent of all condition-monitoring technologies is to provide quantifiable objective evidence of potential failure before functional failure. With this in mind, any condition-monitoring technology used must be aimed at detecting a specific failure. The idea here is to identify what failure you are trying to prevent.

RULE 2—APPLICABILITY. To be considered applicable, the technology should monitor a parameter that correlates to the failure mode identified. Parameter measurements must be accurate enough to provide a reliable trigger for repair work. Also, the technology must detect problems early enough for corrective action to be made—before functional failure.

RULE 3—EFFECTIVENESS. The effectiveness rule evaluates the consequences of the failure. Critical failures affecting human safety or the environment cannot be tolerated and warrant immediate response. All other failures should use cost-effective technologies, where the investment is lower than the cost to repair the failures. A useful tool for selecting which condition-monitoring technology to use is an RCM decision tree, as shown in Figure 12.3.

When applied carefully and properly, condition-monitoring technology will reduce maintenance costs. When used as a tool and integrated to a reliability-centered program, costs will be one-third of a run-to-failure approach. Table 12.7 provides cost benchmarks.

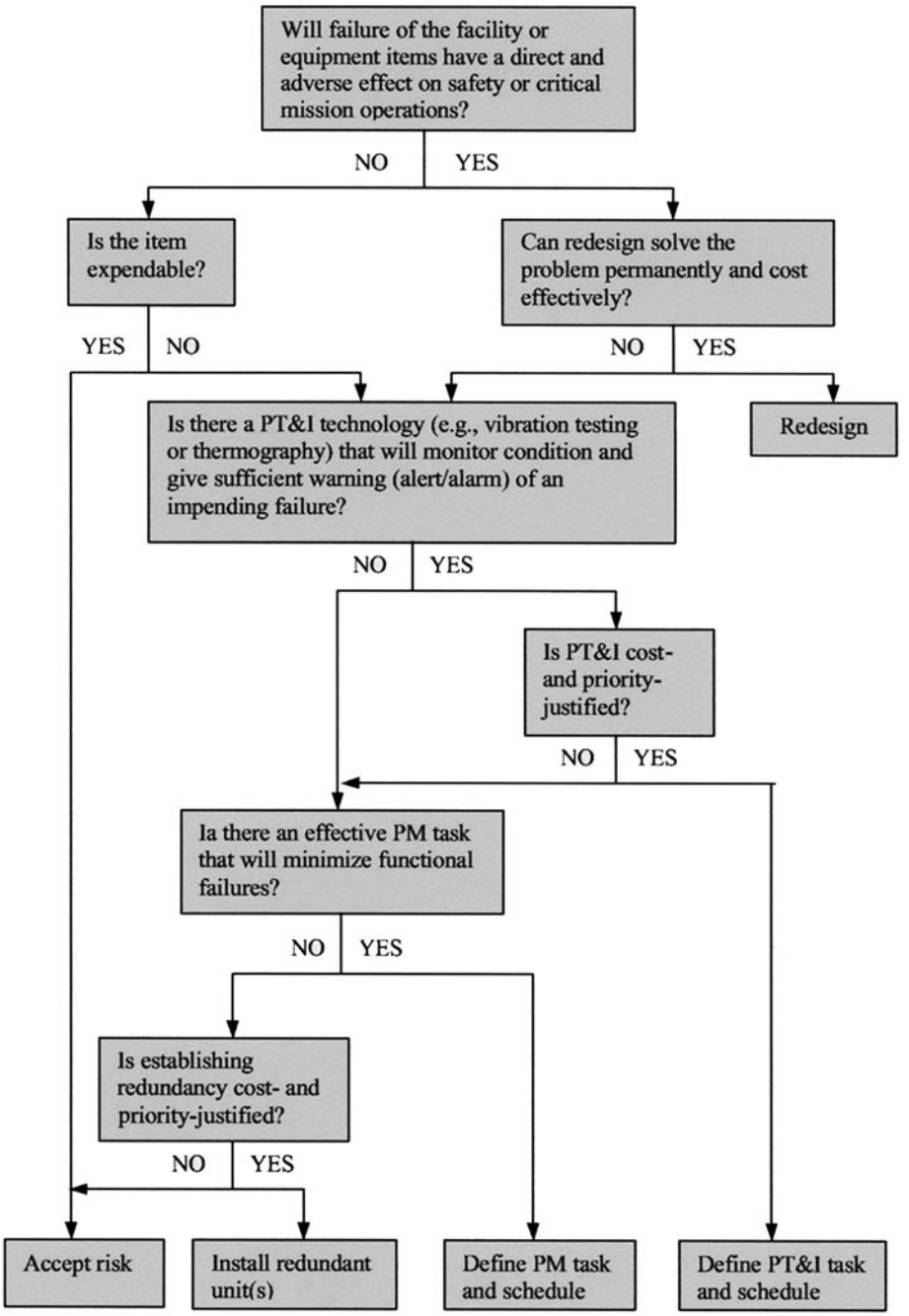


FIGURE 12.3 Reliability-centered maintenance decision tree.

TABLE 12.7 Maintenance costs (Piotrowski, 1996).

Strategy	Cost ($/hp/yr*)
Run-to-fail	18
Preventive	13
Condition-based	9
Reliability-centered	6

*$/hp/yr × 1.33 = $/kW/a.

As additional support to the power of condition-based maintenance, Table 12.8 shows the findings from a survey of 500 plants that have implemented predictive-maintenance methods. Plants included in the survey are from a cross-section of industries.

MEASURING PERFORMANCE—BENCHMARKING

Benchmarking is the practice of measuring performance against a standard. When applied in the proper context, it will objectively demonstrate whether a facility is being operated efficiently as well as quantifying progress and identifying what areas need improvement. Both industry benchmarking, where performance is measured against others in the same industry, as well as best-practices benchmarking, where performance is measured against industry leaders regardless of business, are useful tools for effective maintenance management. The practices provided here are general guidelines, considered to be industry norms, and have been proven to lead to superior performance. Table 12.9 provides wastewater industry specific benchmarks, summarizing information gathered from 90 plants in the United States, with capacities ranging from 15 140 to 3 251 300 m^3/d (4 to 859 mgd) and a median capacity of 208 175 m^3/d (55 mgd) during 1997.

Table 12.10 provides examples of best-practices benchmarks. Note that there are many variables associated with these values and absolute adherence is cautioned. Data

TABLE 12.8 Predictive maintenance cost reductions (adapted from Mobley, 2001).

Benchmark	Value
Maintenance cost reduction	50%
Unexpected machine failure reduction	55%
Repair time reduction	60%
Inventory reduction	30%
Mean time between failure increase	30%
Equipment uptime increase	30%

TABLE 12.9 Wastewater plant industry benchmarks[a] (Benjes and Culp, 1998).

Parameter	Median value[b]	Best-cost producer[c]
Maintenance staff/mgd[d] capacity	0.4	0.2
Secondary treatment	0.4	
Secondary treatment–nitrification	0.4	
Secondary treatment–nitrification–filtration	0.45	
Annual maintenance costs/mgd capacity	$31 816	$9688
Number of major assets/maintenance staff	73	177
Annual work orders/maintenance staff	124	293
Work order backlog (days)	18	3.7
Percentage overtime work	3.30%	0.80%
Percentage maintenance work planned	50%	90%
Maintenance planners/100-mgd capacity	2.2	0.8
Cost of spare parts/mgd capacity	$10 294	$1991

[a]Results are from a 1997 survey of 90 wastewater plants.
[b]Median value—50% of plants higher, 50% of plants lower.
[c]Best-cost producer—10th best in survey.
[d]mgd $\times$ 3785 = m^3/d.

TABLE 12.10 Best-practices benchmarks.

Parameter	Benchmark
Material dollars installed/labor dollars expended	0.5–1.5
Maintenance costs/equipment replacement value	1.5–2.0%
Number mechanics/total site workers	15–25%
Repairs requiring rework	<0.5%
Equipment downtime/scheduled run-time	0.5–2.0%
Failures addressed by root-cause analysis	>75%
Predictive/preventive schedule compliance*	>95%
Ratio corrective work orders/P/PM inspections	1:6
Ratio proactive to total work	75%
Ratio reactive to total work	25%
Ratio predictive PM to total PM	60%
Maintenance overtime percentage	5–10%
Paid maintenance hours captured by work order charges	100%
Percent work orders planned	90–97%
Inventory dollars/equipment replacement value	<1%
Inventory turns per year	2–3

*P = predictive and PM = preventive maintenance.

comparison is a useful tool, and much good can come from identifying where improvements are needed.

RECORDKEEPING AND MAINTENANCE MEASUREMENT

Existing competitive business environments are driving all competitive organizations towards optimized asset-management practices. Asset optimization provides maximum equipment availability and overall equipment effectiveness at the least cost. Computerized maintenance management systems (CMMS) are fundamental in the asset-optimization process, allowing the user to track equipment and the work associated with it. This type of information system is essential for planning, scheduling, establishing baselines, measuring improvements, and providing quantifiable decision support. Assigning failure codes can be quite useful in root-cause failure analysis and can help monitor the extent and cost of downtime. A good CMMS will provide standard reports, such as equipment repair history, and can help identify equipment that is costing too much. The many benefits of accurate work order tracking include better reliability and more accurate repair–replace decisions.

Selection of a CMMS should be based on user-developed objectives, goals, and measurements. For the most part, all CMMS packages available in the market provide the same basic maintenance management functions. A well-thought-out vision for the maintenance process is an essential starting point for a CMMS purchase. Dahlberg (2004) provides a listing of 52 companies that provide CMMS packages.

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INTRODUCTION

PURPOSE AND BACKGROUND. This manual is intended to be a reference of practice for operators involved in managing air emissions from wastewater conveyance, treatment, and residuals processing facilities. *Control of Odors and Emissions from Wastewater Treatment Plants* (WEF, 2004) presents a comprehensive review of available information on a variety of subjects concerning odor control in wastewater conveyance and treatment systems and should be referenced by operators in addition to this Manual of Practice.

The collection, treatment, and disposal of municipal and industrial wastewater often emit odors and other air contaminants. In the past, odors commonly associated with wastewater treatment plant operation were accepted by the public. This is no longer the case. There is increasing public concern and intolerance of odors and other air contaminants from wastewater treatment facilities, and management of air emissions has become a significant activity at most treatment plants. Furthermore, federal, state, and local regulations require that a number of air pollutants be contained and controlled. Today, odors, whether a health and safety issue or a nuisance condition, are not tolerated by the community. In fact, odors have been rated as the first concern of the public regarding wastewater treatment facilities. Once a facility has been marred for any reason, including odor, it is very difficult to change the image of the treatment facility in the mind of the public.

Factors contributing to the prevalence of odor concerns include construction of large, regional facilities with long septic travel times in the collection system; urbanization that moves people and industry closer to plant sites; increasing amounts of more complex industrial wastewater discharges; environmental regulations requiring a higher level of treatment; wastewater treatment plant design; facility operation and maintenance; and a more informed citizen who is concerned with the health and safety aspects of public services. Consequently, present wastewater treatment facility design, construction, and operation must address odor concerns as a high priority. In addition, corrosion problems are usually associated with odor detection. Solving an odor problem can minimize corrosion of concrete, including sewer pipe walls, exposed metal, and paints. Odors, particularly hydrogen sulfide, also contribute to the corrosion of galvanized structures and electronics.

Today, in addition to operating wastewater treatment facilities to meet water-quality objectives that protect and preserve limited natural water resources, facilities must provide adequate odor control that the public finds acceptable. This is a difficult task because the realm of odor control is subjective, and the final judge, according to the law or public acceptance, is the human nose.

Controlling air emissions encompasses a broad range of activities used to treat or modify the compounds in the liquid phase, minimize release into the ambient air, provide treatment through an odor control system, and increase the dispersion and dilution of the released gases. Proper odor control is closely coupled to the design and operation of collection systems, liquid treatment facilities, and solids processing systems.

Successful control of air emissions requires proper planning, proficient management, appropriate design, and attentive operation and maintenance. Managers of wastewater treatment facilities must perform odor measurement and characterization, understand modes of odor generation throughout the treatment process, apply the appropriate

odor control methods and technologies, and operate and maintain odor control equipment to successfully control air emissions from the facility. Proactive efforts with regulatory agencies and the public should also be considered to avoid unwanted legal and political activities.

WHAT IS ODOR?

Of the five senses, the sense of smell is the most complex and unique in structure and organization. The human olfactory process has both a physiological and psychological repose to odors.

THE OLFACTORY PROCESS. ***Physiological Response.*** The brain and the nose work together to create what an individual identifies as an odor. Odor perception begins well up in the nasal cavity where humans are outfitted with a collection of highly specialized receptor cells. As individual odorous molecules are drawn into the nasal cavity, a portion is dissolved in the mucous film that covers these specialized detectors (Minor, 1995). Once an odorous molecule is captured in the system, it will become attached to more or more of the individual receptor cells based on a shape match. Depending on the molecule, it may be captured by one or several of the specifically shaped receptors. Once a receptor has been stimulated, an electrical signal is transmitted to the brain and the amazing process of identifying odors begins (Campbell, 1996).

Once a signal is generated, the brain takes over and a person responds. When smelling an odor, the reaction may be to flee because of an association with danger or it may be to linger because of the perceived desirable situation. It has been asserted that human beings can detect over 10 thousand different odors even though humans can identify only a small percentage of these (Mackie et al., 1998; Minor, 1995). This sense of smell is much more precise than is our ability to describe the odor we have perceived.

Psychological Response. The psychological response to odor is more complex and far less understood than the physiological process discussed above. Evidence suggests that each individual learns to like or dislike certain odors. Children like almost all smells (Campbell, 1996). It is only as we mature and begin to talk about the odors that we develop a sense of likes and dislikes. Obviously, individuals react differently to the smell of any one odor source.

Perceptions about an odor are based on personal experiences that people have had throughout their life. For some individuals, this experience includes exposure to wastewater treatment, and therefore some level of odor may be acceptable to them. For others who may not have been exposed to such situations, any wastewater treatment odor may be perceived as very offensive and unacceptable.

The human nose provides the accepted standard for detecting and determining odor intensity. No machine has yet been developed that can simulate the human response. The human nose can distinguish differences in more than 5000 odors and detect some compounds with concentrations as low as 0.14 $\mu g/m^3$ (0.1 ppb) (WEF, 2004). In addition, most individuals can discern odors better with the left nostril, women are typically more sensitive to odors than men, and odors can alter or create moods. Simply put, "the nose knows".

ODOR GENERATION. Odors can be generated and released from virtually all phases of wastewater collection, treatment, and disposal. Most odor-producing compounds found in domestic wastewater and in the removed solids result from anaerobic biological activity that consumes organic material, sulfur, and nitrogen found in the wastewater. These odor-producing compounds are relatively volatile molecules with a molecular weight of 30 to 150. Domestic wastewater normally contains enough organic and inorganic compounds to cause an odor problem.

Odorous compounds include organic or inorganic molecules. The two major inorganic odors are hydrogen sulfide and ammonia. Organic odors are usually the result of biological activity that decomposes organic matter and forms a variety of extremely malodorous gases including indoles, skatoles, mercaptans, and amines. A list of common, malodorous, sulfur-bearing compounds is presented in Table 13.1. The odors produced, whether strong and persistent or merely a nuisance, are likely to be objectionable at the plant or in the community.

HYDROGEN SULFIDE ODORS. Hydrogen sulfide (H_2S) is the most common odorous gas found in wastewater collection and treatment systems. Its characteristic rotten-egg odor is well known. The gas is corrosive, toxic, and soluble in wastewater. Hydrogen sulfide results from the reduction of sulfate to hydrogen sulfide gas by bacteria under anaerobic conditions. Desulfovibrio bacteria, which are strict anaerobes, are responsible for the majority of the reduction of sulfate to sulfide, according to the following equation:

$$SO_4^{2-} + 2C + 2H_2O \rightarrow 2HCO_3^- + H_2S \qquad (13.1)$$

An illustration of the sulfur cycle is presented in Figure 13.1. At a pH of approximately 9, more than 99% of the sulfide dissolved in water occurs in the form of the nonodorous hydrosulfide ion (HS^-). Consequently, odorous amounts of hydrogen sulfide gas will not be released if a pH above 8 is maintained. Below this pH value, hydrogen sulfide gas is released from the wastewater. In comparison, odorous ammonia gas is released primarily at a pH greater than 9.

TABLE 13.1 Odorous compounds in wastewater (AIHA, 1989; Moore et al., 1983; Jiang, 2001; U.S. EPA 1985).

Substance	Formula	Molecular weight	Odor threshold, ppb	Odor descriptions
Odorous nitrogen compounds in wastewater				
Ammonia	NH_3	17.03	17000	Sharp, pungent
Methylamine	CH_3NH_2	31.05	4700	Putrid, fishy
Ethylamine	$C_2H_5NH_2$	45.08	270	Ammonia-like
Dimethylamine	$(CH_3)_2NH$	45.08	340	Putrid, fishy
Pyridine	C_6H_5N	79.10	660	Pungent, irritating
Skatole	C_9H_9N	131.2	1.0	Fecal, repulsive
Indole	C_2H_6NH	117.15	0.1	Fecal, repulsive
Odorous sulfur compounds in wastewater				
Allyl mercaptan	CH_2=C-CH_2-SH	74.15	0.05	Strong garlic
Amyl mercaptan	CH_3-$(CH_2)_3$-CH_2-SH	104.22	0.3	Unpleasant, putrid
Benzyl mercaptan	$C_6H_5CH_2$-SH	124.21	0.2	Unpleasant, strong
Crotyl mercaptan	CH_3-CH=CH-CH_2-SH	90.19	0.03	Skunklike
Dimethyl sulfide	CH_3-S-CH_3	62.13	1.0	Decayed vegetables
Dimethyl disulfide	CH_3-S-S-CH_3	94.20	1.0	Decayed vegetables
Ethyl mercaptan	CH_3CH_2-SH	62.10	0.3	Decayed cabbage
Hydrogen sulfide	H_2S	34.10	0.47	Rotten eggs
Methyl mercaptan	CH_3SH	48.10	0.50	Decayed cabbage
Propyl mercaptan	CH_3-CH_2-CH_2-SH	76.16	0.50	Unpleasant
tert-Butyl mercaptan	$(CH_3)_3$C-SH	90.10	0.1	Skunk, unpleasant
Thiocresol	CH_3-C_6H_4-SH	124.24	0.1	Skunk, rancid
Thiophenol	C_6H_5SH	110.18	0.1	Putrid, garliclike
Other odorous compounds in wastewater				
Acids				
Acetic acid	CH_3COOH	60	0.16	Vinegar
Butyric acid	$CH_3(CH_2)_2COOH$	74	0.10	Rancid
Valeric acid	$CH_3(CH_2)_3COOH$	102	1.8	Sweaty
Aldehydes and ketones				
Formaldehyde	HCOH	30	370	Acrid, suffocating
Acetaldehyde	CH_3CHO	44	1.0	Fruity, apple
Butyraldehyde	$CH_3(CH_2)_2CHO$	72	4.6	Rancid, sweaty
Isobutyraldehyde	$(CH_3)_2CHCHO$	72	4.7	Fruity
Valeraldehyde	$CH_3(CH_2)_3CHO$	86	0.10	Fruity, apple
Acetone	CH_3COCH_3	58	4580	Fruity, sweet
Butanone	$CH_3(CH_2)_2COCH_3$	86	270	Green apple

Key parameters that affect sulfide generation include

- Concentration of organic material and nutrients,
- Sulfate concentration,
- Temperature,

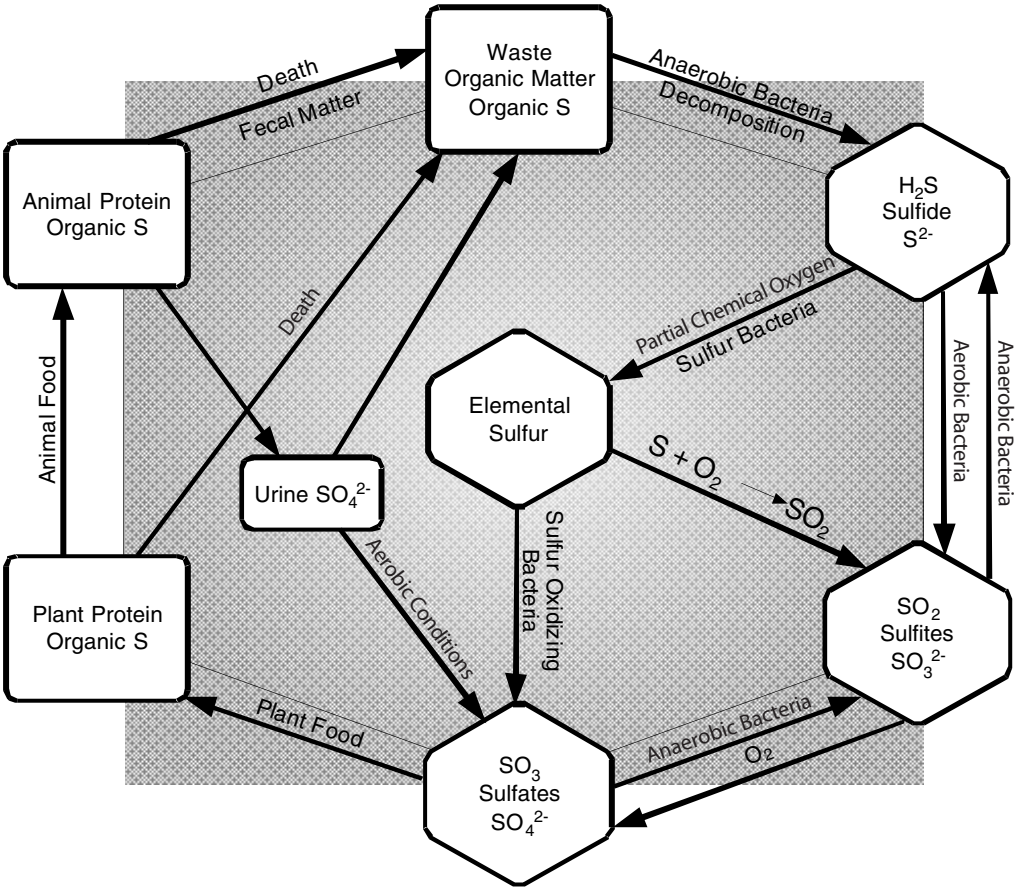


FIGURE 13.1 The sulfur cycle (U.S. EPA, 1985).

- Dissolved oxygen, and
- Detention time.

The characteristics of hydrogen sulfide gas are summarized in Table 13.2.

Sulfate is reduced to hydrogen sulfide by sulfate-reducing bacteria. Some sulfate is assimilated by organisms to form cell components. Upon mineralization, organic sulfur is converted to hydrogen sulfide. Hydrogen sulfide is transformed to elemental sulfur and then to SO_4^{2-} by sulfide-oxidizing bacteria. Anoxygenic phototrophic bacteria also convert hydrogen sulfide to SO_4^{2-} via elemental sulfur. Elemental sulfur may be transformed back to H_2S by sulfur-reducing bacteria.

TABLE 13.2 Characteristics of hydrogen sulfide (WEF, 2004).

Molecular weight	34.08
Vapor pressure, −0.4 °C	10 atm[a]
25.5 °C	20 atm
Specific gravity (vs air)	1.19
Odor detection threshold	0.5 ppb
Odor character	Rotten eggs
Typical 8-hour time weighted average (TWA) exposure limit	10 ppm
Imminent life threat	300 ppm

[a]atm × 101.3 = kPa.

SAFETY AND HEALTH CONCERNS. The first priority in any aspect of wastewater treatment plant operation is safety. There are two major safety and health concerns in the area of odor control. First, confined-space entry procedures must be used. Second, several odorous gases are toxic. These gases must never be treated with an odor control method that would mask their presence and render them less noticeable to an employee's senses. The Occupational Safety and Health Administration (OSHA) has provided maximum allowable exposure levels of several air pollutants for workers. These values are listed in Table 13.3. *Safety and Health in Wastewater Systems* (WEF, 1994) should be consulted for both confined-space entry and odor control methods.

Hydrogen sulfide is a colorless, toxic gas with a characteristic rotten egg odor. It is considered a broad-spectrum poison, meaning it can poison several different systems in the body. Breathing very high levels of hydrogen sulfide can cause death within just a few breaths. Loss of consciousness can result after fewer than three breaths.

Exposure to lower concentrations can result in eye irritation, a sore throat and cough, shortness of breath, and fluid in the lungs. These symptoms usually go away within a few weeks. Long-term, low-level exposure may result in fatigue, loss of appetite, headaches, irritability, poor memory, and dizziness. The health effects typically seen at various hydrogen sulfide levels are listed in Table 13.4. The OSHA permissible exposure limits for hydrogen sulfide are 10 ppm (time-weighted average) and 15 ppm (short-term exposure limit).

PUBLIC RELATIONS. Odors typically pose a long-term problem that affects the community. This situation requires a good public relations program with community residents. The community constitutes a part of the wastewater treatment organization and deserves honest communications. Key elements of a communications system include one specific person to act as the source for information; an odor complaint telephone hotline; an odor complaint investigation form that is completed when each com-

TABLE 13.3 Maximum allowable exposure of air pollutants for workers.

	OSHA standard, ppm	
Substance	**TWA[a]**	**Ceiling[b]**
Ammonia	50	–
Bromide	0.1	–
Carbon dioxide	5000	–
Carbon monoxide	50	–
Chlorine	–	1
Chlorine dioxide	0.1	–
Ethyl mercaptan	0.5	–
Hydrogen peroxide (90%)	1	–
Hydrogen sulfide	10	15
Iodine	–	0.1
Liquefied petroleum gas	1000	–
Methyl mercaptan	0.5	–
Ozone	0.1	–
Propane	1000	–
Pyridine	5	–
Sulfur Dioxide	5	–

[a] Time-weighted average.
[b] A ceiling value is the employee's exposure that shall not be exceeded during any part of the day. For all other values given, the employee's exposure (in any 8-hour work shift of a 40-hour work week) should not exceed the 8-hour TWA shown.

TABLE 13.4 Health effects of hydrogen sulfide exposure.

Concentration, ppm	Health effect
0.03	Can smell. Safe for 8-hour exposure.
4	May cause eye irritation. Mask must be used as exposure damages metabolism.
10	Maximum exposure for 8-hour period. Kills sense of smell in 3 to 15 minutes.
20	Exposure for more than 1 minute may cause eye injury.
30	Loss of smell, injury to blood brain barrier through olfactory nerves.
100	Respiratory paralysis in 30 to 45 minutes. Needs prompt artificial resuscitation. Will become unconscious quickly (15 minutes maximum).
200	Serious eye injury and permanent damage to eye nerves. Stings eyes and throat.
300	Loses sense of reasoning and balance. Respiratory paralysis in 30 to 45 minutes.
500	Asphyxia. Needs prompt artificial resuscitation. Will become unconscious in 3 to 5 minutes.
700	Breathing will stop and death will result if not rescued promptly, immediate unconsciousness. Permanent brain damage may result unless rescued promptly.

plaint is received and investigated; daily odor tours through the community by plant personnel; and regular public meetings or newspaper articles to inform the public of progress toward solutions to odor problems. Furthermore, treatment plants frequently provide tours of the facility, and many of those individuals taking the tour have the ability to influence the future of the sewer district. It is vital that they leave the tour with the best impression possible. Their impression of the treatment facility will persist into the future regardless of what explanation may be offered about the odors at the treatment plant.

ODOR MEASUREMENT, CHARACTERIZATION, AND DISPERSION

SAMPLING METHODS. Solving any odor problem begins with sampling and analyzing gases to identify and characterize the odors. The principal tools for diagnosing an odor problem are the techniques used for odor quantification and characterization. In general, odors can be quantified by direct sensory measurement of their concentration and intensity, using the human olfactory sense as the odor detector. Alternatively, chemical analysis of odor constituents could be performed. This is an indirect method, because the results of a chemical analysis still need to be related to odor concentration and intensity in some way. Odor regulations vary from location to location and may involve sensory, analytical, or both types of sampling and testing. In both cases, the samples must be carefully prepared to prevent sample contamination.

QUALITATIVE METHODS—SENSORY ANALYSIS. Sensory testing involves evaluating odors with the human nose. Odor concentration, intensity, character, and hedonic tone need to be determined for full characterization of odors (Figure 13.2). Although the nose provides only a subjective response to the presence or absence of an odor, several recently developed techniques quantify the human response.

Odor Panel Evaluations. Odors are usually defined as physiological or psychological responses resulting from stimulation of the human nose. An odor panel, the most common method used to evaluate odor nuisances, includes a group of people, typically eight or more, divided equally between men and women. Samples of odorous gas are collected, diluted several times, and delivered to the odor panel for sniffing. The average person can report the presence or absence of an odor with more certainty than its characteristics or objectionability. Therefore, an odor panel member responds either yes or no to the presence of an odor for each of the dilutions sniffed. A variety of sniffing devices can provide static or dynamic (continuous flow) portions of the sample for

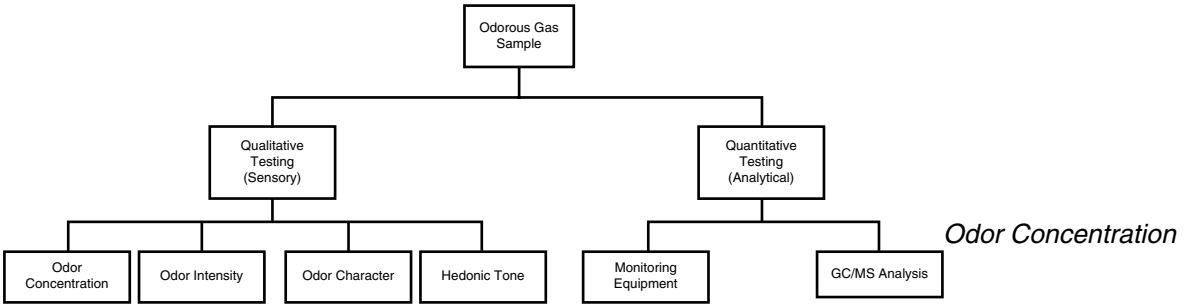


FIGURE 13.2 Odor sensory evaluation methods.

evaluation. The equipment to perform this testing, called an olfactometer, is commercially available. Testing can also be performed by an odor sciences laboratory.

Odor Concentration. The strength of an odor is determined by the number of dilutions with odor-free air necessary to reduce the odor to a previously defined, detectable level. One method of characterizing odors is to assign an odor threshold number representing the lowest concentration at which the human nose can detect some sensation of odor: The stronger the odor, the higher the odor threshold number. The establishment of odor thresholds requires several evaluations by an odor panel to determine when the odor is no longer detectable. Table 13.1 presents specific odorous compounds found in wastewater, their odor threshold numbers, and characteristic smells.

A second approach to odor strength includes determining the threshold odor concentration or the effective dose number (ED_{50}) with an odor panel test. The ED_{50} represents the number of dilutions necessary for the odor to be detectable by 50% of the panel members. In other words, the stronger the odor, the higher the value of the ED_{50}. The ED_{50} is expected to approximate the minimum concentration detectable by the average person. A more detailed discussion of odor concentration can be found in *Control of Odors and Emissions from Wastewater Treatment Plants* (WEF, 2004).

Odor Intensity. Odor intensity is measured using an odor intensity reference scale. The intensity scale in use in this country is based on *n*-butanol as the reference substance. The scale is composed of a series of solutions of *n*-butanol in air. Odor intensity is determined by alternately sniffing the odor with unknown intensity and the *n*-butanol odor at successive steps on the scale, in an effort to find the best intensity match. In using the scale, an effort is made to ignore the differences in odor character and the

attention is focused on perception of intensity alone (WEF, 2004). A more detailed discussion of odor intensity can be found in *Control of Odors and Emissions from Wastewater Treatment Plants* (WEF, 2004).

Odor Character. Odor character is used to distinguish among different odors. There are three types of descriptors: general, such as "sweet," "pungent," "acrid," etc., a reference to an odor source such as "skunk," "sewage," "paper mill;" or a reference to a specific chemical, such as "ammonia," "hydrogen sulfide," or "methyl mercaptan." The ability to distinguish odor characteristics is helpful for determining the source of an odor in ambient odor monitoring or in odor complaint investigations (WEF, 2004). A more detailed discussion of odor character can be found in *Control of Odors and Emissions from Wastewater Treatment Plants* (WEF, 2004).

Hedonic Tone. Hedonic tone of an odor relates to the degree of pleasantness or unpleasantness of the sensation. It is measured by means of category estimate scales or magnitude estimate techniques. Such measurements, however, are usually confined to laboratory research or investigations and involve primarily odors that are intended to be pleasant such as perfumery. While this property of odor, by definition, seems to determine objectionability, in reality the frequency, location, time, intensity, character, and our previous experience with the specific type of odor determines our response (WEF, 2004). A more detailed discussion of hedonic tone can be found in *Control of Odors and Emissions from Wastewater Treatment Plants* (WEF, 2004).

QUANTITATIVE TESTING—ANALYTICAL METHODS. Only a few instruments have been developed for continuous measurement of specific gases. These gases include hydrogen sulfide, chlorine, oxygen, and sulfur dioxide. Gas chromatography (GC) can be used on many odorous organic compounds, but the analysis is complex and expensive. A variety of portable gas-monitoring devices are discussed later in this chapter.

Gas chromatography requires an instrument for the separation of minute quantities (ppb levels) of organic and inorganic substances in a gas or liquid. The GC analysis separates a gas sample into its relative components but does not quantify the concentration of each component. Influent and effluent gas measurements indicate the relative change of specific compounds in a gas stream. These changes can be used to assess the effectiveness of a particular odor control technology. Levels as low as parts per billion of separated components can be specifically identified through mass spectrometry (MS). A complete identification is termed a GC–MS analysis. However, test results from wastewater treatment facilities can be difficult to interpret because the threshold concentrations of many odorous compounds are less than the detection levels of the GC–MS equipment used for analysis.

Portions of the GC-separated gas components can be directed to a sniffing port, allowing a technician to develop an odorgram for the sample. The technician assigns odor numbers to the results from the GC analysis and prepares a graph called an odorgram from these numbers. The odorgram identifies the specific compounds contributing most to the odor and allows comparison of the levels of the same compound in different samples.

ODOR GENERATION AND RELEASE IN WASTEWATER TREATMENT SYSTEMS

Odors can be generated and released from virtually all phases of wastewater collection, treatment, and disposal. The potential for the initial release or later development of odors begins at the point of wastewater discharge from homes and industries. It continues with collection and movement of wastewater in gravity sewers, lift stations, and force mains, ending with the actual wastewater treatment and solids handling and disposal at the plant or disposal site.

Hydrogen sulfide gas, a major odor source in wastewater treatment systems, results from septic conditions in the wastewater or solids. Metallic sulfide compounds in the wastewater produce a black color, indicating the presence of dissolved sulfide. Ammonia and organic odors are also common. Odors from wastewater and its residuals become significantly more intense and develop much higher concentrations of odorous compounds when the oxygen in the waste is consumed and anaerobic conditions develop. For this reason, much of the discussion of odor generation focuses on the anaerobic conditions that can develop in sewer systems upstream of the wastewater treatment plant as well as unit processes such as primary clarifiers, gravity thickeners, and sludge storage tanks in which anaerobic conditions are likely to develop.

Figure 13.3 illustrates locations in the collection or treatment system where odors initially develop and later become worse due to poor design, such as insufficient ventilation or excessive turbulence. *Design of Municipal Wastewater Treatment Plants* (WEF, 1998) addresses odor problems that can be controlled through proper design considerations. Housekeeping procedures, operational practices including process control and chemical treatment, facility maintenance limitations, and enforceable regulatory policies can also affect odors. Regulatory policies include the development and enforcement of local sewer use ordinances and industrial pretreatment regulations.

COLLECTION SYSTEMS. Wastewater in the collection system may contain a variety of odor-causing substances from many sources. While small gravity collection systems generate and release little odor, larger more complex systems often emit nuisance

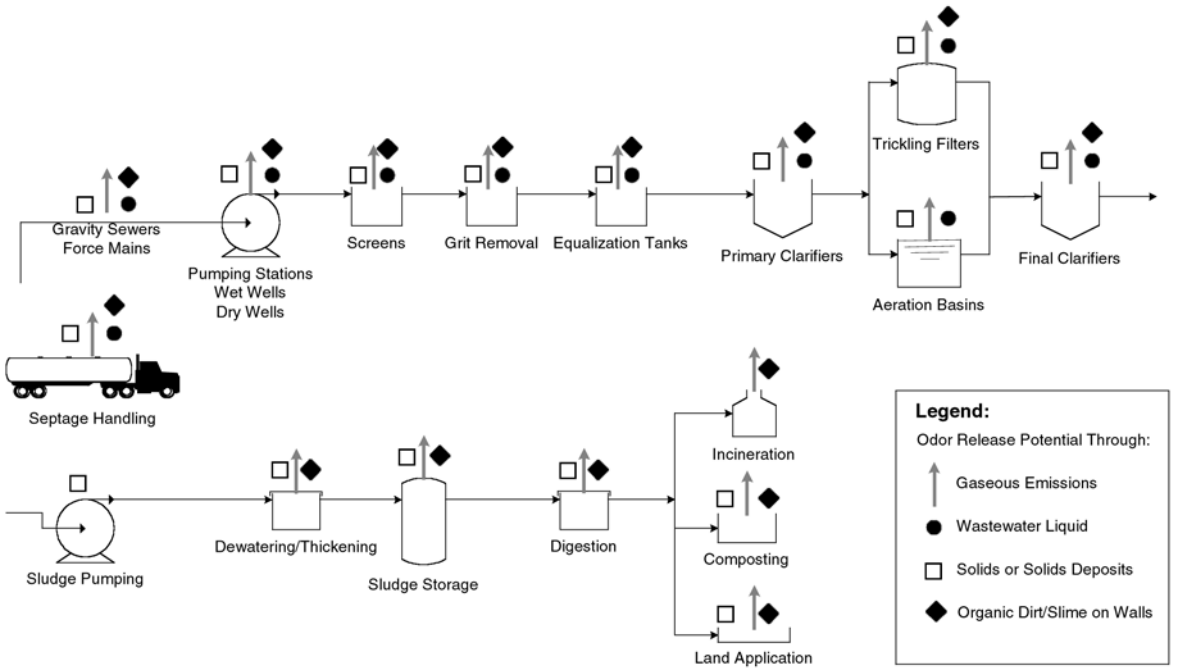


FIGURE 13.3 Locations in wastewater systems where odors may develop (adapted from U.S. EPA, 1985).

odors. This results from a combination of factors, including the presence of force mains, large gravity interceptors, long detention times, inverted siphons, industrial discharges, and so forth. Solutions to such problems can be costly and include chemical addition to the wastewater, injection of air or oxygen, and collection and treatment of the odorous air to prevent release into surrounding areas.

Industrial Discharges. Industrial wastewater discharges can contain odor-causing substances or contribute to the development of conditions resulting in odor release in the sewer or at the plant. Both conditions can be controlled at the source by enforcing industrial source regulations, summarized in Table 13.5. Smaller plants can control industrial contributions by developing and enforcing local sewer-use ordinances; larger plants can also implement an industrial pretreatment program as part of the discharge permit process. Existing regulations can be strengthened or additional regulatory requirements adopted to obtain end-of-pipe control.

Gravity Sewers. Odors in collection systems result principally from hydrogen sulfide gas and other reduced-sulfur compounds produced by anaerobic sulfate-reducing bacteria in sludge deposits and slime layers. Preventing or limiting the source conditions

TABLE 13.5 Regulatory parameters for industrial discharges.

Regulated parameter	Unregulated effect
pH limitations	At a pH below 8.0, sulfide changes to molecular hydrogen sulfide gas and is available for release.
Temperature	Higher temperatures increase microbial action of anaerobic bacteria and increase the release of volatile organic compounds from the liquid to the gaseous phase.
Slug loads	Large organic slugs reduce the oxygen concentration of the wastewater by exerting high oxygen demand.
Toxic discharges	Inhibits or kills microorganisms involved in biological treatment systems.
Flash point or lower explosive limit	Safety and odor problems resulting from organic solvent and gasoline discharges.
Fats, oils, and greases	Can collect and anaerobically degrade in wet wells or on tank water surfaces.
Chemical discharges	Odorous gases result.

that allow the bacteria to grow will reduce the odors. General design and operational control measures include

- Designing sewers with sufficient slope to maintain flow velocities adequate to prevent solids deposition,
- Minimizing hydraulic detention times in pipes and wet wells,
- Minimizing the use of drop manholes and other structures that result in significant turbulence,
- Maintaining clean pipes and walls through proper operations and maintenance (O&M) practices such as sewer inspections,
- Maintaining proper hydraulic flows, and
- Ensuring proper collection and treatment of odorous air.

Flow maintenance can be improved through the sewer connection permit process, control of infiltration and inflow, and industrial discharge permits.

Force Mains. Force mains with long hydraulic detention times can allow wastewater to become anaerobic, releasing odors at air release valves and at the force main outlet. In developing areas, temporary flows below the design flow can lead to long residence times. If anaerobic conditions develop in force mains, hydrogen sulfide gas and other odorous compounds will form, creating odors and causing corrosion. Procedures to

control sulfide formation include increasing the oxygen level (proper O&M procedures, and air or oxygen injection) and chemical addition (chemical oxidation, inhibition of sulfate reduction, and pH control). Proper hydraulic designs will help maintain sufficient flow velocities and reduce stripping of odorous compounds through turbulence. Often, vapor-phase treatment of odorous compounds is required at pressure-relief valves.

Pumping Stations. The causes of and cures for odor problems in pumping stations are similar to those in the collection system. However, the pumping station wet well provides an ideal location for the release and collection of gases previously trapped in the sewer and for solids deposition due to low velocity. Consequently, additional odor concerns for pumping stations include

- Adequate ventilation of the wet-well area to ensure the health and safety of employees;
- Recirculation of fresh, nonodorous outside air throughout the ventilation system;
- Pump sequencing to maintain proper hydraulic detention times;
- Proper wet-well design to avoid dead areas, including weekly flushing to prevent solids deposition and accumulation;
- Aeration in the wet well to minimize anaerobic conditions;
- Frequent cleaning to remove slime growths on walls or trapped floating fats, oils, and greases; and
- Collection and treatment of the vented odorous air.

LIQUID TREATMENT PROCESSES. Influent wastewater entering the treatment facility from the collection system may contain high concentrations of sulfide and volatile organic compounds (VOCs). In general, the preliminary and primary treatment processes are often major sources of emissions. Secondary treatment processes are not normally significant sources of offensive odor as long as sufficient oxygen is supplied to keep the various processes aerobic. Facilities downstream of the secondary treatment processes (filtration and disinfection) are not normally strong sources of odor.

Septage Disposal. Septage is reasonably dilute (approximately 97% water), malodorous, high in nitrogen (up to 500 mg/L total N), highly putrescible (2000 to 5000 mg/L biochemical oxygen demand [BOD_5]), and likely to contain large numbers of harmful viruses, bacteria, and other microorganisms (WEF, 2004). Septage collected from portable toilets, septic tanks, or dockside pump-out stations may also contain chemicals that can upset biological treatment processes.

The uncontrolled discharge of relatively large volumes of septage into a wastewater treatment plant would probably result in a rapid dissolved oxygen depletion

and subsequent odor generation. Also, septic wastewaters containing sulfides can lead to activated sludge bulking conditions involving filamentous organisms such as *Thiothrix* sp., *Beggiatoa*, and Type 021N (Jenkins et al., 1986).

The handling and receiving of septage at wastewater treatment plants can emit noxious odors and contribute to conditions that result in odor release in downstream treatment processes. Anaerobic septic tank wastes are typically received on a periodic, unscheduled basis.

To minimize upsets and odors in biological treatment systems, the septage discharge should contain less than 10% of the volatile solids in the plant influent, measured concurrently with the septage discharge (WEF, 2004). Excess septage, based on that limit, should be stored or pretreated to provide a lesser, more uniform discharge into the plant influent. An odor control system on the storage tank may be necessary. Chemicals to raise the pH, such as lime or caustic, can be metered into the septage during discharge.

Other possible septage control measures include

- Enforcing existing sewer-use ordinances and changing them if necessary,
- Adopting and implementing chain-of-custody practices, and
- Laboratory testing such as pH or oxygen uptake rate monitoring to prevent unregulated septage discharges of industrial wastewater that could inhibit downstream biological processes and cause odors.

Preliminary Treatment. Trapped or dissolved odorous gases in raw wastewater can escape to the atmosphere at the plant headworks. Wastewater turbulence, designed for headworks areas to ensure mixing and prevent solids deposition, accelerates the release of the gases. If the odors cannot be controlled upstream in the collection system, then the total headworks structure or the immediate area of turbulence may need to be enclosed for collection and treatment of the odorous air. Prevention of odor generation within the headworks itself requires clean influent structure walls and channels, including flow equalization basins, achieved through scheduled washing of slime and sludge accumulations.

High organic septic sidestreams from solids-processing operations, such as filtrates and digester supernatants, which are returned to the head of the plant, may also release odorous gases.

Odors in preliminary treatment emanate primarily from the screening and grit collection processes. Organic matter will adhere to the screens and produce odors if the screening solids or drainage become septic. Accumulated screening solids need daily removal, and units must be kept clean and odor-free. Closed containers store the collected material until it can be transported to a landfill for burial or dewatered for

incineration. Drainage systems for screening should quickly collect drainage and return it directly to the raw wastewater instead of allowing it to flow along the floors.

Grit chambers can be cleaned manually or mechanically. Some are aerated, while others depend on proportional weirs or other devices to regulate velocity and grit separation. Aerated grit chambers may release odorous gases during aeration. Because the organic material collected with the grit is the major cause of grit system odors, removal of this material may require grit washing to prevent septic odors generated in the plant and at the grit disposal site. Prevention of the problem requires proper regulation of air or controlled water velocities to remove heavier inorganics while allowing the lighter organics to remain in the wastewater stream.

Primary Clarification. Primary clarifiers can be a major source of odor emissions, particularly if the influent wastewater contains significant levels of dissolved sulfide. Primary clarifiers represent a large odor-emitting surface area, and the character of the odor is often considered objectionable. The turbulent effluent launders often represent a significant portion of the total clarifier odorous emissions. The greater the free fall over the effluent weirs, the greater the release of odorants. Covered effluent troughs and ventilation to a vapor-phase odor control system can minimize odor release resulting from excessive detention times or turbulence as the effluent flows to the next treatment process. Covering the entire basin and treating in an odor control system can reduce off-site odor impacts of primary clarifiers.

Accumulations of scum on the tank water surface and of organic matter on the effluent weirs can generate odors. Scum collection and conveyance equipment needs frequent cleaning, using hot water and abrasion to remove grease and slime buildups. Good odor prevention practice includes skimming floating solids and grease from primary tanks at least twice daily, and immediately removing floating sludge. Tank walls, weir troughs, sludge pits, and open channels need frequent cleaning. The operator should cover the sludge pits whenever possible.

Primary sludge odors will also result if settled solids remain for long periods on the tank floor or in the sludge collection area. Therefore, frequent sludge removal from operating tanks is necessary to prevent the production of gases that could cause the sludge to rise to the surface, releasing odors and inhibiting solids settling. Close control of the sludge removal frequency is required, particularly when concentrated digester supernatant, filtrate, or secondary sludge are returned to primary tanks. Septic conditions can be prevented by providing minimum hydraulic detention times, increasing the frequency of settled solids scraping, and providing the sludge-pumping rates necessary for effective thickening while minimizing detention time. Some plants continually withdraw a thin sludge and pump it to a separate thickener to minimize primary

clarifier odors. Sludge collectors need adjustment to allow delivery of most of the sludge to the hoppers on each pass. Generally, sludge is removed several times a day.

Many facilities are designed to provide excess primary clarifier capacity and the tendency is to operate all available clarifiers. Based on the design flows and loads for a given facility, it may be possible to remove primary clarifier tanks from service that are not required for the current flowrates. This prevents excessive detention time across the primary clarifiers, decreasing H_2S generation.

Primary settling tanks removed from service can become a major source of odor unless odor prevention procedures are followed. When any tank is removed from service for two days or more, all contents should be drained and the tank cleaned. If the tank is to remain out of service temporarily, it should be filled with chemically treated (typically chlorinated) water to prevent algal and bacterial growth. If the tank is to remain out of service permanently, it should be cleaned and left empty.

Secondary Treatment Processes. *Fixed-film processes.* Fixed-film processes, such as trickling filters or rotating biological contactors, generate odors if the air supply to the biological film is insufficient to maintain aerobic conditions. Both processes require a continuous, uniform distribution of the raw wastewater over the film area, together with an air supply sufficient to maintain proper slime thickness. Hydraulic overloading of either process or plugging of the trickling filter media or underdrains can reduce air circulation, allowing septic conditions to develop. Odors may also be generated when these processes are highly loaded in terms of BOD. Covering the processes and ventilating the odorous air to a control device provides effective odor control.

Activated sludge process. Biological aeration tanks and secondary settling tanks must be aerobic to function efficiently. Keeping these units aerobic is the most important odor control consideration. The two major sources of objectionable odors in activated sludge tanks are development of anoxic or anaerobic conditions in the aeration tank and entry of dissolved odorous compounds into the aeration tank.

As the first odor source, poor mixing or inadequate dissolved oxygen in the mixed liquor impairs the aerobic environment, causing settled deposits with resultant anaerobic conditions at the bottom of the tank. Because most diffusers can become clogged, routine cleaning is necessary. If the plant is equipped with swing-type, air-diffusion piping, operators can change clogged diffusers and flush air headers without emptying the aeration tanks. Mechanical aerators with the highest turbulence levels typically produce the highest odor and VOC emission rate, followed by coarse-bubble diffusers. Because of the low level of turbulence, fine-bubble diffusers typically have the lowest emission rate assuming all other factors (wastewater characteristics, mixed liquor suspended solids, and surface area) are equal (WEF, 2004).

Solids may settle in aeration basins as a result of low turbulence near the points where recirculated activated sludge enters the basins. Such deposits, combined with a limited oxygen supply, will usually generate objectionable odors. Aeration tank walls require regular cleaning to remove deposits.

As the second odor source, even with aerobic conditions, dissolved oxygen compounds may enter the tank with the primary clarifier effluent or with anaerobic return sludge flows; aeration then releases the compounds to the atmosphere. Aerosols formed during the aeration process can be carried by air currents far beyond the local tank environment. Both of these problems require control at the source.

Even a well-operated aeration basin emits a slight organic odor. The characteristic earthy, musty, organic odor of activated sludge results from the volatilization of complex organics and the production of intermediate compounds.

Secondary clarification. The causes of odors in secondary clarifiers are similar to those for primary tanks. Accumulations of scum on tank water surfaces, sludge accumulations on tank walls, and organic matter on effluent weir troughs can produce odors without proper daily housekeeping. Frequent, mechanical high-pressure water spraying will minimize algae growth, minimizing odor release.

Secondary sludge odors will develop if the settled solids remain on the tank floor or in the sludge collection area for long periods. Anaerobic conditions resulting from slow removal of settled sludge may produce rising sludge that hinders settling. Floating sludge can also cause violations of effluent suspended solids limitations.

Although an adequate return sludge concentration must be maintained, odors will be minimized if the settled mixed liquor is removed from the tank floor as quickly as possible and returned to the aeration tanks. Consequently, some secondary clarifiers have been designed with hydraulic, rapid sludge-removal systems to minimize the solids retention time on the tank floor. Similar to the control of primary clarifiers, sludge blanket control in secondary clarifiers attempts to maximize thickening and minimize solids retention.

If secondary sludge withdrawal rates are too slow, odors can develop and the septic sludge will exert an additional oxygen demand when it is returned to the aeration tanks. Septic sludge is also difficult to thicken and dewater. The operator controls the solids retention time in the secondary clarifiers to prevent a negative oxidation–reduction potential allowing sulfate-reducing bacteria to produce hydrogen sulfide gas. In addition to chlorinating the return sludge for control of filamentous organisms (Jenkins et al., 1986), some plants chlorinate it intermittently for odor control during odor problem periods or continuously as background for odor control during the warmer months.

Disinfection. The addition of excessive amounts of a disinfecting agent such as chlorine or ozone can cause residual odors, along with concerns for employee health and safety. Using automatic controls to pace the chlorine dosage to flow avoids adding excess chlorine and minimizes odor emissions.

SOLIDS TREATMENT PROCESSES. Solids-handling systems are typically a significant source of odors in wastewater treatment plants. Odors from solids-handling processes are typically complex mixtures of reduced-sulfur compounds including hydrogen sulfide, mercaptans, dimethyl sulfide, dimethyl disulfide, and others. Ammonia may also be present. Organic acid odors are also a concern when handling solids.

The incidence and concentrations of reduced-sulfur compounds is dependent on not only the type of treatment process, but also on how the unit processes are operated. For example, excessive detention times in sludge holding or blend tanks can cause high levels of non-H_2S sulfur compounds to be formed. It is important to process activated sludge without holding for more than 12 hours to prevent septicity.

Sidestreams Treatment. Sidestreams from solids processing, generally returned to the headworks of the plant, can contain high concentrations of BOD, chemical oxygen demand (COD), total suspended solids, and ammonium nitrogen. Returned sidestreams can cause odors directly through the release of odorous gases at the headworks structure, or indirectly from organic overloading and the consequent rapid dissolved oxygen depletion of the receiving wastewater.

Material balances within the plant must account for sidestream contributions. Solids in thickener underflows that are returned to the primary clarifier can alter the primary-to-secondary ratio of the feed sludge into downstream heat treatment or dewatering processes. Some sidestreams contain active anaerobic bacteria that enhance septicity if the sidestreams combine with settled, primary solids to produce various gases that hinder sludge settling as they rise.

Recycled sidestreams are generated periodically if thickening or dewatering processes operate intermittently. Consequently, flow equalization and storage of sidestreams may be necessary to supplement odor control equipment. Pretreatment of sidestreams to minimize odors includes aeration, biological treatment, and chemical addition.

Transfer Systems. Equipment used to transfer sludge or solids includes pumps, screw or belt conveyors, and vacuum systems. Most of these transfer systems emit an odor, regardless of the condition of the sludge. Consequently, the objective in controlling such odors is to minimize them. When possible, transfer equipment odors should be

contained, collected, and treated. Enclosed screw conveyors or the pumping of sludge through pipes will minimize odors. This requires proper daily housekeeping practices to ensure that equipment, walls, and floors remain clean from sludge, solids, and supernatant.

Thickening. Thickeners, including gravity units, dissolved-air flotation units, gravity belts, or centrifuges, need odor-controlled rooms or covers with odorous air collection and treatment. The sludge blanket on flotation units needs prompt removal during operation and complete removal during shutdown. The feeding of fresh primary solids to thickening processes will minimize the release of dissolved or trapped odorous gases. Secondary sludge, specifically waste activated sludge, has an earthy odor that is lower in intensity than the odor of primary sludge. It is important to process waste activated sludge without holding to prevent septicity.

Gravity thickeners treating primary sludge can be a significant source of objectionable odors. Adding elutriation water or chlorine solution to keep the supernatant from becoming septic, minimizing sludge blanket levels to prevent sulfide generation in the settled sludge, and frequent flushing of the surface and weir troughs can help reduce odor emissions (WEF, 2004). Co-thickening biological and primary solids results in the combination of a hungry population of organisms and a surplus of food in an oxygen-deficient environment and has the potential to create severe odors. The solution to this problem is to thicken primary and biological solids in separate tanks, if possible. If only one tank is available, it may be necessary to add chemicals along with the influent solids to treat sulfide as it is formed.

Dissolved air floatation (DAF), typically used for thickening waste-activated sludge, uses a high aeration rate to float solids, so any sulfide or odors present in the secondary solids will be stripped out in the DAF thickener. As with gravity thickeners, chemical pretreatment may be needed to control odorous emissions.

Chemical addition to the sludge prior to thickening reduces odor generation and release during the thickening process. Covering and ventilating odorous air to a vapor-phase odor control system improves indoor air quality and reduces the risk of the odors traveling off-site.

Blending and Holding. Holding tanks are used to collect and store sludge before treatment, or to blend primary and secondary sludge before downstream dewatering. Maintaining the proper solids retention time (typically less than 12 hours) will minimize odor production. Holding times in excess of 24 hours can cause a significant increase in the production of reduced-sulfur compounds. This not only increases odor emissions from holding or blending tanks, but also increases emissions from subsequent dewatering processes. If possible, the tanks should be covered and the odorous gases collected and

treated. Chemical additions will also control hydrogen sulfide release. Tank mixing during the off-shifts will minimize the release of trapped gas during the day.

Stabilization. Stabilization processes include chlorine oxidation, anaerobic digestion, aerobic digestion, composting, lime treatment, and alkaline chemical-fixation processes. With any of these processes, odor problems can develop if adequate stabilization of organic material is not attained, if residual odors are generated by a change in pH levels or specific chemical additives, or if housekeeping practices are poor.

Aerobic digestion processes generate odors similar in character to those from activated sludge aeration basins, if operated with sufficient dissolved oxygen concentrations. Anaerobic digestion occurs in closed vessels, and there is limited opportunity for odorous gas to escape. Points of odorous gas escape include open or inadequately sealed overflow boxes, annular spaces around floating digester covers, and unlit flares. Care should be taken to avoid these conditions.

Specific odor concerns include

- Hydrogen sulfide gas from upset anaerobic digesters;
- Overloaded aerobic digesters;
- Ammonia generation during lime stabilization;
- Residual chlorine odors from chlorine oxidation systems; and
- Release of ammonia during an alkaline, chemical-fixation processes.

Dewatering. Most dewatering processes used today are mechanical systems such as belt filter presses or centrifuges. Relatively few (typically smaller) facilities use drying beds. The characteristics of the odor released from these processes are a function of the characteristics of the feed solids. For example, a belt filter press dewatering aerobically digested solids from a facility with no primary clarifiers has significantly less odor than a belt press handling a blend of thickened primary and waste-activated sludge that has been stored for several days.

Turbulence created in any dewatering process will release the odorous gases generated by septic solids. Solids must be kept fresh, with hydrogen sulfide controlled by chemicals or by pH levels greater than 8 to prevent gas formation. Chemicals used for conditioning may also produce residual odors. For example, polymers often release a fishy odor during the dewatering process. Thus, polymer selection should consider odor potential as well as cost-effectiveness for coagulation.

Chemical addition effectively reduces odor release during dewatering. This method in combination with ventilating odorous air to a control device is the most common practice at the majority of treatment facilities today.

Composting. When the composting process was first developed in the early 1970s, odors were of little concern. When the process was implemented at many wastewater plants, however, it became apparent that odor emissions from composting operations were causing complaints. Many composting facilities were subsequently shut down because of odors. Even today, composting facilities continue to wrestle with odor issues, and the cost to control the odors significantly increases the overall costs of the process.

In most cases, odor release is the direct results of agitation (mixing, pile stacking, loading, etc.) of the composting piles. Most operations occur in a pole-barn-type structure (roof with no walls), providing little impediment to odor transmission off-site. Currently, many composting systems operate with negative aeration and discharge the process air to an odor control system, often a biofilter.

Thermal Drying. Thermal drying processes are advantageous because of the high volume reduction they achieve. However, control of both odor and particulate emission is necessary for most drying processes. Thermal oxidation processes are often used to treat the process off-gas because of the relatively high temperature and the complex constituents of the air stream.

Incineration. Incineration processes include multiple-hearth and fluidized-bed incineration, flash drying, wet oxidation, and pyrolysis. The primary source of odors is the escape of incompletely oxidized gases. Avoidance or control of this problem depends on designing and maintaining proper operating temperatures, turbulence, contact time, and oxygen levels.

Land Application. Odor emissions from land application of solids are a function of the characteristics of the material and the method of application. The greater the odor of the applied solids, the higher the odor emissions rate and potential for downwind complaints. Spray application is likely to have the highest odor emission rate. The lowest odor emissions are associated with application methods such as subsurface injection in which the material is immediately incorporated to the soil. Regardless of the method of application, the highest odor emission rates occur during application. Odor tends to dissipate to background levels within 24 to 48 hours.

ODOR CONTROL METHODS AND TECHNOLOGIES

Odor control is a complex and time-consuming challenge, often requiring a combination of methods for treating odorous gases and for removing or reducing the potential causes of the odors. If an odor problem is severe enough to affect the community, an emergency response and solution to the problem(s) must be carried out quickly.

Table 13.6 lists several odor control methods and technologies that can reduce an odor problem. The approach for selecting an odor control method or technology, summarized in Figure 13.4, includes the following steps:

1. Identify the odor source and characteristics through sampling and analysis.
2. List and assign priorities to controlling a specific odor problem, recognizing considerations such as cost, plant location, future upgrading of various wastewater processes, severity of the odor problem, and the nature of the affected area.
3. Select one or more odor control method or technology for implementation to meet the objectives of steps 1 and 2, taking into consideration the advantages and disadvantages of each.
4. Monitor odor emissions from the treated air for process adjustments and for feedback to evaluate the solution's effectiveness.

When odor problems develop, plant personnel sometimes lack the resources necessary to implement many of the control methods and technologies listed in Table 13.6. The containment, collection, and treatment alternatives may require design services, capital expenditures, and a best-available control technology (BACT) review by the local regulatory office.

The capital and O&M costs of the various BACT alternatives differ significantly. However, the costs associated with odorous gas capturing and handling (typically the major expenditures) will be the same regardless of the technology selected.

Control of Odors and Emissions from Wastewater Treatment Plants (WEF, 2004) provides an in-depth discussion of the theory, design, and application of the various odor

TABLE 13.6 Odor control methods and technologies.

Vapor-phase odor control methods	Atmospheric discharge and dilution
	Masking agents and counteraction chemicals
	Chemical wet scrubbing
	Activated carbon adsorption
	Biofiltration
	Biotrickling filters
	Air ionization
	Thermal incineration
	Aeration system treatment
Liquid-phase odor control methods	Chemical addition
Operational odor control methods	Source control
	Housekeeping improvements
	Process or operational changes

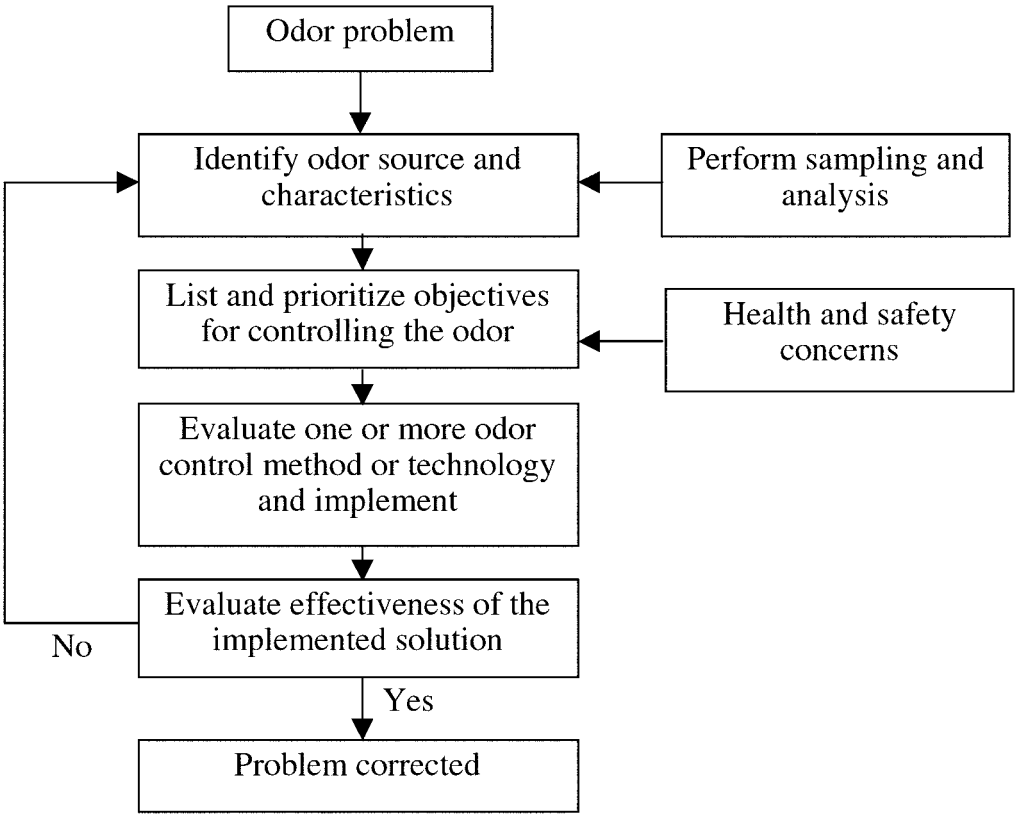


FIGURE 13.4 Flowchart for selecting an odor control method or technology.

control technologies. The following sections discuss odor control methods and technologies that apply to the problems facing a plant operator with normal, limited, day-to-day resources of materials, labor, and money.

CONTROLLING HYDROGEN SULFIDE GENERATION. Hydrogen sulfide production can be controlled by maintaining conditions that prevent the buildup of sulfides in the wastewater. The presence of oxygen at concentrations of more than 1.0 mg/L in the wastewater prevents sulfide buildup because sulfide produced by anaerobic bacteria is aerobically oxidized to thiosulfate, sulfate, and elemental sulfur. Maintaining an aerobic environment also inhibits the anaerobic degradation process contributing to the generation of hydrogen sulfide.

The dissolved oxygen concentration in collection systems can be increased by several techniques, including

- Providing air access by such items as manholes with air vents and plumbing vents in structures,
- Minimizing oxygen depletion by O&M procedures,
- Periodic cleaning of manholes and wet wells, and
- Injecting air, pure oxygen, or chemical oxidant into the wastewater stream.

Chemical addition can control sulfides by chemical oxidation, sulfate reduction, inhibition by providing an additional oxygen source, precipitation, or pH control. Minimizing septicity depends on maintaining sufficient velocities to prevent solids deposition and providing, to the extent possible, short detention times in gravity sewers and pumping station wet wells.

Chemical addition at the headworks can control sulfides in the wastewater treatment plant, but sulfides should typically be controlled upstream in the collection system. This approach also protects concrete and metals from corrosion. Preaeration may add the necessary oxygen if H_2S does not already exist in the influent flow. Proper operation and maintenance of all wastewater treatment processes are necessary, with special emphasis on

- Providing sufficient turbulence to prevent solids deposition and to ensure complete mixing (excessive turbulence will release odors already generated but maintained in the liquid phase);
- Maintaining at least 1.0 mg/L of dissolved oxygen in the aeration tanks;
- Keeping settled sludge fresh through adequate return rates;
- Ensuring proper hydraulic and solids detention times in all tanks;
- Adhering to typical process control ranges; and
- Developing an aggressive industrial pretreatment program to control the discharges of industrial wastewaters containing substances with high COD and BOD or odor-contributing compounds.

OPERATIONAL CONTROL METHODS. Offensive, localized odors often result from poor operational or housekeeping practices. Control of such odors depends on preventing the conditions leading to odor generation. Preventive operational measures include

- Maintaining adequate dissolved oxygen concentrations in the wastewater;
- Providing sufficient velocity (not turbulence) to ensure complete mixing, thus preventing organic solids deposition;

- Preventing sludge accumulations in tanks or excessive sludge aging through proper mixing, withdrawal rates, and process control parameters;
- Preventing overloading by recirculating, equalizing flows, or putting additional tanks into operation; and
- Ensuring uniform organic loading of biological processes.

Preventive housekeeping measures include

- Regular hosing of channels and walls to prevent solids accumulations, especially during tank dewatering operations.
- Use of hot water, cleaning solutions, and abrasives to remove slimes and greases.
- Rapid and complete drainage and flushing of tanks. Dewatered, clean concrete tanks can still emit offensive odors resulting from sorption of sludge by the concrete. This can be controlled by flushing with a strong chlorine solution.
- Regular skimming of floating scum and solids on water surfaces.

CHEMICAL ADDITION. Chemical addition can control odors in gravity sewers, force mains, and the wastewater treatment plant by preventing anaerobic conditions or controlling the release of odorous substances. These chemicals fall into four basic groups based on their mechanisms for odor control, shown in Table 13.7:

1. Chemicals to oxidize odorous compounds into more stable, odor-free forms;
2. Chemicals to raise the oxidation–reduction potential and prevent the chemical reduction of sulfates to hydrogen sulfide;
3. Bactericides to kill or inactivate anaerobic bacteria that produce malodorous compounds; and
4. Alkalis to raise the pH and thereby keep sulfides in their ionized form, rather than hydrogen sulfide.

The effectiveness of chemical addition as an odor control technology depends on such variables as cost, dosage, presence of odor-causing compounds, effects of chemical accumulations in sludge and process waters, equipment maintenance, space limitations, and safety or toxic substance concerns. Typical odor-control applications include collection systems, headworks, primary clarifiers, process sidestreams, aeration tanks, solids-handling applications, and storage lagoons. In general, it is more cost-effective to treat odors in the liquid phase than in the vapor phase.

Common chemical agents used to control odors include iron salts, hydrogen peroxide, sodium hypochlorite (chlorine), potassium permanganate, nitrates, and ozone.

TABLE 13.7 Chemicals used for liquid-phase odor control.

Chemical	Effective against
Oxidizers	
Ozone	Atmospheric hydrogen sulfide only
Hydrogen peroxide	Hydrogen sulfide, also acts as an oxygen source
Chlorine	Hydrogen sulfide and other reduced sulfur compounds
Sodium and calcium hypochlorite	Hydrogen sulfide and other reduced sulfur compounds
Potassium permanganate	Hydrogen sulfide and other reduced sulfur compounds
Raising the oxidation–reduction potential	
Oxygen	Higher temperatures increase microbial action of anaerobic bacteria and increase the release of volatile organic compounds from the liquid to the gaseous phase.
Nitrate	
Hydrogen peroxide	
Chlorine	
Bactericides	
Chlorine	
Hydrogen peroxide	
Potassium permanganate	Kill or inactivate anaerobic bacteria
Chlorine dioxide	
Sodium hypochlorite	
Oxygen	
pH modifiers	
Lime	Prevent offgassing of hydrogen sulfide; at a very high pH acts as a bactericide on sewer wall slimes
Sodium hydroxide	

Iron Salts. Iron salts react with sulfide to form insoluble precipitates and are widely used for control of sulfide at wastewater facilities. Both ferric and ferrous chemicals provide effective sulfide control, but ferric chloride also enhances primary settling and reduces downstream process loadings. The use of the ferric chemical will also enhance phosphorous removal. The lowest treatment costs are usually obtained by purchasing the product from a local supplier to minimize transportation costs. One advantage of iron salts over oxidation chemicals is that the salts do not react with wastewater organics and they are fairly sulfide-specific. Effective treatment has been obtained with an iron-to-sulfide dosage rate of 3.5 kg/kg (3.5 lb/lb). One disadvantage of iron salts is their absorbance of light, which can impair ultraviolet disinfection.

Hydrogen Peroxide. Hydrogen peroxide is a commonly used oxidant that chemically oxidizes H_2S to elemental sulfur or sulfate depending on the pH of the wastewater. Like other oxidant chemicals, however, peroxide reacts with organic material in the wastewater, so higher dosages are required. For some applications, successful treatment

has been reported at a peroxide-to-sulfide ratio of 2:1, but other applications have required as high as 4:1 (Van Durme and Berkenpas, 1989). Peroxide is fast acting, which makes it useful for addition immediately upstream of problem locations. However, it is also quickly consumed, so multiple injection sites are required to treat long reaches of collection systems.

Chlorine. Chlorine is a relatively inexpensive, powerful oxidant, and equipment required for its use is inexpensive and widely available. Chlorine is available as pure gas, hypochlorite solution, or hypochlorite granules or tablets. Commercially available solutions of sodium hypochlorite or calcium hypochlorite are the most common forms. Gaseous chlorine is used at many wastewater treatment plants for disinfection, but storage and handling requirements make it less desirable for collection system odor control applications.

Chlorine is an oxidant, so unlike iron salts it is not sulfide specific and much of the chemical is consumed through reaction with organics in the wastewater. Actual practice has shown that, depending on pH and other wastewater characteristics, between 5 and 15 parts by weight of chlorine are required per pound of sulfide (U.S. EPA, 1985). Chlorine can also act as a bactericide because it is a strong disinfectant. Depending on the point of application and the dose, it can kill or inactivate many bacteria that cause odors. However, because chlorine is nonselective, it will also kill organisms beneficial to the wastewater treatment processes. Care should be exercised when chlorine is added in the collection system near wastewater treatment plants.

Potassium Permanganate. Potassium permanganate is a solid chemical that is easy to handle and has been cost-effectively applied for pretreatment of both solids thickening and dewatering processes. For treatment of solids processes, such as a belt press, permanganate dosage rates have been found to be as high as 16:1. Permanganate is an oxidant that treats a wide range of other odorous compounds. Reducing the odor in the dewatered cake will decrease the amount of odor that escapes when the solids are transported off-site.

Nitrates. Nitrate addition controls dissolved sulfide by prevention and removal. For prevention, nitrate is added to wastewater to be used as a substitute oxygen source. This results in the projection of nitrogen gas and other nitrogenous compounds, rather than sulfide. For removal, nitrate can be added to septic wastewater to remove dissolved sulfide by a biochemical process, converting sulfide to sulfate.

Ozone. Ozone is an extremely powerful oxidant that can oxidize H_2S to elemental sulfur. It is also an effective disinfectant when bacteria levels are low. Although ozone reacts with nearly everything in wastewater, including dissolved sulfide, its principal

usage has been to treat odorous gas streams. Ozone is unstable and must be generated on-site. It is also potentially toxic to humans at concentrations of 1 ppm or greater in air. There are no applications that suggest that ozone treatment of dissolved sulfide in wastewater collection systems is economical on a long-term basis.

The selection of chemicals to control odors can be a trial-and-error process. Each of the chemicals has distinct advantages and disadvantages to be considered when seeking the best solution for a specific odor control problem. In many cases, a combination of chemicals, process changes, or other odor control methods may be necessary to solve the problem effectively.

CONTAINMENT. There is a full-range of available odor cover and containment systems alternatives. These are commonly used in conjunction with an odorous gas treatment process, such as wet scrubbers, activated carbon, or biofiltration. The selection of the appropriate cover and containment system will depend on several factors, including

- Site-specific unit processes that need to be controlled,
- Area climate,
- Worker safety,
- Ease of construction,
- Staff needs,
- Aesthetics,
- Effectiveness,
- Durability, and
- Cost.

Covers or domes contain gases emitted by odorous units. This method of odor containment works well on equipment such as headworks structure, screens, grit removal equipment, channels, effluent launders, primary clarifiers, aeration tanks, processing units, holding tanks, and screw pumps. When considering odor containment, focusing on the specific areas of odor release can minimize the actual area to be covered. The odorous air is exhausted from the containment and treated with an appropriate odor control technology.

The odorous gases contained under covers are often extremely corrosive or toxic. Flat, low-profile covers should be specified whenever possible to minimize headspace. Minimal headspace also reduces air-exchange volumes and related odor control equipment capacities. All electrical controls should be explosion proof and located outside the covered areas. Cover selection considerations include minimizing condensation problems and supporting snow and ice loads in northern regions.

Covers should have corrosion-resistant materials (although even aluminum will pit severely without adequate air collection); lifting lugs and apparatus where necessary to prevent injuries; and nonslip surfaces for flat cover areas that serve as walkways.

Aluminum and fiberglass covers have been used in numerous wastewater applications for covering small as well as large structures. Aluminum and fiberglass covers are known to be corrosion resistant and durable and can be assumed to have at least a 20-year service life. In many past wastewater applications, dome covers, shown in Figure 13.5, have been used to cover large circular basins. In recent years, flat covers (Figure 13.6) have been considered for many wastewater applications because the volume of air requiring treatment can be reduced. Minimizing that air space is critical to the ultimate sizing of the transfer duct work, blower capacity, and odor control technology. The major disadvantage of flat covers is the limited operator visibility and accessibility.

There are several manufacturers that produce fabric covers, shown in Figure 13.7, which have been used in wastewater applications. The fabric covers are relatively durable, as the manufacturer suggests using a 10-year life for the purposes of life-cycle costing.

MASKING AGENTS AND COUNTERACTION CHEMICALS. Odor problems can be addressed at the source or at the symptom. Masking (odor modification) and counteraction (odor neutralization) can be effective as an emergency, short-term solution for the symptom, but generally, long-term control of the odor problem at



FIGURE 13.5 Full dome covers (Photo by Gayle Van Durme).



FIGURE 13.6 Full flat covers (Photo by Alicia D. Gilley).

its source will be necessary. Masking and counteraction are usually applied to the air outside of buildings and enclosures or to odorous air discharged through building exhaust vents, including pumping stations. For example, masking or counteraction chemicals can be applied to a building exhaust system for short-term odor control until a permanent odor-control technology is installed or the odor problem is controlled at the source. Neither masking nor counteraction is completely effective if several



FIGURE 13.7 Flat fabric covers (Photo courtesy of ILC Dover).

odorous compounds exist or if their threshold concentrations vary. Regardless of the application, neither technique should ever be used to cover the presence of potentially dangerous gases.

The effectiveness of masking is difficult to predict because of varying odor characteristics and changing weather conditions. Masking agents usually consist of organic aromatic compounds such as heliotropin, vanillin, eugenols, benzyl acetate, and phenylethyl alcohol. Masking agents, used primarily where the level of odor is relatively low, always increase the total odor level. Without any chemical reaction, the individual constituents of the odor remain unchanged. The main advantages of masking agents are their low cost and nonhazardous nature. A disadvantage is their tendency to separate from the odor downwind. Sometimes, the fragrance is as offensive as the original odor. Applying high concentrations of masking agents for short periods of time provides a simple method to track and identify a specific odor source in the affected area of the community.

VAPOR-PHASE CONTROL TECHNOLOGIES. This section provides a general review of vapor-phase treatment technologies that are appropriate for wastewater applications. The main types of vapor-phase technologies are described in the following paragraphs. These include chemical wet scrubbers, activated carbon adsorption, biofiltration, biotrickling filters, and activated sludge treatment.

Chemical Wet Scrubbers. Chemical wet scrubbers, shown in Figure 13.8, operate by passing the odorous air through a chemical solution spray to remove the odorous constituents prior to discharge to the ambient air. The odorous gas is absorbed in the liquid phase, followed by a chemical reaction. The effectiveness of a chemical scrubber is dependent on adequate liquid–gas contact and proper maintenance of the chemical environment.

Wet scrubbers use pH-controlled absorption and chemical oxidation to remove odorous compounds from an air stream. A variety of chemical scrubbing solutions can be used, including sodium hydroxide (caustic), sodium hypochlorite (bleach), chlorine dioxide, hydrogen peroxide, and potassium permanganate. Acidic scrubbing solutions are typically used to remove ammonia and amines, while caustic solutions are used for hydrogen sulfide. Sodium hypochlorite is the most commonly used oxidant to treat H_2S and other odorous compounds prevalent at wastewater applications. If ammonia and/or mercaptans and hydrogen sulfide must be removed, a two-stage scrubbing system is usually implemented using caustic and sodium hypochlorite or another oxidant.

Activated Carbon Adsorption. Another type of air emission treatment commonly used for wastewater applications is activated carbon adsorption, shown in Figure 13.9.

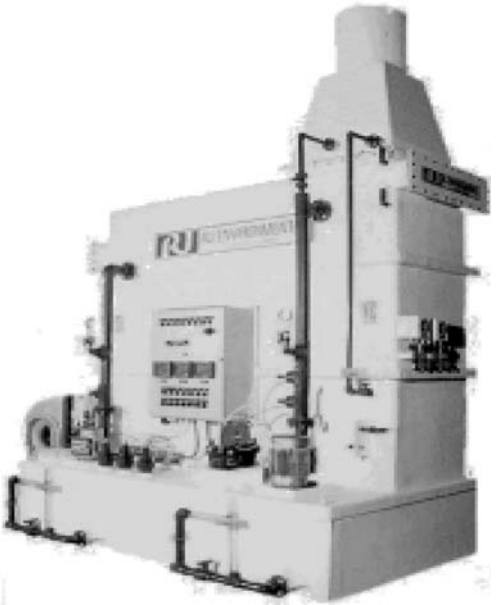


FIGURE 13.8 Chemical wet scrubber (Courtesy of USFilter–RJ Environmental products).



FIGURE 13.9 Activated carbon adsorption (Photo by Alicia D. Gilley).

Activated carbon is used to remove pollutants by surface adhesion. The highly porous structure of the carbon supplies a large surface area per unit volume. Systems typically consist of a stainless steel or fiberglass vessel containing a single bed or dual beds of granular activated carbon, through which the odorous air is discharged. Conventional carbon units are sized for face velocities of 203 to 380 mm/s (40 to 75 ft/min) and typically use a media depth of 0.9 m (3 ft).

There are four main types of carbon media: virgin, caustic impregnated, water washable, and high-capacity carbon. Virgin carbon has a greater capacity for removing VOCs than impregnated carbon. It also removes H_2S, but has about one-third the capacity of impregnated carbon. Caustic impregnated carbon has a greater H_2S capacity, but a diminished ability to remove other odorous compounds. Caustic carbon can be chemically regenerated in situ, but this is not recommended because of chemical handling concerns. Water washable media has a lower initial H_2S capacity than caustic carbon, but it can be regenerated multiple times with water. Water washable media costs more than caustic carbon initially, but it is more cost-effective over the long term. High capacity carbon has a very high H_2S removal capacity, about double that of caustic carbon. It is designed to be used once and replaced.

Biofiltration. Biofiltration, shown in Figure 13.10, is a biological process using soil, compost, or other media as a substrate for microbes that remove odorous contaminants from an air stream as it travels through the media. Sufficient residence time must be provided for microbes to accomplish effective contaminant treatment, so biofilters must use a low air velocity. For H_2S removal, typical residence times range from 40 to 60 seconds. Longer residence times may be necessary for airstreams containing high concentrations. Because the biodegradability of compounds differs, some compounds

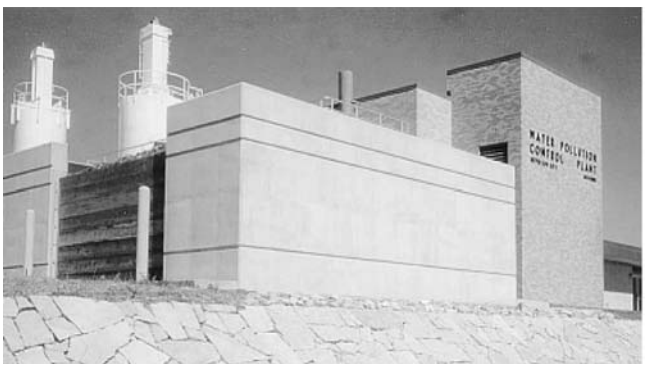


FIGURE 13.10 Biofiltration (Photo by Gayle Van Durme).

require several minutes of residence time for effective removal. Biofilters can also be designed to remove odorous VOCs and specific compounds.

The key elements in biofilter design are media, air distribution, and moisture. Biofilter media can be composed of organic materials, such as wood chips, compost, soil, peat moss, or some combination of these. Improper media can compact or become too wet, whereas a properly formulated media will last longer. Media porosity is important to minimize the head loss in the bed. Bed depths are typically 0.9 to 1.5 m (3 to 5 ft) with face velocities of 10 to 40 mm/s (2 to 8 ft/min). The low velocity results in very large footprint. Organic biofilter media degrade during use and must be replaced. The lifecycle is dependent on contaminant concentration, but typically ranges from 2 to 3 years. Inorganic media are also available through several vendors and provide a longer media life of 10 years. The media are approximately three times the cost of organic media, but provide a much longer lifecycle.

Because of their larger size and labor-intensive construction, biofilters can cost significantly more to build than wet scrubbers or activated carbon units. The higher initial costs may be offset by lower operational costs, depending on the H_2S concentrations being treated. Pre-engineered biofilters, which reduce labor requirements for construction, are becoming more prevalent.

Biotrickling Filters. In general, biotrickling filters, shown in Figure 13.11, consist of a containment vessel with some type of inorganic media to support microbial growth. Foul air is introduced at the bottom of the media while water is sprayed over the top of



FIGURE 13.11 Biotrickling filter (Photo by Gayle Van Durme).

the media. The water flows downward through the media and provides a moist environment that encourages microbial growth. The water also serves to flush the metabolic byproduct of sulfuric acid from the system. At wastewater treatment plants, nonpotable water can be used to supply sufficient nutrient for the microbes. For collection system applications, potable water is used and supplemental nutrients are required to support the bacteria.

Activated Sludge Treatment. The activated sludge treatment (AST) odor control technique routes foul air through the air diffusers in an aeration basin system for treatment by the activated sludge microorganisms. One issue with AST is that the foul-air flows requiring treatment must match the aeration basin process air requirements. Activated sludge treatment offers several advantages: It can perform well even at high concentrations of H_2S; the system is very simple to operate and maintain; it does not require storage, handling, and containment of hazardous chemicals; and it does not have the visual impact that a tall scrubber and exhaust stack present. One of the disadvantages of AST is the corrosion-resistant material required for the aeration basin piping and blowers.

ODOR CONTROL STRATEGIES FOR THE OPERATOR

Previous sections presented basic information on odor problems, odor development in wastewater collection and treatment systems, and available odor control methods and technologies. This section presents an odor control strategy for the plant operator, using previously presented information coupled with recent operational experiences in solving odor problems at wastewater treatment facilities.

OPERATOR'S APPROACH TO SOLVING AN ODOR PROBLEM. When an operator first becomes aware of an odor problem, it is important to evaluate all simple solutions quickly. Otherwise, the release of odors will have adverse effects on-site and possibly in the community. Generally, the operator's available resources restrict corrective approaches to improving housekeeping practices, implementing process or operational changes, or adding chemicals to the wastewater and solids streams. The operator should immediately determine the source of the odors and the specific odor-causing compounds. These sources must be determined before selecting a solution for the problem. Liquid and solid process control measures are listed in Tables 13.8 and 13.9, respectively. The sequence of steps to be considered when approaching an odor control problem is illustrated in Figure 13.12.

Table 13.10 presents a summary of odor control methods used by operators of several wastewater treatment facilities and lists specific effects and problems. The list pre-

TABLE 13.8 Liquid process operational emissions control (Rafson, 1998).

Process	Problems	Control measures
Preliminary treatment		
Coarse bar screens Fine bar screens	Influent sulfide and VOCs are stripped by turbulence inherent to these processes.	Upstream chemical addition. Recycle return activated sludge (RAS) to headworks. Containment and ventilation to a vapor-phase control system.
Parshall flumes	Turbulence causes stripping.	Use ultrasonic or magnetic flow measurement. Containment and ventilation to a vapor-phase control system.
Grit basins	Aerated grit basins induce stripping.	Vortex and horizontal-flow grit basins are less turbulent. Containment and ventilation to a vapor-phase control system.
Primary treatment		
Primary clarifiers	Sulfide formed in basins during holding. Sulfide and VOCs stripped at weirs. Sulfide forms in settled solids.	Remove unneeded basins from service. Raise water level in flume to decrease weir drop. Pump sludge more often. Avoid cosettling of sludge. Add iron salts directly or upstream. Containment and ventilation to a vapor-phase control system.
Flow equalization basins	Odor from residual solids in flow equalization basins.	Install collection and removal equipment and flush solids with high-pressure hoses after each basin dewatering.
Secondary treatment		
Trickling filters Rotating biological contactors (RBCs)	Influent sulfides stripped at distributors. Sulfide formed when overloaded or oxygen deficient.	Add iron salts upstream. Limit loading. Provide power ventilation. Slow distributors or increase wetting rate to maintain a thin aerobic film.
Aeration basins	Influent sulfide and VOCs stripped at head of basin. Sulfides form when oxygen deficient.	Decrease aeration at head of basin. Fine-bubble diffusers cause less stripping than coarse bubble. Pure oxygen causes lowest odor emissions.
Disinfection		
Chlorination	Volatile chlorinated by-products formed during disinfection.	Use automatic controls to pace chlorine dosage to flow. Convert to ultraviolet disinfection.
Advanced treatment		
Effluent filters	VOCs formed by chlorine used during backwashing to clean and control algae.	Minimize filter backwashing. Cover filters to block sunlight and control algae.

TABLE 13.9 Solids process operational emissions control (Rafson, 1998).

Process	Problems	Control measures
Thickening		
Gravity thickeners	Co-thickening biological and primary sludge causes sulfide generation. Long detention under anaerobic conditions is problematic.	Avoid co-thickening, if multiple basins are available. Use direct chemical treatment to reduce sulfide formed during thickening. Provide containment and ventilation to a vapor-phase control system.
Dissolved air flotation	Aeration strips sulfide and odors from sludge.	Use chemical pretreatment to remove sulfide from sludge before processing. Provide containment and ventilation to a vapor-phase control system.
Dewatering		
Belt presses	Pressing strips sulfide and VOCs from feed sludge into belt press room.	Potassium permanganate or hydrogen peroxide will treat sulfide and other odorous VOCs. Provide containment and ventilation to a vapor-phase control system.
Stabilization		
Anaerobic digesters	The H_2S formed in the process corrodes combustion equipment. Air quality is a concern, because H_2S is converted to sulfur dioxide during combustion.	Maintain proper temperature and pH in the process. Add iron salts directly to the digester, at headworks, or at primary clarifiers.
Aerobic digesters	Odorous compounds form when process is overloaded or oxygen-deficient	Provide adequate aeration and mixing to maintain aerobic conditions. Feed at uniform organic loadings.
Lime stabilization	Ammonia is released due to high pH.	Vent ammonia to outside unless concentrations are very high or the site is in a sensitive area.
Composting	Decomposition of organics at high temperature produces a wide variety of odorous compounds.	Aerate piles. Draw air down through pile and treat. Avoid overly wet sludge. Use wood ash as an amendment. Apply pile surface treatment chemical. Provide containment and ventilation to a vapor-phase control system.
Storage		
Short-term	Storage of combined biological and primary sludge generates sulfide.	Avoid storing combined sludge. Provide mixing to maintain aerobic conditions. Add iron salts directly to storage tanks to treat sulfide formed. Provide containment and ventilation to a vapor-phase control system.
Long-term	Lime-stabilized biosolids may become odorous in long-term storage. Breakdown of storage piles releases odor.	Add supplemental lime to maintain pH during long-term storage. Limit open face exposure, and cover when possible. Break down piles under favorable weather conditions.
Land application	Odor is released during application of biosolids to a large land area.	Separate high odorous biosolids for further processing or other disposal. Use subsurface injection to minimize odor.

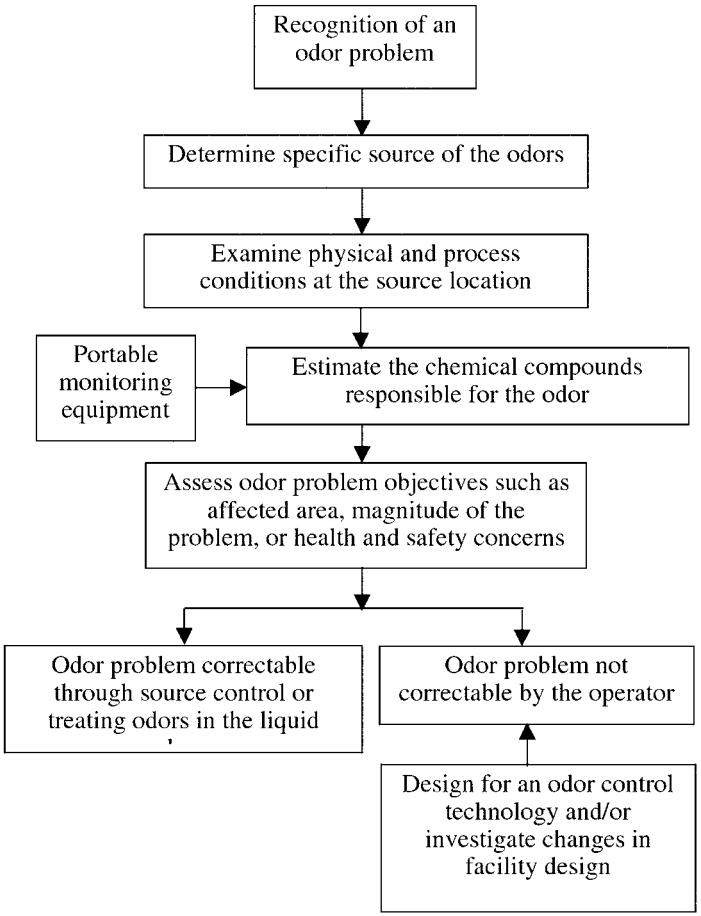


FIGURE 13.12 Operator's approach to solving an odor problem.

sents the results-oriented methods controlled by the operator. The methods requiring design and significant capital investments include biofilters, chemical wet scrubbing, activated carbon adsorption, and combustion.

MONITORING. Many odors at wastewater treatment plants can be identified using portable monitoring equipment, described in Table 13.11, combined with the operator's sense of smell. Regular monitoring of treatment processes can prevent many odor releases as well as provide valuable information on operating procedures. It is important to continually monitor wind direction and speed and maintain a record for later reference, particularly in relation to odor complaints. When the wind is not blow-

TABLE 13.10 Summary of odor control technology applications at wastewater treatment facilities.

Methods	Effects	Problems
Operating practices		
• Industrial process changes		
○ Lower waste temperature	Hydrogen sulfide evolution much retarded	
○ Pretreat to remove odorous organics		
• Collection system		
○ Mechanical cleaning	Hydrogen sulfide reduction	
○ Aeration		
○ Ventilation		
• Grit chamber		
○ Daily grit washing	General odor reduction	
• Primary clarifiers		
○ Increase frequency of solids and scum removal	General odor reduction	
• Aeration tanks		
○ Remove solids deposits		
○ Increase aeration to maintain dissolved oxygen at 2 mg/L	General odor reduction	
• Trickling filters		
○ Increase recirculation rate		
○ Keep vents clear	General odor reduction	
○ Check underdrains for clogging		
• Anaerobic digesters		
○ Check waste gas burner	General odor reduction	
○ Relief valves should close tightly		
• Aerobic digesters		
○ Maintain constant loading	General odor reduction	
○ Maintain adequate aeration		
Liquid-phase control alternatives—Chemical addition		
• Ozone	Oxidizes water-insoluble odorants into water-soluble projects	Requires onsite regeneration
• Iron	Controls slime growth; precipitates sulfide; enhances settling	Increases solids
• Nitrates	Inhibits production of sulfides	Costly
• pH adjustment		
○ Alkali: NaOH	pH 8 hinders bacterial growth in sewers and retards evolution of hydrogen sulfide.	
○ Acid: HCl or H_2SO_4	Acid combines with basic ammonia and amines	
• Chlorine (gas and hypochlorite)	Inhibits growth of sulfate-reducing bacteria in sewers; oxidizes hydrogen sulfide and ammonia	
• Potassium permanganate	Reacts with sulfide and other organics to reduce odors	

TABLE 13.11 Portable monitoring equipment for odor control.

Equipment	Monitoring use	Comments
Gas-phase monitoring		
Oxygen meter	Oxygen (percent volume in air)	Applicable to confined space entry monitoring; replace sensor yearly.
Hydrogen sulfide meter	Hydrogen sulfide gas, ppm or ppb	Meter should have calibration capability with a known gas.
Colorimetric tubes	Many organic and inorganic compounds, including hydrogen sulfide, ammonia, and mercaptans	Some analyses subject to interference, applicable to many different concentration levels.
Combustible gas meters	Total combustibles as a lower explosive limit	Applicable to confined space entry monitoring.
Liquid-phase monitoring		
Oxygen meter	Dissolved oxygen (mg/L)	Monitor aerobic conditions in wastewater.
pH meter	Hydrogen ion (pH units)	pH levels control the form of hydrogen sulfide, ammonia and other odorous molecules.
Oxidation–reduction potential meter	Oxidation–reduction potential (mV)	Indicates if a wastewater is in an oxidizing or reducing state.
Portable wastewater testing kits	Dissolved sulfide (mg/L)	Colorimetric comparison.

ing in the direction of the community, or at certain times of the day or days of the week, the detected odor may come from a source other than the wastewater treatment plant.

TIME OF DAY, WEEK, OR YEAR. Time is important when planning potential odor-causing O&M procedures at the wastewater treatment plant or conducting short-term operations when a higher degree of odor control must be provided. The scheduled work time will influence the number of community members who detect an odor and their location with respect to the wastewater treatment facility. Most people work during the day and follow established traffic patterns. Thus, potentially odorous work should not be planned for the early morning or late afternoon and, if possible, should be scheduled during the off-shifts. The day of the week will determine whether people are at work or are outside during the weekend or on a holiday. Yearly time periods will show traditional vacation periods, standard industrial shutdowns, or planned community events for the general public.

WEATHER CONCERNS. Regardless of how efficiently a wastewater treatment plant is operated, local weather conditions, particularly seasonal characteristics, will greatly affect how and where odors are perceived by the community. Most plants have an odor season that typically coincides with warmer weather. When higher temperatures volatilize larger amounts of odorous compounds from the wastewater, local residents will readily detect odors because they have open windows in their homes and worksites and spend more time outside than they do in colder seasons. High humidity will also increase an odor's persistence and perception.

Inversion conditions with low wind speeds can temporarily reduce the dissipation of odors to the atmosphere and contain them closer to the ground. These conditions often occur before a rainstorm. The earthy, musty smell of a well-operated, activated sludge plant can become a nuisance to local residents if the odors become concentrated above the aeration basins and then are slowly moved by gentle breezes.

ODOR COMPLAINTS. The simplest and most common odor evaluation technique determines an odor's characteristics—what does it smell like? Plants with odors that affect the community can establish an odor telephone hotline to receive citizen complaints. Each complaint should be investigated, and an odor-complaint form should be completed. An example of an appropriate complaint form is shown in Figure 13.13. The form will improve public relations efforts and develop the information necessary to determine the odor source. The form includes information on characteristic smells, intensity, time of day, and weather conditions.

The plant also needs a wind direction meter and recorder. While investigating a complaint, the operator can examine the recorder to determine whether the wind direction matches that of the complaint. If not, the odor is probably coming from a source other than the wastewater treatment facility. During potential odor-problem periods, an odor tour through the community during each shift can help to identify problems early and minimize their effect.

SUMMARY

Odor perception is subjective, and solving odor problems may seem to be more of an art than a science. However, the pathway from problem to solution should follow a logical evaluation process if it is to succeed. Initially, the most important concern is to identify the odor source and characterize it. Ultimately, the odor control method selected will depend on the class of chemical compounds responsible for the odor.

When an odor problem arises, the operator should consider two simultaneous problems: the symptom and the cause. First, the symptom of the problem (the smell)

Date _____ **Time** _____

Location of Odor Complaint _____

_____

Smells Like	**Intensity**				
	1 Very Weak	2 Moderate	3 Strong	4 Very Strong	5 Unbearable
_____ 1.Burnt, smoky					
_____ 2.Ammonia like					
_____ 3.Petroleum					
_____ 4.Sweet, solvent-like					
_____ 5.Rotten eggs					
_____ 6.Garlic, onion					
_____ 7.Metallic					
_____ 8.Garbage Truck					
_____ 9.Sharp, biting, acid					
_____ 10.Musty, mouldy grainlike					
_____ 11.Outhouse					
_____ 12.Chemical, disinfectant					
_____ 13.Other (specify)					

Investigation

Date _____ **Time** _____

Comments _____

_____

Name _____ **Temperature**

Wind Direction _____ **Wind Speed** _____

FIGURE 13.13 Sample odor complaint investigation form.

must be addressed immediately with a short-term solution. Typically, this involves adding chemicals, improved housekeeping procedures, or changes in process control or operational procedures. The operator should never mask toxic gas odors that could become a safety problem. In most situations, these short-term actions will correct the problem. If they do not, then more involved situations must be investigated. Generally, long-term solutions can be costly and may require changes in plant design or construction of an odor control technology.

The problems associated with an odor event depend primarily on the affected area. On-site odors may affect employee safety and health or create unpleasant working conditions. Odors that leave the wastewater treatment site can become a community problem and impact public relations. Characteristics such as topography, weather conditions, and the proximity of neighborhoods play a dynamic role in how off-site odors are perceived by the community.

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Chapter 14

Integrated Process Management

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INTRODUCTION

OVERVIEW. Individual processes cannot be operated in a vacuum. The operator must be cognizant of the interrelationships among the equipment, biological kinetics, and chemistry that make up a process and the potential effects of upstream processes and effects on downstream processes. Note that specific equipment control strategies are not discussed in this chapter. An expansive discussion of this subject is presented in the Water Environment Federation (WEF) Special Publication *Automated Process Control Strategies* (1997) and is not repeated here.

A wastewater treatment plant (WWTP) consists of many separate processes. Process performance is related primarily to flow characteristics (flowrate, biochemical oxygen demand [BOD], total suspended solids [TSS], nitrogen, and phosphorus) and equipment operation. To optimize operation of a WWTP, the operator must be knowledgeable about the individual treatment units and familiar with the interrelationships that exist among the processes. For example, optimization of a primary clarifier would result in more solids and potentially higher quantities of BOD removed. This would reduce the oxygen demand in the aeration basins, lowering costs by lowering oxygen requirements (and power costs) and increasing the ratio of primary sludge to secondary sludge, which may also improve dewatering characteristics. On the other hand, though the primary treatment system would be optimized, subsequent systems may suffer adverse effects. For example, thickening and digestion facilities may be overloaded or inadequate quantities of food may be available for the secondary system, particularly facilities that practice denitrification or biological phosphorus removal. This will require adjustments in sludge pump settings, mixed liquor concentrations, blower output settings, etc. The plant is interconnected and interdependent such that a change in one area affects other processes, thus necessitating an integrated approach. Many plants are large and an operator may work in only one part. It is easy to overlook the operator's contribution to plant performance as a whole. Nevertheless, operators' actions can and do affect other processes and overall facility performance. Operators should be aware of how other processes affect their work area and the way the process they operate affects other areas.

INTEGRATED PROCESS MANAGEMENT. It is not enough to understand how a pump operates, a compressor runs, or even how a specific process works. The operator must know how a process works and how each process in turn affects every other. Consequently, the operator must be intimately familiar with every process and auxiliary facilities such as chemicals, scrubbers, and energy recovery systems. An example approach for assessing process interrelationships follows. For demonstration purposes, a schematic of a secondary treatment facility is presented as Figure 14.1. Recycle flows and chemical-addition points are included.

Based on the schematic, a table can be developed to consider the effects on and from each process. The performance of one process and the characteristics of its sidestreams affect subsequent processes. Within the plant, each process has an interrelationship with other processes that may not be readily apparent. For example, anaerobic digestion typically bears the brunt of poor dissolved air flotation (DAF) performance resulting from low solids concentrations. The quality of the DAF return overflow is often overlooked but, nonetheless, can have a sizable effect on overall plant performance. Recognizing the importance of these relationships, Table 14.1 highlights the effect that one process has on another. This table is not meant to be definitive, but presents some of the more relevant effects to highlight the importance of the process interactions.

To create a table like Table 14.1, the operator should take the following steps. Start at the beginning of the plant and choose one process to evaluate. Write the process

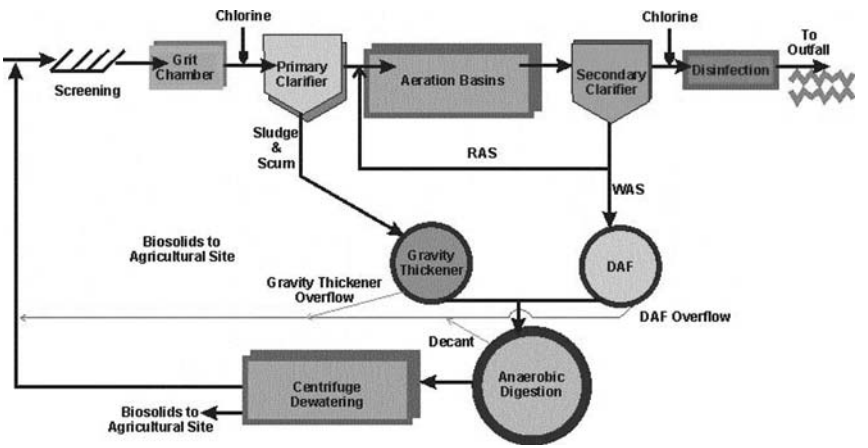


FIGURE 14.1 Plant schematic (DAF = dissolved air flotation, RAS = return activated sludge).

TABLE 14.1 Integrated process management considerations.

Process	Effects from upstream processes	Downstream process effects
Screenings	Collection system constituents (flow, total suspended solids, sulfides, pH) may create an overload or caustic condition. High flows may tax units in service, add additional unit, or open manual bar screen.	Large objects may clog pipes and pumps. Tank volumes (digesters in particular) may be reduced and detention times decreased.
Grit removal	High effluent flows may bring increased amounts of grit and sand. Excessive screening may settle on diffuser equipment and diminish effectiveness.	Channel and tank volumes may be reduced by the accumulation of grit. May plug up channel air diffusers. Excessive grit content may scour, abrade, or obstruct downstream process equipment or piping. May cause excessive prechlorination rates if insufficient grit is removed. Low solids content in dewatered grit may create handling and disposal problems.
Primary clarification	High solids or hydraulic loadings may be caused by in-plant return flows from mechanical dewatering, DAF overflow, gravity thickener overflow, or digester decant, etc. Tank volumes may be reduced by the accumulation of grit. Excessive grit content may scour, abrade, or obstruct process equipment and pipes.	Primary clarifier constituents (BOD, ammonia nitrogen, and phosphorus) determine level of mixed liquor required for the secondary system. Primary sludge concentration greater than 2% will settle better in the gravity thickener. Concentrations greater than 5% will tax centrifugal pumps. May cause septicity and generate organic acids. Septic sludge containing hydrogen sulfide may increase digester gas
Activated sludge	High influent flows may wash out biomass. Inadequate screening or grit removal may block air diffusers. Primary clarifier effluent constituents (BOD, ammonia nitrogen, and phosphorus) determine level of mixed liquor required for the secondary system. High solids loadings present in the collection system or in plant recycle flows (DAF overflow, gravity thickener overflow, Centrate, or digester decant).	Low dissolved oxygen will cause filamentous organism growth and poor solids separation in the secondary clarifier, diminishing effluent quality. Solids retention times greater than 10 days may be needed for full nitrification. Partial or full nitrification may cause solids separation problems unless secondary clarifier was designed for this mode.

TABLE 14.1 Integrated process management considerations (*continued*).

Process	Effects from upstream processes	Downstream process effects
Activated sludge *(continued)*	Excessive detention time in the primary clarifier may create septic conditions and formation of organic acids, which could cause excessive filamentous growth. Poor scum removal in primary clarifier may contribute to filamentous growth.	
Secondary clarifier	High effluent flows may wash solids into the effluent. Poor solids separation caused by insufficient or excessive dissolved oxygen, filamentous organisms, hydraulic or solids overload. *Nocardia* may cause foaming removal problems.	Poor solids separation may increase BOD, TSS, and turbidity, creating disinfection problems. Excessive waste activated sludge rates may overload the DAF.
Dissolved air flotation	Excessive waste activated sludge rates may overload the DAF and increase solids in the return overflow.	High recycled return overflow constituents may increase primary and secondary treatment loadings. Low thickened sludge concentration will diminish digester performance by hydraulically overloading the unit or making it difficult to maintain temperatures.
Gravity thickener	Septic primary sludge will create settling problems, which may increase solids and sulfides in the return overflow.	High recycled return overflow constituents may increase primary and secondary treatment loadings. Low thickened sludge concentration will diminish digester performance by hydraulically overloading the unit or making it difficult to maintain temperatures. Septic sludge containing hydrogen sulfide may increase digester gas hydrogen sulfide concentrations.
Anaerobic digestion	Tank volume may be reduced by the accumulation of grit or rags. Low thickened sludge concentration will diminish digester performance by hydraulically overloading the unit or making it difficult to maintain temperatures.	Low solids concentration increases dewatering equipment operation and chemical usage. Decant constituents (BOD, COD*, TSS, hydrogen sulfide) are recycled to the head of the plant and may increase plant loadings.

TABLE 14.1 Integrated process management considerations (*continued*).

Process	Effects from upstream processes	Downstream process effects
Anaerobic digestion *(continued)*	Septic sludge containing hydrogen sulfide may increase digester gas hydrogen sulfide concentrations. Excessive thickened sludge feed rates may hydraulically overload the unit, making it difficult to maintain temperature and diminish detention time to less than required for stabilization.	
Mechanical dewatering	Poor screenings and grit removal may damage equipment. Large objects may clog pipes and pumps. Low solids concentration increases dewatering equipment operation and chemical usage.	High centrate constituents are recycled to the head of the plant and increase plant loadings. Low cake solids may hamper transportation and subsequent application to agricultural or disposal sites.
Disinfection	Poor solids separation in the secondary clarifier may increase BOD, TSS, and turbidity, creating disinfection problems.	Receiving water quality may be degraded if low dissolved oxygen is present, coliform counts are high, or BOD/TSS concentrations are excessive.

*COD = chemical oxygen demand.

name in the first column. Look at all possible flows and conditions entering the process. Enter in the second column the consequences that each of these flows might have on that specific process. Finally, determine what the ramifications of process failure would be on downstream processes. Enter those in the third column. Do the same for each process.

The elements of creating an integrated process management strategy include

- Developing and implementing unified process control plans,
- Reviewing and evaluating process performance and control data, and
- Assessing changes in process control strategies.

Plant complexity frequently determines the tools necessary to implement the most appropriate operational strategy for given circumstances. Consequently, many techniques are outlined in this chapter with detailed explanations.

DATA COLLECTION

The basis of good operational decisions is built on a foundation of sound information. At a minimum, this includes flow measurement, analytical data, process control data, and maintenance reports.

FLOW MEASUREMENT AND QUANTIFICATION. Flow measurement facilities enable accurate information to be obtained concerning flowrates and volumes. When combined with analytical data, flow measurements are used to quantify mass constituents that are being treated and removed and are an essential tool for good plant control and optimization. Adding flow meters is not an expensive investment and is well worthwhile. Pump speed is a poor substitute for flow measurement.

Loading to the plant varies over the time. Consequently, flows should be measured continuously so that the total volume at a certain time period (day, month, or year) can be determined. Further, wastewater samples should be taken frequently as flow-weighted composite samples. If that is not possible, the monitoring program has to be optimized to determine the most representative time for sampling to occur. Typically, those samples may be taken at high flow, as that is when the processes are under the heaviest loads. The optimum sampling periods may differ between days of the weeks or seasonally.

An application of the use of flow measurement and quantification would be in process management, a change in the feed sludge volumes (thickened primary and waste activated sludge), or the ratio of the two sludges that would affect digestion, dewatering, and biosolid reuse operations.

ANALYTICAL ANALYSIS. Best results are obtained with sound sampling practices and techniques. To obtain a representative sample, collect them at points where there is a high turbulent flow to ensure good mixing. If obtaining samples from a pipeline, the line should be flushed before taking the sample. If the flow is not mixed properly, the suspended solids and other constituents may be unequally distributed in the water column, which may cause considerable error. Sampling location, samplers, and sampling apparatus must be cleaned regularly to avoid excess contamination by sludge, bacterial film, etc. Chapter 17, Characterization and Sampling of Wastewater, should be reviewed for analytical and sampling practices used in the treatment process.

Samples may be taken as grab or composite and then transported to an on-site laboratory or sent to a commercial laboratory for analyses. Some analyses such as dissolved oxygen and chlorine residual must be taken in situ. Many constituents have specially designed analyzers that provide continuous analyses that can be transmitted

to a central location and displayed, stored in a central database, used in part of the system control logic, or simply monitored. The WEF publication, *Instrumentation in Wastewater Treatment Facilities* (1993), provides instruction in the fundamentals of instrumentation and addresses specific sensors, theories of operation, and distinctions between online and laboratory instrumentation.

MAINTENANCE REPORTS. Maintenance and plant operations are inseparable. Regular review of preventive, corrective, and predictive maintenance reports can be instrumental in maintaining effective plant operation, reducing costly repairs, and in reducing unscheduled downtime. The well-operated plant should schedule maintenance on structures, gates, valves, pumps, electrical devices, and instrumentation. A review of maintenance reports also serves as a tool for equipment replacement.

Information on equipment may be drawn from plant control systems that have the capacity to track run times. Review of process graphs may also serve as an indicator of equipment performance. A sudden drop-off in pump capacity can be an indication of a partially blocked (closed) line or valve or a pump obstruction.

PROCESS CONTROL DATA. Process control data consist of direct readings (such as flows and analytical data) or generated data such as organic and hydraulic loadings, feed rates, and detention times. These values are tracked over time for changes or compared design values for excessive or insufficient values. It is important to look at every piece of information and determine its value. For example, pump revolutions per minute may not be useful by themselves; however, if that same piece of information is expressed as a percent of maximum, the operator may be alerted to an overload condition. Many plant control and monitoring systems (i.e., supervisory control and data acquisition [SCADA]) are programmed to collect and generate some of this information. The SCADA system could calculate a flowrate if the revolutions per minute and pump capacity curve were input values. Comparing the calculated flowrate with the flow meter would also act as an operational check that would send an alarm if the difference between the two readings becomes excessive. The SCADA system can also take care of the tedious, but important, jobs such as graphing information. Once graphs are defined, the SCADA system can be programmed to automatically pop up operational screens or activate an alarm when unusual trends are detected.

Computer modeling, once restricted to the design, research, and development arena, is creeping into many plant control systems. Process modeling and computer-based technologies offer a predictive component to confirm that current operational strategies are appropriate. These same models can act as simulators that allow the op-

erator to run "what-if" scenarios for units that are taken out of service or to predict the consequences or the effect events would have on current operation. Once added to the plant control system, the model is calibrated against actual plant operation. This provides improved diagnosis, forecasting, and control of wastewater treatment processes. The result is improved plant efficiency, leading to large savings in capital and operating costs.

STANDARD OPERATING PROCEDURES

Standard operating procedures (SOPs) are detailed definitions of each segment of the process control plan. These procedures, developed by plant personnel or outside consultants, require an objective, independent thought process. The SOP format should encourage new ideas and creative solutions. Innovation is necessary and the "we have always done it that way" syndrome should be avoided.

An example of a SOP written for a certified operator is presented below in a simple checklist form.

EXAMPLE STANDARD OPERATING PROCEDURE—MECHANICAL BAR SCREEN PUMPING STATION NORMAL OPERATION.

- ✔ The number of screens in operation is dependent on the flow to the pumping station. Screens SC-1 and SC-2 can each handle flows up to approximately 6.97 m^3/s (159 mgd), whereas screens SC-3 and SC- 4 can each handle flows up to approximately 6.22 m^3/s (142 mgd).
- ✔ During wet weather, the screens in service should normally be operated continuously in the manual mode by placing their control (Hand-Off-Auto) selector switches in the **Hand** position and pressing their **Forward** pushbuttons.
- ✔ During dry weather, the screens in service should normally be operated in the automatic mode by placing their control (Hand-Off-Auto) selector switches in the **Auto** position, thus allowing them to be under timer-controlled operation. The cycle timer should be set to operate the screen rake mechanism for a duration that allows the rake to travel 2.5 revolutions.
- ✔ If station flows permit, the screen channels should be alternated to equalize wear on equipment and maintain standby equipment in proper operating condition. The sluice gate at the inlet of the standby screen channels should be closed.

✔ Screening equipment and screen channel walls should be washed down with a hose whenever a channel is taken out of operation (when channels are alternated).

Some organizations prefer a more intensive SOP that is more detailed. An example of this is shown below.

EXAMPLE DETAILED STANDARD OPERATING PROCEDURE. The following is an example detailed SOP.

Big Red Valley Sewer District – Ira A. Sefer WWTP
STANDARD OPERATING PROCEDURE #1 – 600 - 0002

TITLE

Aeration/Clarification Basins—Sludge Wasting

GENERAL DESCRIPTION

An activated sludge secondary treatment process has been designed to treat the wastewater. The biological process is designed to remove carbonaceous BOD and the physical process is designed to remove total suspended solids. The discharge limits are as follows:

Effluent limits		
Characteristic	Weekly	Monthly
BOD, mg/L	40	30
TSS, mg/L	40	30

The treatment process is described as an aeration/clarification basin. The basin is configured as an oxidation ditch and the clarifier portion is incorporated to the oxidation ditch. The clarifier is known as an intrachannel clarifier.

The aeration/clarification basin creates the environment necessary to allow biological reactions to occur and then allow settling to take place ending with a treated wastewater.

The components of the treatment process include an A/C splitter box, four aeration/clarification basins, waste activated sludge pumping station, scum wasting system, and aeration blowers.

Each basin is designed to treat an average daily flow of 10 mgd * and can handle a peak hydraulic loading of 20 mgd. The total average daily flow is 40 mgd, with a total peak hydraulic capacity of 80 mgd.

*mgd $\times$ 3785 = m^3/d.

EQUIPMENT AND SYSTEM OPERATING CHARACTERISTICS

Splitter box	
Number	1
Designation	A/C splitter box
Sluice gates	
Number	4
Designation	SGE – 24, SGE – 25, SGE – 26, SGE – 27
Aeration/clarification basins	
Number	4
Designation	basin no. 1, basin no. 2, basin no. 3, basin no. 4
Blower	
Smaller capacity blowers	
Number	3
Designation	TBU – 1, TBU – 2, TBU – 3
Type	multistage centrifugal
Capacity, scfm	7560
System operating pressure, psi	8.5
Motor, hp	400
Motor, V	4160
Larger capacity blowers	
Number	2
Designation	TBU – 4, TBU – 5
Type	single-stage centrifugal
Capacity, scfm	18 000
System operating pressure, psi	8.5
Motor, hp	800
Motor, V	4160
Diffuser assemblies	
Number per chamber	3
Capacity per assembly, scfm	105

Air flow rate per chamber, scfm	
Maximum	315
Minimum	100
Waste activated sludge (WAS) pumps	
Number, two per station	4
Type	Submersible
Capacity, gpm	2200
Horsepower	20

Note that cfm $\times$ 4.719×10^{-4} = m^3/s; psi $\times$ 6.895 = kPa; hp $\times$ 745.7 = W; and gpm $\times$ 6.308×10^{-5} = m^3/s.

PROCEDURES

General

Wasting sludge is needed to maintain the target mixed liquor suspended solids (MLSS) concentration in the aeration/clarification basins. This is a daily procedure and ideally needs to occur over the entire day. The waste sludge volume and the pumping capacity of the waste sludge pumps do not always allow this to occur. In those cases, evaluate the timeframe and determine if it would be better to waste sludge several times a day. Sludge wasting can be determined by two methods, solids retention time (SRT) and constant MLSS.

Solids Retention Time Waste Sludge Operating Method

One method used to determine sludge wasting is the SRT method. The SRT method is based on holding the biomass in the activated sludge system for a set period of time (days). Target sludge wasting rates are determined using a modified version of the SRT equation. The equation is as follows:

$$\text{WAS, lb/d} = \frac{\text{MLSS, mg/L} \times 8.34 \dfrac{\text{lb/mil. gal}}{\text{mg/L}} \times \text{Aeration basin volume in service, mil. gal}}{\text{Target SRT}_N\text{, days}}$$

Note that lb/d $\times$ 0.453 6 = kg/d; lb/mil. gal $\times$ 0.119 8 = mg/L; and mil. gal $\times$ 3.785 = m^3.

This operating method typically works best when the process organic loading is greater than 75% of the plant design loading. The gallons per day to waste is shown

later in the text. Always remember that the waste rate should not be varied by more than 10% from one day to the next.

Constant MLSS

One method that can be used to determine the target wasted sludge volume is the constant MLSS method. The equation that can be used to determine the waste sludge volume is as follows.

$$\text{WAS, lb/d} = (\text{Measured MLSS, mg/L} - \text{Target MLSS, mg/L}) \times 8.34\ \frac{\text{lb/mil. gal}}{\text{mg/L}} \times \text{Aeration basin volume in service, mil. gal}$$

Note that lb/d × 0.453 6 = kg/d; lb/mil. gal × 0.119 8 = mg/L; and mil. gal × 3.785 = m^3.

Determining the WAS Volume, gpd

After the pounds of sludge to waste has been determined by either method, the gallons of sludge to be wasted needs to be determined. A modified version of the equation used to determine pounds of solids and the return sludge concentration is used. The equation to use is as follows:

$$\text{WAS, gpd} = \frac{\text{WAS, lb/d}}{\text{Return activated sludge concentration, mg/L} \times 8.34 \dfrac{\text{lb/mil. gal}}{\text{mg/L}}} \times 1\,000\,000$$

Note that gpd × 3785 = m^3/d; lb/d × 0.453 6 = kg/d; and lb/mil. gal × 0.119 8 = mg/L.

Determine the WAS Frequency, min/d

The wasting rate is determined by adjusting the speed of the pump. The maximum capacity of each pump is 120 gpm. Three pumps can be used to waste sludge. In some cases only one pump may have to be used, at other times multiple pumps will have to be used. Continuous wasting is the most desirable operating condition. The following equation can be used to obtain a value of fewer than 1440 minutes per day.

$$\text{WAS pumping, min/d} = \left(\frac{\text{WAS, gpd}}{\text{Pump capacity, gpm}}\right)\left(1400 \frac{\text{min}}{\text{d}}\right)$$

Note that gpd × 3785 = m^3/d and gpm × 5.451 = m^3/d.

Determine the WAS Frequency, min/h

If the WAS frequency, minutes per day, is fewer than 1440 minutes per day, it may be desirable to waste sludge each hour of the day. The minutes per hour at the selected pumping rate can be determined as follows.

$$\text{WAS pumping, min/h} = \frac{\text{WAS pumping, min/d}}{24\ \text{h/d}}$$

Description of Operating Procedures

Once the volume of sludge to waste has been determined, the operating procedures can be implemented. One set of waste sludge pumps is used by basins 1 and 2 and basins 3 and 4. The waste sludge flow meter is on the main line between the waste sludge pumping stations and the gravity sludge thickeners. This arrangement requires wasting sludge from the basins one at a time to accurately measure the WAS flow. The systems are operated independently so there is no method to waste sludge from a common process.

The sludge wasting has to be initiated manually but is stopped automatically by the plant control system.

The waste sludge flows by gravity into the WAS pumping station wet well. The pumps pump the sludge to the waste sludge meter vault and into the gravity thickeners.

Step-by-Step Procedures

Step 1

Select the basin that will be used for service. The following electrically operated valves will be used to waste sludge.

Aeration/clarification basin	Electrically operated valve
No. 1	2WS/PV – 2
No. 2	2WS/PV – 1
No. 3	2WS/PV – 4
No. 4	2WS/PV – 3

The pump isolation valve needs to be open.

Step 2

Set the time delay control on the plant operating screen to allow the waste sludge valve to remain open for the specified time.

Step 3

Open the valve from the selected aeration/clarification basin. The pump On-Off-Auto selector switch should be in the **Auto** position.

Step 4

The pump will begin operation when the wet well sludge level actuates the pump controls.

Step 5

The plant control system will annunciate an audible alarm when the wasting time nears the end of the cycle. The operator should acknowledge the alarm.

Step 6

The plant control system will annunciate an audible alarm when the wasting cycle is completed. The operator should acknowledge the alarm. The amount of sludge wasted should be check against the target volume. If acceptable, the next wasting period for the reaming basins should be initiated.

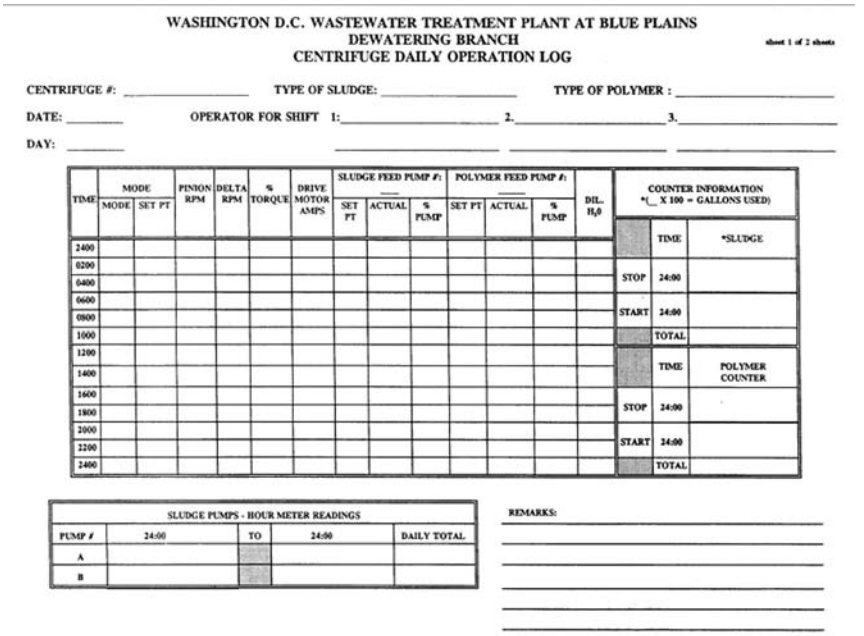
Step 7

Record the volume of sludge wasted each day on the daily log and charts.

End of Procedure

OPERATOR LOGS AND DATA ENTRY FORMS. Records are needed for ongoing process management, compliance reports, and establishment of historical trends. Necessary records include visual observations; sampling and analytical results; process calculations; and logs, diaries, and bench sheets (see Chapter 6, Management Information Systems [Records and Reports]). Data should be assembled and recorded in permanent log books. Diaries and bench sheets should be designed to provide easy transfer to regulatory report forms.

An example of a form used to gather information is shown below in Figure 14.2. Note that this form shows, at a glance, the daily activities that have taken place at the dewatering centrifuge.



WASHINGTON D.C. WASTEWATER TREATMENT PLANT AT BLUE PLAINS
DEWATERING BRANCH
CENTRIFUGE DAILY OPERATION LOG

CENTRIFUGE #: _____ TYPE OF SLUDGE: _____ TYPE OF POLYMER : _____

DATE: _____ OPERATOR FOR SHIFT 1: _____ 2. _____ 3. _____

DAY: _____

TIME	MODE		PINION RPM	DELTA RPM	% TORQUE	DRIVE MOTOR AMPS	SLUDGE FEED PUMP #:			POLYMER FEED PUMP #:			DIL. H_2O
	MODE	SET PT					SET PT	ACTUAL	% PUMP	SET PT	ACTUAL	% PUMP	
2400													
0200													
0400													
0600													
0800													
1000													
1200													
1400													
1600													
1800													
2000													
2200													
2400													

COUNTER INFORMATION *(_ X 100 = GALLONS USED)		
	TIME	*SLUDGE
STOP	24:00	
START	24:00	
	TOTAL	
	TIME	POLYMER COUNTER
STOP	24:00	
START	24:00	
	TOTAL	

SLUDGE PUMPS - HOUR METER READINGS				
PUMP #	24:00	TO	24:00	DAILY TOTAL
A				
B				

REMARKS: _____

FIGURE 14.2 Operator work log: centrifuge dewatering (gpd $\times$ 0.003 7 = m^3/d).

PROCESS CONTROL CONCEPTS

Poor plant performance often results from failure to apply known process control concepts. Therefore, the process control plan is one of the plant's most important management systems. Specifically, a detailed written description of how the process should be controlled must be developed that

- Assigns responsibility for individual processes,
- Presents methods for checking performance, and
- Explains procedures for changes (fine tuning) necessary to produce the required results.

One person, typically the chief operator, should be responsible for setting the process operating parameters for the facility. Operational parameters to be considered include operating directions, process guidelines, units in service (based on design criteria), sampling schedule, analysis, and calculations for optimizing performance. That person must then approve, in writing, any changes in the parameters or guidelines. Once the process control plan is developed or changed, all employees need to be in-

formed of the plan's integrated process management elements through a workable communications system.

Testing and monitoring the process control parameters requires planning and organization so that performance trends departing from targeted goals are clearly noticeable. Control elements can be brought back to the operator's established limits before permit violations or process upsets occur.

PROCESS GOALS AND PLANNING

A process control plan (Table 14.2) establishes specific wastewater treatment goals, defined in part by the National Pollutant Discharge Elimination System (NPDES) permit, local ordinances, plant policies, and contracts regarding delivery of byproducts. Land application of biosolids, digester gas use, and effluent reuse are also typically included. The plan identifies routine process control parameters (BOD, TSS, alkalinity, etc.) and potential problems associated with each wastewater treatment process. A range of performance indicators can be set by analyzing historical data for a specific process. Finally and most importantly, the plan includes the actions necessary to keep the process parameters within the established limits.

The manager should review data daily with respect to the process control plan and determine the cause of deviations from the defined target and values that fall beyond the expected range. The manager may then adjust controls as necessary to bring the unit process closer to the set targets. Interactions among processes, including those from recycle streams and their byproducts, need to be considered. Sidestream beneficial use must also be accounted for. The plan and process control strategy must be practical, responsive, and viable for implementation.

Process control planning must provide valid process information by ensuring that flow metering, online sensors, and laboratory analyses provide accurate and timely data necessary for operating decisions. The sampling and analysis plan discussed in Chapter 17, Characterization and Sampling of Wastewater, should be reviewed to ensure that sampling points, frequencies, and procedures will provide representative samples necessary for laboratory testing and analyses. The tests also require quality assurance and quality control (QA/QC) to ensure they will provide all data necessary for process control.

The plant's operations and maintenance (O&M) manual, design criteria, facility-as-built drawings, manufacturer's literature, WEF manuals of practice, and U.S. Environmental Protection Agency technical documents provide useful information for forming the plan. Valuable assistance in preparing the plan may be obtained from the design engineering firm and its O&M group, regulatory agencies, and managers of similar plants.

TABLE 14.2 Primary clarifier process control plan.

Goals
1. Provide stable food source for secondary treatment process
2. Remove 60% of the influent total suspended solids
3. Remove 25% of the influent biochemical oxygen demand

Process guidelines
1. Influent biochemical oxygen demand = 180 mg/L
2. Influent total suspended solids = 160 mg/L
3. Surface loading rate = 1200 gpd/sq ft[a]
4. Detention time = 2 hours

Calculations

$$\text{Removal efficiency} = \frac{\text{In} - \text{out}}{\text{In}} \times 100$$

Surface loading rate,

$$\text{gpd/sq ft} = \frac{\text{Influent flow, gpd}^{b}}{\text{Primary clarifier area, sq ft}^{c}}$$

Detention time,

$$\text{hours} = \frac{(\text{Volume, gal}^{d})(24\ \text{h/d})}{\text{Flow, gpd}}$$

Analytical data and schedule

Test	Schedule	Type
Suspended solids	D	C
Settleable solids	D	C
Total and volatile solids	D	C
Biochemical oxygen demand	D	C
pH	Continuous	
Grease and oil	M	G

Contact the chief plant operator for clarification or in an emergency.

Operating instructions
1. Four of six units in service
2. Ensure that drives are running (D)
3. Inspect helical scum skimmer (D)
4. Check pump schedule (D)
5. Check process guidelines (D)
6. Pump down scum well (W)
7. Clean baffles and weirs (W)

Troubleshooting

Observation	Check
Poor solids removal	Hydraulic overloading; activate another clarifier.
Sludge hard to remove from hopper	Check pump operation. Check grit removal facility for poor operation.
Sludge has low solids content	Check sludge pump timers for excessive pump operation. Hydraulic overloading; activate another clarifier. Check for short-circuiting.
Short-circuiting of tank flow	Ensure that weir settings are even. Damage to inlet baffle.

D = Daily C = Composite
M = Monthly G = Grab

[a] gpd/sq ft × 40.74 = L/m^2·d.
[b] gpd × 0.003 7 = m^3/d.
[c] sq ft × 0.092 9 = m^2.
[d] gal × 3.785 = L.

In summary, the process control plan should detail in a step-by-step fashion how the particular process operation is set and who is responsible for the implementation. The following areas should be addressed:

- Assignment of responsibilities for controlling individual processes within established guidelines;
- Identification of technical support sources, including experts from neighboring plants, design engineering firms, technical schools, regulatory agencies, and training centers;
- Establishment of a reference library; and
- Provision for continuous process management where possible, including off-duty call lists for plants with 24-hour staffing.

PROCESS CONTROL MANAGEMENT

Once developed, the process control plan must be managed and carried out. This entails clarification, correction, improvement, and updating, all of which require effective communications.

COMMUNICATIONS. Process management requires a timely response to process changes. This indicates the need for communications links that promote passage of information. Such linkage might be as simple as a verbal message at shift change or a posted process parameter adjustment. Those who are responsible for process control must have immediate access to these messages and process status reports. Some facilities use a more structured approach where a "process control change order" is issued with signatures of both of the responsible persons at the shift change. To accomplish this, an overlapping time between the operator starting and leaving the shift is needed.

ACCURATE MEASUREMENTS. Accurate information is needed for process control decisions. Nonrepresentative samples or inappropriate sample points lead to errors in control decisions, with possible severe consequences. The information must be timely. For example, five-day BOD test results are much too late for most daily process decisions. In this case, surrogate testing, such as chemical oxygen demand (COD), may be used as a timely indicator if a consistent relationship exists between the two analyses.

LABORATORY AND PROCESS RELATIONSHIP. Timely and accurate laboratory results supplemented by visual and sensory observations are necessary if

process control is to succeed. The laboratory capacity and schedules must conform to the NPDES monitoring requirements and generate process control data without conflicts. Process control tests do not have to meet quality requirements of NPDES analyses with respect to QA/QC. Thus, some shortcuts, such as microwave ovens for drying solids samples, can be used to facilitate timely results. Surrogate methods or testing should be checked periodically to ensure that reliable data are obtained.

Timely feedback is very valuable. Ideally, the relevant laboratory result should be posted immediately or, in larger facilities, the information could be shared electronically (e-mailed or with a shared spreadsheet) to the pertinent process areas upon completion. More commonly, either the turn-around time is poor or the laboratory data go to managers and rarely to the operators who can also use them. As a result, the operators typically ignore the laboratory and use a microwave or similar device to follow the process and drive their decision making. These valuable data are, at best, entered into a log book and not shared with anyone outside of the area. Logged into a common spreadsheet and shared across a network, both the process area and laboratory data could be viewed and used to evaluate process performance.

OVERVIEW ANALYSIS. Individual process units must be integrated to an efficient wastewater treatment system. The chief operator should learn to recognize key indicators of the performance of the overall plant and monitor them daily. Cause-and-effect relationships in the plant can be detected only by a complete analysis of all data.

Among the chief operator's responsibilities is cost control. The overview analysis allows identification of high-cost processes and will perhaps disclose cost-saving measures.

DISCRETE PROCESS TRACKING. Plant loadings and the resultant treatment efficiency must be analyzed to identify any weak links. Computerized data systems can provide this information quickly. With manual tracking, at least a monthly analysis is needed.

Should a single process unit show signs of distress, the operator should determine whether operating procedures or excessive loading is the cause. In either event, the deficiency requires correction.

As a guidance mechanism for process control, upper and lower operating limits should be established for each unit process. These limits provide operations personnel with the guidelines for holding the process on target. As best practice, data from the process control testing are plotted on trend charts with the upper and lower limits are shown. Facilities that include SCADA controls are able to designate these values as part of the programming logic and, based on the specific values, the control logic may be altered or suggested or alarms can be generated.

COMMON PROBLEM AREAS. Certain problems such as the following occur in most plants:

- Solids may accumulate within the plant as a result of inadequate storage, inadequate dewatering facilities, or weather-induced restriction of land application. The process control plan should identify the means of preventing or reducing this problem.
- Process instruments frequently fail. This results in erroneous data or no data and, as a consequence, incorrect process decisions. If a pH meter is important, then redundancy is necessary. Provide redundant meters or install two meters in parallel, then set alarms if the reading or the response is unreasonable. The operator, once notified, can set a course of action while the instrument calibration and operation is checked. As plants become more highly automated, the shortage of instrument repair technicians grows, and plants will need to provide training to upgrade the skill sets of their staff.
- Dependence on traditional data may result in late problem diagnosis. This can be avoided by using surrogate or signal performance such as the movement of organisms in mixed liquor. The operator should refer to the individual process chapters for more details.
- Intermittent heavy loadings from plant recycle may upset the plant process. Digester supernatant and filter backwash can overload a plant if flows are not distributed over a long period. Draining plant processes may also inadvertently add a load to the plant.
- Odors quickly arouse indignation and quickly convince the public that the plant is poorly operated, regardless of whether this is the case. A thorough discussion of the causes of plant odors and methods for their prevention and control is presented in Chapter 13, Odor Control, and in *Control of Odors and Emissions from Wastewater Treatment Plants* (WEF, 2004). The World Wide Web has made a lot of information available; much of it is credible, and some is not so good. Professional organizations such as the Water Environment Federation (www.wef.org) also provide forums for discussion groups and may be a good source of information.

PROCESS CONTROL TOOLS

Four steps are essential to manage any process: gather information, evaluate the data, develop and implement a proper response, then reevaluate. First, information is collected in the form of analytical data, hour meters, visual observations, and other miscellaneous facts. Information is only as good as the device used for the analysis. Reli-

able instrumentation that has been carefully selected for the application and properly maintained will provide the best information. Much information is in the form of numerical data. Making sense of all this information can be daunting. Several tools such as graphs, mass balance analysis, and basic statistics can make the job of evaluation much easier. The WEF–ASCE publication, *Design of Municipal Wastewater Treatment Plants* (1998), provides a good explanation of mass balance.

Once the information is analyzed, it is then a matter of applying operational principles of a given process to formulate a proper response. Finally, it is necessary to reevaluate how plant performance and conditions have changed since the operating strategy was implemented.

GATHER INFORMATION. Gathering information is a basic troubleshooting task that requires knowledge of the specific plant, waste constituents received, and specific processes. The following guidelines will assist in gathering information:

- Determine whether a problem exists or the test results are in error.
- Find out when the problem was first observed and what was done about it.
- Examine the biomass with a microscope to evaluate the state of the microorganisms, their diversity, motility, and numbers.
- Determine whether the operation of the plant contributes to the problem. Check the upstream unit for contributory problems, including the sewer system and recycle streams.
- Complete the flow and mass-balance analysis. Check each unit process separately because one weak process can overload the whole plant.
- Use a quality assurance program to improve the accuracy of test results.
- Check for pipeline leaks that can divert flows, including chemicals.
- Check for changes in treatment chemicals.
- Ensure that air-delivery systems work.
- Determine whether mechanical or electrical failures are causing problems. Check for such failures when problems occur. A brief power outage can stop equipment, requiring manual restart.
- Separate the symptoms from the problem. Listen to everyone's observations but mistrust everyone's interpretation. Identify the root cause, not the symptom. Things are not always as they first appear; do not be too quick to jump to conclusions.

The operator should prepare a checklist for the plant and add to it whenever a unique situation is encountered. This information should be part of the plant SOP and can be incorporated to the specific process troubleshooting guides.

Process and Instrumentation Diagrams. Process and instrumentation drawings (P&IDs) are typically developed during the construction phase of a project and illustrate the relationship and interconnections between the mechanical equipment and instrumentation. These documents also define and locate equipment tag numbers, which facilitate developing wiring diagrams, bills of materials, purchasing, receiving, and installation. The P&IDs are a complement to the other forms of process control logic documentation.

The Instrumentation Society of America has defined standards for producing P&IDs. Within a set of construction plans, the first instrumentation drawing contains information that defines the meaning of the identification letters, symbols, and bubbles.

A P&ID diagram for the flotation thickened sludge skimmer drive is presented as Figure 14.3. The P&ID contains the following information about the DAF drive:

Each instrument is part of the equipment control loop 628.
A local instrument: weight switch (WS).

Located on variable-frequency drive (VFD) control panel:

- Start/stop handswitch (HS-$1^{A/M}$);
- Automatic/manual handswitch (HS-$2^{S/S}$);
- Timer, indicator, and control (SIK);

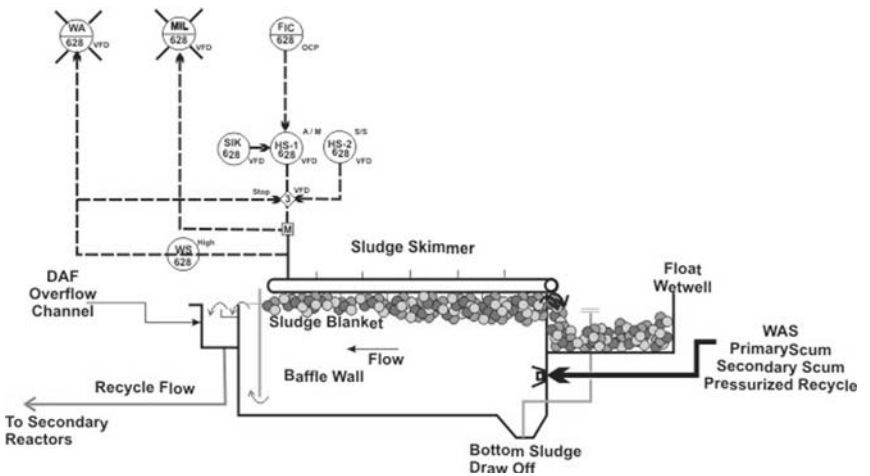


FIGURE 14.3 Example P&ID diagram.

- Weight alarm (WA); and
- Moisture indicator light (MIL).

Located on the operator control panel (OCP): flow indicator and controller.

Field-mounted instruments are shown as plain circles (no line within the circle). Primary location instruments, typically located on a control panel, are shown as a circle bisected by a line. The location of the instrument is noted in the bottom right-hand side of the circle. Example: FIC-628 shows the "OCP" in that location. Consequently, the instrument is located on the OCP. If the instrument is located locally, no notation is needed. Dotted lines are drawn between the instrument "bubbles" and indicate that this is instrumentation logic and the direction it flows, input or output. If the line is continuous, the instrument is located on the front of a panel. Once the basics of reading a P&ID are understood, the reader can put together the "story" that is being conveyed. The DAF sludge skimmer control logic is as follows:

1. There are two hand switches located on the VFD control panel that control skimmer operation.
2. There is an interlock (the diamond with a "3") that required three conditions to be met—the weight alarm cannot be activated, the VFD must be started, and the there must be a signal from the mode selector switch (HS-1$^{A/M}$).
3. A moisture sensor is located in the skimmer drive motor; when moisture is detected, a light illuminates on the VFD control panel (MIL-628).
4. When the mode selector switch (HS-1$^{A/M}$) is in **Auto**, it receives a signal from FIC-628 that flow is being sent to the DAF. The skimmer operates based on the timer (SIK-628) unless the weight switch high setting is reached. If the high setting is reached, an alarm goes off on the VFD panel (WA-628) and the skimmer stops.
5. When the mode selector switch (HS-1$^{A/M}$) is in **Manual**, skimmer operation is controlled manually with speed adjusted at the VFD control panel.

Hydraulic and Mass Solids Balance. One of the best tools for understanding how a plant or process is operating is mass-balance analysis. The objective is to account for all solids or flow that enter and leave a given process. This concept is readily adapted for use as an evaluation and process control tool.

Flow diagrams are developed to represent a process, using conditions appropriate to the problem that needs to be resolved. For example, the accuracy of a metering system needs periodic verification. The operator can simply check the sum of the subme-

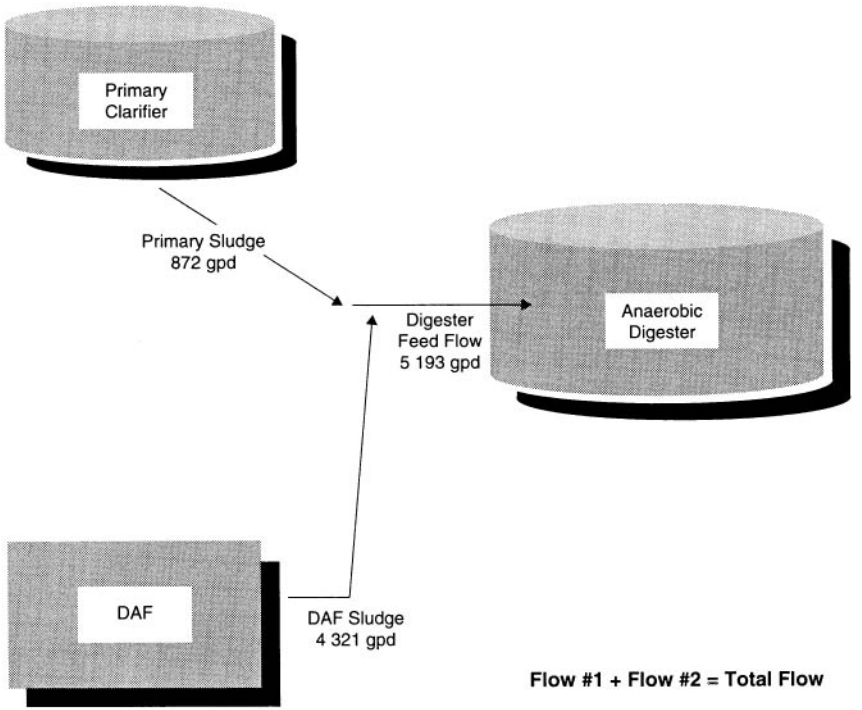


FIGURE 14.4 Hydraulic flow balance (gpd $\times$ 0.003 7 = m^3/d).

ter readings against the master meter to perform a hydraulic balance. An anaerobic digester is fed primary and thickened sludge using a gravity belt thickener. Given the configuration and flows from Figure 14.4, the sum of the two flows should be fairly close to the meter that reads the combined digester feed flow. If these two values differ significantly, all three meters need to be calibrated. Because some processes lag (such as the effluent meter compared to the influent meter), choosing the appropriate meter and time interval may be important in the overall analysis.

Using the same logic, any process flow stream can be evaluated. The balancing method is simple to use. From a hydraulic basis,

$$\text{Flow no. 1} + \text{Flow no. 2} = \text{Total flow}$$

Similarly, from a solids or constituent perspective,

$$\text{Solids in} = \text{Solids out}$$

Balancing solids within process units and throughout the plant can help the operator predict process operation, troubleshoot problems, and plan a course of effective treatment. Mass solids balance may be used on one process, such as thickening, or may be used on a plant-wide basis. Regardless, the methodology remains the same. With the availability and power of the personal computer, setting up a spreadsheet with cells for information about the plant can make quick and accurate work of both hydraulic and mass-balance analysis.

To put mass solids balance to use, the operator should first sketch a diagram of the process or plant to be evaluated and write down the flow characteristics. The next step is to calculate the desired constituent on a kilograms-per-day (pounds-per-day) basis and prepare to evaluate. In Figure 14.5, primary clarifier solids entering the clarifier are compared with those leaving the clarifier (primary sludge and primary

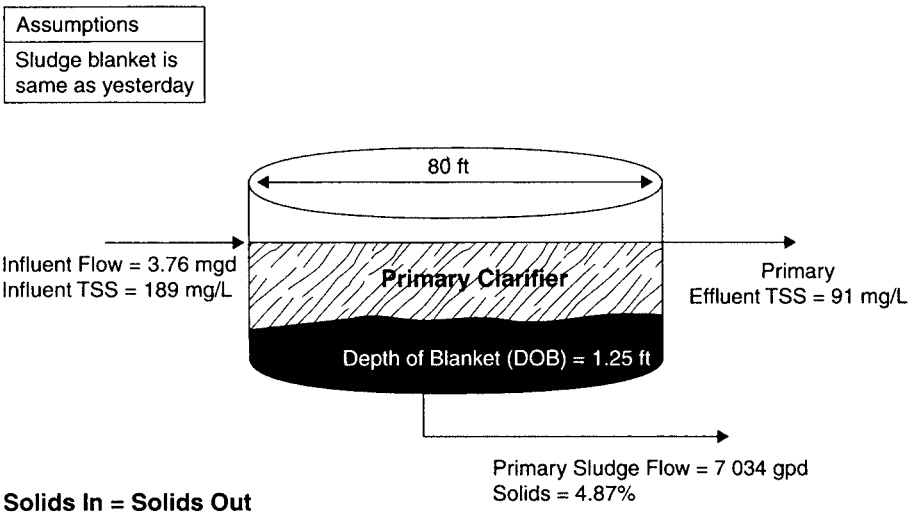


FIGURE 14.5 Solids in = solids out (lb × 0.453 6 = kg; lb/d × 0.453 6 = kg/d; and mgd × 43.83 = L/s).

effluent). Primary scum need not be considered unless a substantial amount of solids is incorporated to the flow. From this exercise, the following conclusions can be drawn:

- Solids entering the clarifier are about the same as the combined solids leaving the clarifier because the blanket level has not changed.
- Primary sludge pump rates are sufficient for these conditions.
- Primary sludge pumps are working.
- The primary sludge flow meter does not need calibration because metered values are within 5 to 10% of each other.
- Laboratory analysis is being performed consistently because calculated values are within 5 to 10% of each other.
- Expect that the solids removal efficiency falls within design parameters.
- Expect the clarifier surface to be clear with no signs of rising sludge.

Rising sludge may indicate excessive sludge in the clarifier or equipment failure; check flow meter and review analytical data.

Mass balance is a powerful tool in setting and evaluating process operations. Problems typically manifest themselves in the most unlikely places. A solids separation problem in the gravity thickener may not actually be rooted in the thickener. In essence, it is only a symptom of the problem. Recycle flows, conversion of soluble BOD to biomass, solids in the plant effluent, and conversion of solids to liquid and gas must all be taken into account. Determination of the correct cell yields, alpha and beta factors, conversion rates, etc., should be part of the process design memorandum for a specific facility. If unavailable, the values are presented in *Design of Municipal Wastewater Treatment Plants* (WEF and ASCE, 1998).

EVALUATE DATA. Quantitative data collection for the plant is so voluminous (analytical data, meter readings, and expenses) that the data defy analysis and interpretation unless they are organized. Small- to medium-sized treatment plants may collect most of these data manually. Larger or more sophisticated treatment schemes may have automated control systems that monitor, collect, and store the information in a database. Once collected, the data must be organized, displayed, and evaluated to be useful. One way to make sense of the data is to organize them in a tabular format. The information can also be organized visually, creating a picture by constructing a graph. There are many types of graphs, including line, bar, scatter, and pie. Graph choice depends on the data and how the information will be used. In general, a graph is a chart used to show relationships between two or more factors.

Line Graph. The simplest picture is the line graph, which is used to represent factors on two different scales. It is particularly suitable for recording historical data of a parameter that constantly changes.

The graph in Figure 14.6 shows changes in plant influent flows during the month. A line has been drawn across the graph to show the design average dry weather flow. Values above or near this line may indicate that downstream processes are taxed. Used in this way, the graph is sometimes referred to as a trend chart. The *x*-axis contains the days of the month. The range for the *y*-axis was selected based on the peak plant capacity of 0.8766 m^3/s (20 mgd).

Line graphs can be developed to summarize performance characteristics such as determining the pump output of a variable-speed pump. The range of the axes in Figure 14.7 is determined by the purpose of the graph; in this case, pump capacity (gpm) and the percent speed of the variable-frequency drive (VFD). To develop this graph, the analyst first determines the actual volume pumped at several points (a minimum of three or four). The pump was run at 20, 40, 60, 80, and 100% speed and liquid volume measures. Then the analyst plots the points on the two axes (VFD speed on the *x*-axis; volume of liquid pumped on the *y*-axis). Finally, the points are connected to establish a curve. The user can now easily determine the flowrate at any given VFD setting.

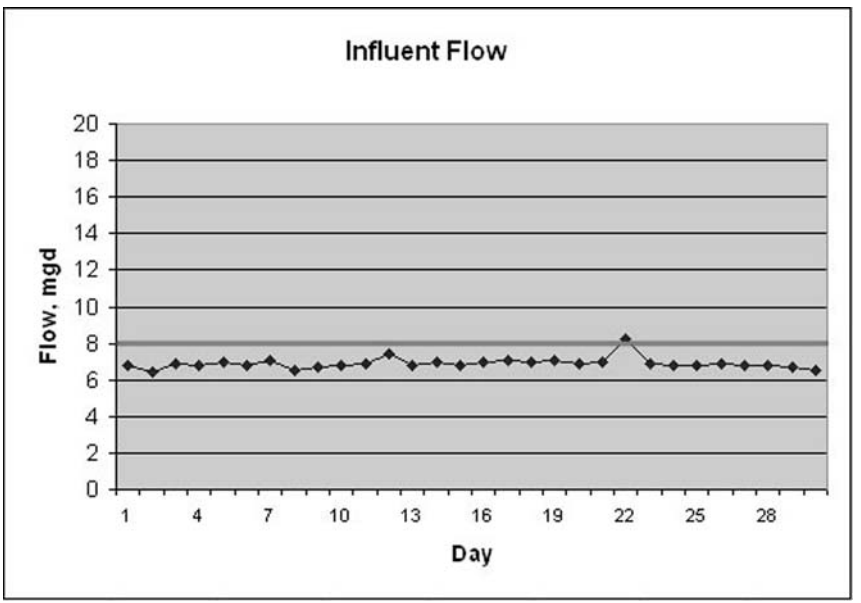


FIGURE 14.6 Line graph showing trends (mgd × 3785 = m^3/d).

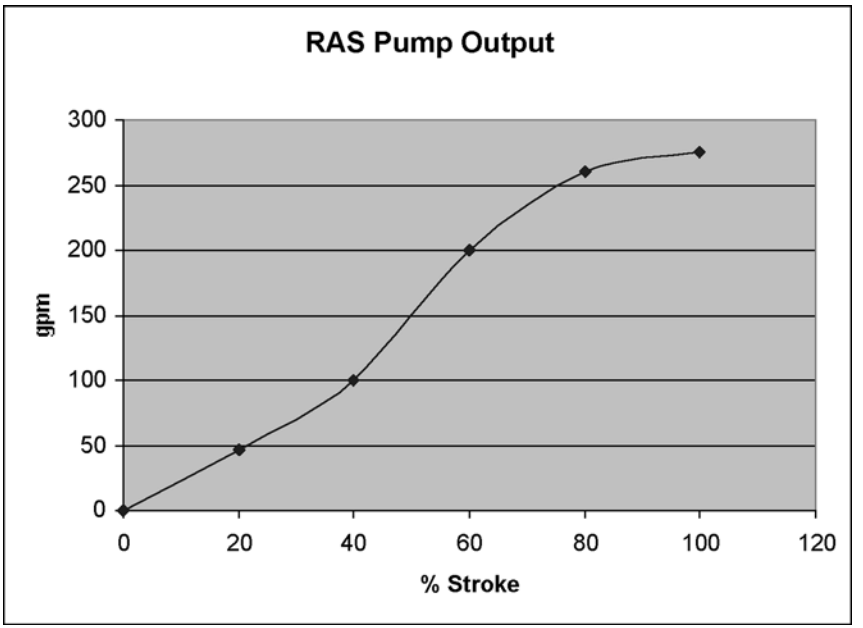


FIGURE 14.7 Line graph summarizing performance (RAS = return activated sludge; gpm × 0.063 08 = L/s).

Bar Graph. Bar graphs use parallel bars to compare amounts of the same type of measurement and are best used to summarize data. The bar graph in Figure 14.8 depicts electrical usage (*x*-axis) at the WWTP during a two-year period on a monthly basis (*y*-axis).

The height of the bar indicates the electrical kilowatt usage. The horizontal axis indicates the specific month the usage occurred. Bars with different patterns or colors were used to distinguish between the two sets of data. A solid bar indicates the year 1 data and a gray bar indicates the year 2 data.

A second type of bar graph, called a stacked bar graph, shows different types of values by "stacking" a bar on top of the previous bar to form a single bar. Different colors or patterns can be selected to differentiate among parts of the bar.

In Figure 14.9, a facility experiencing high influent solids elected to sample each of the flow streams that entered the plant. In addition to the collection system influent, plant sidestreams were analyzed, which makes this a "confluent sample" versus an "influent sample". Sidestreams and recycle flows from the plant may make a significant contribution when the constituents are examined independently as seen in this figure. Each sample stream has a different bar pattern. The *x*-axis displays data by year;

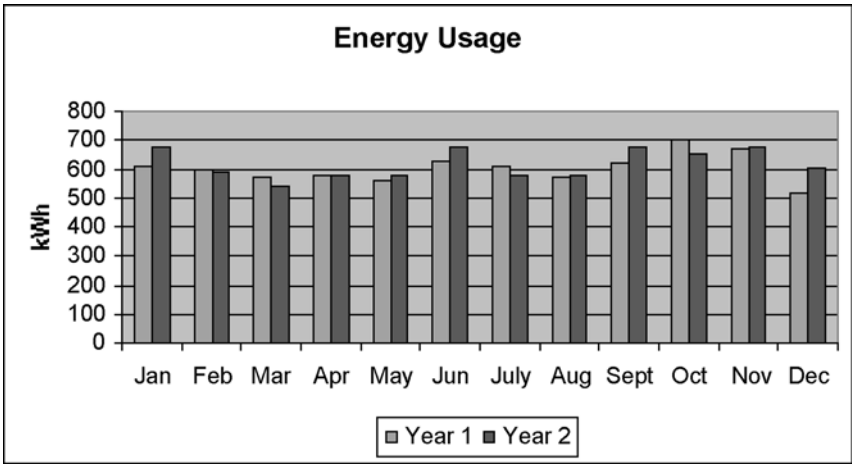


FIGURE 14.8 Bar graph.

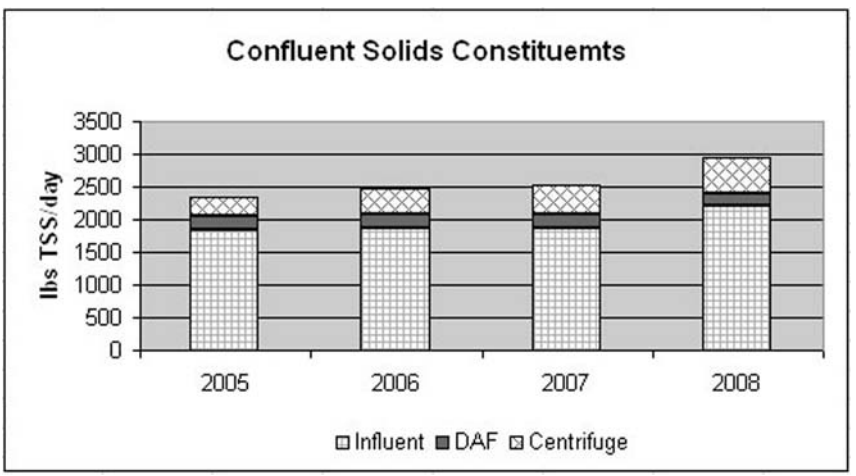


FIGURE 14.9 Stacked bar graph: (1) the bottom hatched pattern represents the solids contribution from the collection system, the "plant influent"; (2) the middle solid pattern represents the contribution of solids from the DAF; (3) the top cross-hatch pattern on the top portion of the bar reflects the solids contribution from centrifuge dewatering (when data are viewed in this manner, it is evident that, over the last four years, the contribution from the centrifuge dewatering operation is increasing) (lb/d $\times$ 0.453 6 = kg/d).

the *y*-axis shows the total quantity of solids entering the plant. A stacked bar graph may assist in evaluating and troubleshooting process problems.

Pie Chart. A pie chart resembles a pie, divided into "slices" according to quantities. The pie graph is generally developed on a percentage basis. The whole pie represents 100% of the value. Each slice represents the percentage that its value contributes to the total.

A pie chart is ideal for representing a facility budget (Figure 14.10). Each slice of the pie represents the proportion of the budget allocated for each of the categories identified in the legend. The total budget allocation of $4,371,308 is noted on the figure. Each budget item is divided by the total budget amount (times 100) to obtain its percentage share. After all items are calculated, they should add up to 100%. The pie is then divided proportionally.

Scatter Graph. A scatter graph, also called an *x*–*y* graph, is used to show how values change relative to other values. It is generally invoked to determine if there is a relationship between the two sets of data. The "*x*" data are the control parameter, a value that may be manipulated such as MLSS, detention time, or loading rates. The "*y*" data are associated with performance or the result, such as BOD, TSS, or ammonia level. A line of best fit, the regression line, may be drawn or calculated for the data and correlation analysis performed to determine the strength of the relationship between the two variables. This subject is discussed in greater detail later in this section.

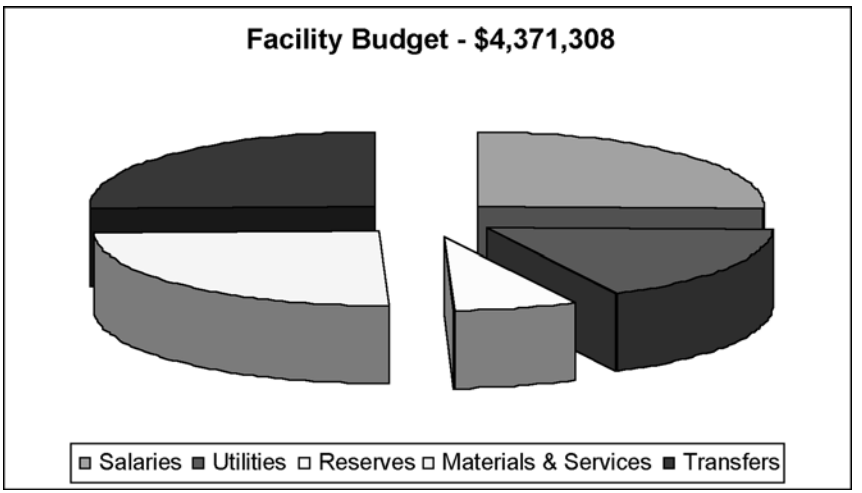


FIGURE 14.10 Pie chart.

As seen in Figure 14.11 using the scatter graph, primary effluent BOD quality is plotted on the *y*-axis and primary effluent COD is plotted on the *x*-axis. The data pairs are plotted and a regression line is drawn through the points to determine a line of best fit.

From these data, one might expect that at a COD value of 200 mg/L, the BOD would be 115 mg/L. If the relationship between the COD and BOD remains the same, then good estimates of primary effluent BOD can be made.

Elementary Statistics. Monitoring performance using tables, graphs, and mass balance analysis is only the beginning in the art of process control. Reviewing and evaluating plant data are an overwhelming task with the amount of analytical data and process performance information available. It is important to track plant performance parameters, such as effluent quality characteristics, to demonstrate compliance with regulatory permits. However, in the pursuit of high-quality effluent, selecting the variables that most directly influence process performance can be difficult.

Typically, operators review historical data to help develop future process control strategies. Given the multitude of associations to check (control parameters versus

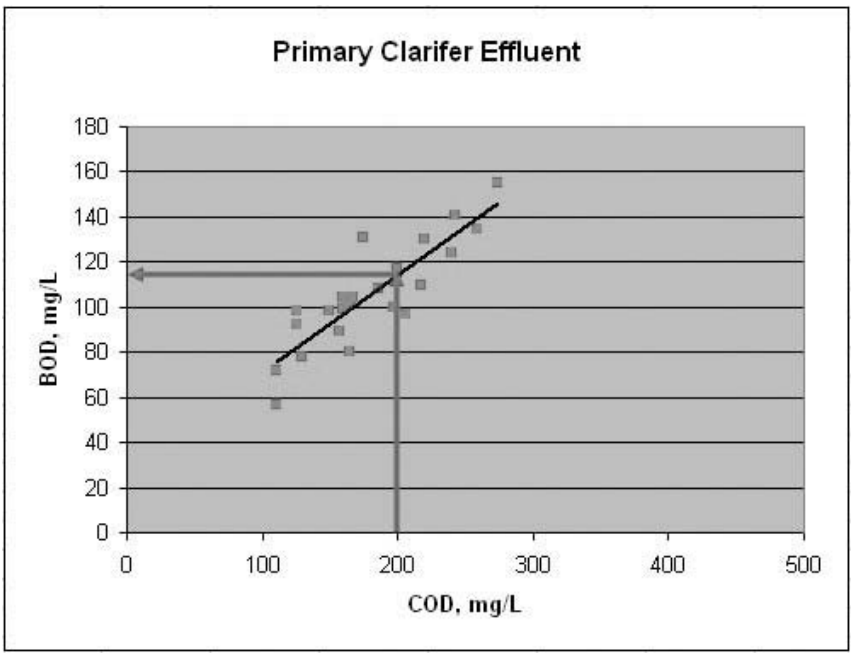


FIGURE 14.11 Scatter graph.

process performance), a few statistical tools can help limit the parameters to monitor. In choosing criteria to monitor, the operator should periodically review the validity of tracking a particular parameter. This is nothing more than verifying that a connection exists between a variable and how the process performs. Statisticians call this a correlation. Several basic statistical methods can be used to determine how strong the relationship is between factors; these include linear regression, correlation analysis, and the attainment frequency method. The first two relationships are discussed below. The attainment frequency method was developed to address dynamic systems, which tend to produce data with a high degree of scatter (points are not clustered tightly about a straight line) and low correlation coefficients. The attainment frequency method was developed to meet a defined performance within a defined frequency, thereby accounting for and quantifying data scatter. Using this method produces quantitative results that can be applied directly to process control in treatment facilities. See Cochrane and Hellweger (1994) for more information on this method.

Line of Best Fit—Linear Regression. Scatter graphs plot variables of two different measurements. Should the data appear to be randomly scattered about a line, some insight may be drawn regarding the relationship between the two variables. If the points are clustered tightly about a straight line, the data may be used as a prediction tool for process control. A portion of a WWTP'S MLSS and the resulting effluent BOD values for the same day are shown in Table 14.3. Mixed liquor suspended solids compose the control parameter (x) and BOD is the process performance indicator (y). One value is plot-

TABLE 14.3 Line of best fit data.

	Mixed liquor suspended solids, mg/L	BOD, mg/L
	x	y
	2 708	25
	2 489	18
	2 465	14
	2 418	10
	2 629	19
	2 633	17
	2 603	14
	2 220	12
	2 412	10
	2 598	17
	2 653	27
	2 599	21
Sum	30 427	204

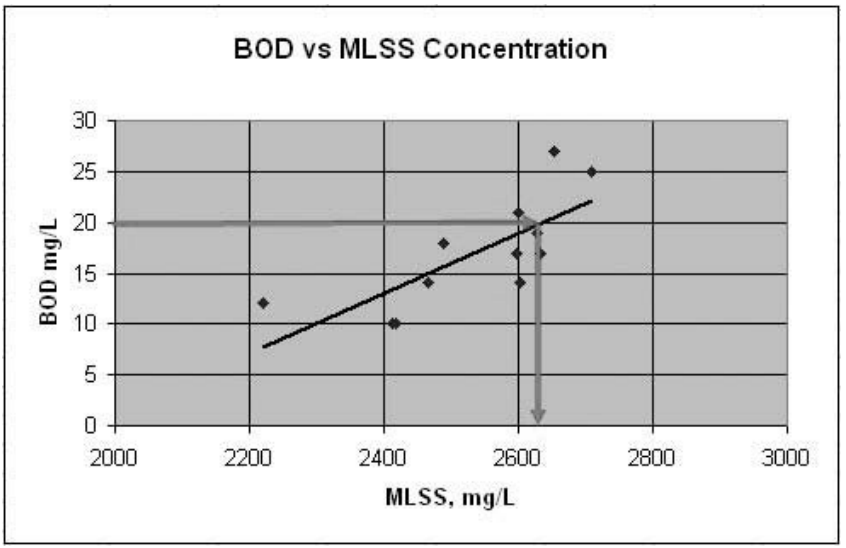


FIGURE 14.12 Line of best fit.

ted for each pair of values. These values and the calculated regression line are plotted in a scatter graph as Figure 14.12.

Although these values do not fall in a straight line, they are clustered around the drawn line. A straight line was drawn through the points in such a manner as to pass as close to the data points as possible. Using this line, rough estimates of the effluent BOD based on the aeration tank mixed liquor solids level may be extrapolated. To produce an effluent BOD less than 20 mg/L, the mixed liquor concentration should be approximately 2600 mg/L. Placing the line "by eye" is quite subjective and, while adequate for quick estimates, leaves a lot of room for argument. A more accurate method would be to calculate the line from the data given by expanding Table 14.3 as seen in Table 14.4 using the following set of formulas:

$$\hat{Y} = mx + b$$

Where

$\hat{Y}$ = the predicted process indicator value,
m = the slope of the line,
x = the control parameter, and
b = a constant (the y-intercept).

Where

$$m = \frac{\sum xy - (\sum x)(\sum y)/n}{\sum x_2 - (\sum x)^2/n}$$

and

$$b = \frac{1}{n}\left(\sum y - m\sum x\right)$$

The symbol "∑" is mathematical shorthand for "the sum of". For example: $\sum xy$ means that you multiply the value of x by the value of y for each data pair, then add up the products to arrive at the sum.

The symbol n stands for the number of observations. Using the data in Table 14.3, the number of observations (n) equals 12.

To set the line, select two values of the control parameter and calculate the value of $\hat{Y}$ and plot the results on the graph, drawing a straight line between the two points. This line becomes the line of best fit, or the regression line.

Using the sums in Table 14.4 to fill in the formulas:

The values of m and b are calculated to be 0.029 6 and −58.14, respectively. Substituting those values into the prediction formula, the equation is now:

$$\hat{Y} = (0.0296)(x) - 58.14$$

TABLE 14.4 Line of best fit—regression data.

	Mixed liquor suspended solids, mg/L	**Biochemical oxygen demand, mg/L**		
	x	y	xy	x^2
	2 708	25	67 700	7 333 264
	2 489	18	44 802	6 195 121
	2 465	14	34 510	6 076 225
	2 418	10	24 180	5 846 724
	2 629	19	49 951	6 911 641
	2 633	17	44 761	6 932 689
	2 603	14	36 442	6 775 609
	2 220	12	26 640	4 928 400
	2 412	10	24 120	5 817 744
	2 598	17	44 166	6 749 604
	2 653	27	71 631	7 038 409
	2 599	21	54 579	6 754 801
Sum	30 427	204	523 482	77 360 231

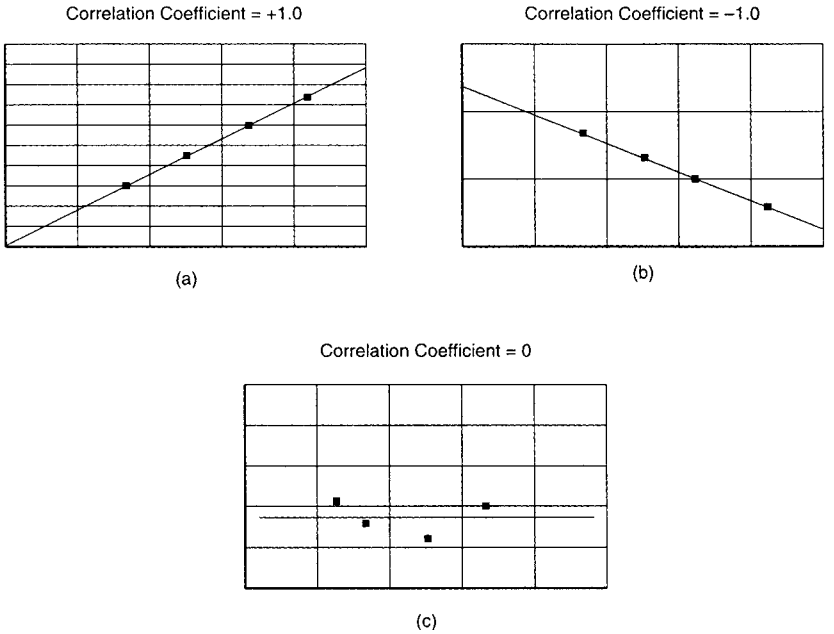


FIGURE 14.13 Correlation analysis.

Then select two or more MLSS values to determine the line. Using MLSS values of 2400 and 2600 for x, the predicted BOD values are 13 and 19 mg/L, respectively.

Correlation Analysis. Correlation analysis takes the equation of a straight line, previously developed, and calculates a correlation coefficient between the data pairs. The correlation coefficient r gives a numerical rating of how closely the data plots to a straight line. A perfect correlation results in a coefficient of +1.0 or −1.0 and results in a straight line, as seen in Figures 14.13 (a) and (b), with a positive (line rises from left to right) or negative (line falls from left to right) slope, respectively.

The closer the value is to 1, the more meaningful the relationship. Because wastewater treatment plants are dynamic in nature, there is a high variability or "scatter" in the plant data. A correlation coefficient of 0 indicates that the data are distributed around a horizontal line and therefore have neither a positive nor a negative relationship, as in Figure 14.13 (c). For dynamic biological systems such as wastewater treatment facility systems, a good correlation coefficient will range between 0.6 and 0.7. The correlation coefficient is calculated as follows:

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{n\sum x^2 - (\sum x)^2}\sqrt{n\sum y^2 - (\sum y)^2}}$$

Where

n = the number of observations,
x = the control parameter (MLSS, SRT, flowrate), and
y = the process performance indicator (effluent TSS, BOD, percent volatile reduction).

The easiest way to calculate r, the correlation coefficient, is to expand the previous table, find the needed sums, and substitute them into the formula. The data set in Table 14.5 is used in the illustration.

Using the sums in Table 14.5 to fill in the formula, n = 12, the number of observations.

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{n\sum x^2 - (\sum x)^2}\sqrt{n\sum y^2 - (\sum y)^2}}$$

$$r = \frac{12(523\ 482) - (30\ 427)(204)}{\sqrt{12(77\ 360\ 231) - (30\ 427)^2}\sqrt{12(3794) - (204)^2}}$$

$$r = \frac{74\ 676}{\sqrt{2\ 520\ 443}\sqrt{3912}}$$

$$r = 0.752$$

Considering the dynamic systems involved, a 0.752 correlation would be considered good. A strong relationship exists between the control parameter and the process performance indicator. From this, one may choose to use MLSS as a predictor of effluent BOD as a reliable process control tool.

Data Handling Summary. There are many conventional tools available for handling data generated at WWTPs. Time plots containing several parameters on the y-axis versus time on the x-axis are useful in evaluating data trends. Sometimes, especially with dynamic biological systems, change occurs more gradually. It may be more useful to use a multiday running average in evaluating process performance. Examining relationships between two variables is best assessed using a scatter graph to show the direction of the potential relationship. From this information, regression lines may be developed for use as a predictive tool and their validity checked using correlation analysis. Selecting the proper tool for the right job to obtain the desired results requires knowledge of the strengths and weaknesses of each analytical method.

TABLE 14.5 Correlation analysis.

Mixed liquor suspended solids, mg/L	Biochemical oxygen demand, mg/L			
x	y	xy	x^2	y^2
2 708	25	67 700	7 333 264	625
2 489	18	44 802	6 195 121	324
2 465	14	34 510	6 076 225	196
2 418	10	24 180	5 846 724	100
2 629	19	49 951	6 911 641	361
2 633	17	44 761	6 932 689	289
2 603	14	36 442	6 775 609	196
2 220	12	26 640	4 928 400	144
2 412	10	24 120	5 817 744	100
2 598	17	44 166	6 749 604	289
2 653	27	71 631	7 038 409	729
2 599	21	54 579	6 754 801	441
Sum 30 427	204	523 482	77 360 231	3794

FORMULATE A RESPONSE. Before making any process change, the operator should complete the fact-finding phase, evaluate pertinent analytical data, and review SOPs. In addition, individual process troubleshooting guides contained in the process chapters may be of assistance.

In formulating process changes, select one parameter to change. Multiple changes may have unanticipated effects when combined and may cloud future evaluation when trying to determine the effectiveness of a given strategy. Most wastewater treatment plants are biological in nature. As such, environmental changes are slow to manifest. A good method is to wait two to three mean cell retention time (MCRT) periods before making any further changes. That allows enough time for the biosystem to acclimate, giving the operator a firm foundation to make subsequent adjustments.

After determining a course of action, the changes should be documented. Process control parameters should be entered into a permanent log for review by all personnel. Verbal communications ensure an opportunity for questions regarding operational philosophy so that a consistent strategy may be followed through all shifts.

REEVALUATE. After adopting a change, the unit process control parameters should be checked daily and evaluated accordingly. In addition to effects on the specific process, effects on downstream processes should be evaluated to determine the overall

consequences on plant operations. If changes appear ineffective after several MCRTs, the operator should go back to the beginning and start the process again. This time, all staff members should be asked to help determine possible effects that may have been misinterpreted or overlooked in the previous evaluation.

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Chapter 15

Outsourced Operations Services and Public–Private Partnerships

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GENERAL OVERVIEW—OPTIONS AVAILABLE

The option to outsource operations of a public (or private) wastewater or water treatment facility to an entity other than the owner has been in existence for over 30 years. In its original form, it was simply identified as *contract operations*, and generally referred to any situation where an outside company was contracted to perform, in whole or part, the operations of a facility. These contracts were typically three to five years in duration, with the contractor accepting only limited risk for facility operations in terms of labor, consumables, and routine repair or replacement of the operating equipment. With the revision of the federal tax law in 1997, often referred to as 97-13 (Internal Revenue Service [IRS] Revenue Procedure 97-13), which removed the time duration limit on a private for-profit entity operating a publicly funded facility for more than five years, the private outsourcing companies were now able to assume a much longer term role and have the ability to assume more risks in the full cost of the facility operation.

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These contract arrangements are considered public–private partnerships (P3) and can include many options in terms of contract services, full permit compliance, capital repair or replacement, capital upgrades, facility expansion, asset management, project financing, the design–build–operate (DBO) approach, and full turnkey services. In general, there is a much higher transfer of risk across many issues from the public sector to the private contractor in a P3. Each project presents its own requirements and challenges with the accompanying benefit opportunity available for the owner.

There are several key areas for consideration in forming any P3, the first of which should be to determine what the problem is to be resolved by the action. The primary motivator often is the potential economic benefits to be gained through forming a P3. The efficiencies available from a core business provider through leveraged purchasing, personnel training, application of technology, and broad industry knowledge can far surpass those found at the typical municipal level. Other factors may include regulatory compliance, financing capability, introduction of new technology, or be political in nature. A second consideration is the procurement process for retaining the services of a service provider. The process must include evaluation of multiple key factors, assigning appropriate weight to each, to arrive at a proper selection, which will deliver a sound, successful, long-term partnership. The third element is the agreement itself. The agreement must be carefully crafted, absent any significant ambiguity, providing a solid platform on which to base the P3. Apportionment of risk must be carefully defined and adequate controls created to protect both parties. The contractor must be afforded the opportunity to operate and manage the facility, without undue hindrance or encumbrance by the public owner, if they are to successfully bring to bear the expertise and capability for which they have been selected.

The term *contract operations* is generally used to describe a project where there are no significant capital projects or improvements included, or private project financing or ownership. This service can be narrowly defined to limit the involvement of the private-sector partner, similar to the original style contract relationship. However, there can be, and often is, significant risk transferred from the owner to the private sector in these projects. The extended time duration of, in some cases, over 20 years, affords the private contractor the ability to level out operating cost considerations, such as major equipment replacement, that otherwise are not possible. This can provide the opportunity for the municipal sector to transfer significant risk to the contractor, realizing such benefits as long-term rate stabilization.

A turnkey approach can be coupled with outsourcing. This involves the contractor providing design and construction services for a new or rehabilitation project, with the owner providing financing. The contractor would then also provide operations ser-

vices, at a predetermined cost for the project. This is often referred to as a DBO project and is becoming more popular in the marketplace.

The application of a DBO solution in the execution of a municipal project is a method that requires unique understanding, procedures, and approaches to ensure success. The use of this approach is commonly driven by the need to complete the project in a more timely fashion at lower costs than are typically associated with the traditional design–bid–build approach. There are numerous advantages delivered in a DBO solution, including the amalgamation of risk and responsibility to one party, the design–build contractor, and a design driven from an operations focus with a vertically integrated project design effort through all disciplines. The resulting facility's components have been selected with life cycle cost analysis, as opposed to "lowest bid", and often provide a project delivering unique solutions to the owner's problem. This approach may be used for an entirely new facility or an upgrade or expansion of an existing one.

The DBO contractor's team will, in its most effective configuration, have the operations sector involved in the design development from the very outset, with continued input throughout the project execution. In some situations, the team is actually led by the operations sector, which perhaps delivers the most cost-effective solution to the owner. This is assured if the operator is required to operate the facility for a significant period of time (20 years), at some level of guaranteed operating cost, and must deliver the project capital component at a competitive cost.

Developer financing further involves the private sector and can be used as a standalone, service-delivery option or in conjunction with either turnkey services or outsourcings. Developer financing is often undertaken when a developer has a vested interest in seeing a facility built or a system expanded, to ensure that development plans move along reasonably quickly. The other factor can be debt-issuance limitations of the municipal entity, which requires an outside funding source. In the normal condition, it is almost always true that municipal debt can be issued at more favorable rates than that of a private company.

A fourth form of public–private partnership is full privatization. This term is often used to include those arrangements previously discussed and involves the private sector with all aspects of the project or system, including, most significantly, ownership through the sale of the asset to the private contractor. This approach can provide the public body with broad-scope solutions to regulatory pressure to construct, expand, or upgrade a facility. Full privatization may also be a response to economic pressures in the community to moderate rate or tax increases.

In the privatization of a new wastewater treatment facility, the private sector can be involved in the design, construction, financing, ownership, and operation of the facility. The public sector may be involved in various components of this service delivery

option, including participation in the selection of the technology or other decisions associated with facility design and construction.

Privatization, as applied to an existing facility, may serve to upgrade or expand it or simply to reduce and contain operating costs. Where the public entity has financial demands in other community areas, privatization of an existing facility, which is the sale of the facility (assets) to the private sector, may serve as a cash source to address other demands. This can be accomplished with a true ownership transfer or a long-term leaseback arrangement.

The economic scope that must be considered in a privatization effort is much broader than basic outsourcing. Specific issues include the existing debt on the facility and the type of debt involved. The present worth or book value of the facility will establish the selling price and debt level that the existing rate structure will support. These factors must be analyzed carefully to determine the benefits of privatization. Opportunities exist for a municipality to reap the rewards of privatization of wastewater facilities, but it must be accomplished with great care.

The final P3 is a merchant facility. Perhaps the best example of a merchant facility is the siting, construction, and operation of a water reuse facility by the private sector. In this example, the private sector takes the initiative in constructing facilities and maintains ownership and operation responsibilities of the facilities providing service to all customers, processing wastewater to provide water for industrial, irrigation, and other demands. Unlike a privatization option, a merchant facility serves more than one customer and typically does not restrict service to those who have fixed contracts with the merchant facility owner or operator.

The P3 service delivery options may also be referred to as build–own–operate–transfer (BOOT) and build–operate–transfer (BOT), or DBO. These arrangements contemplate that the facility ownership will transfer from the contractor to the municipal client at some point in the contract, typically at the end. The terms of transfer can be defined in the contract to address requirements of procurement laws, bond and tax issues, and project financing.

SERVICE DELIVERY INDUSTRY

The service delivery industry, in its simplest form and in its core business offering, is considered contract operations. This approach is not a new concept in providing non-core-business services or in providing water and wastewater treatment services for municipalities. Contract operations has, for many years, been widely used outside the utilities industry, in such areas as transportation, transit services, prisons, schools, hospitals, airports, fleet maintenance, janitorial services, street sweeping, and solid waste

collection and disposal. In the water and wastewater treatment industry, outsourcings arrangements have existed for many years, and currently there are well in excess of 1400 agreements for the operation and maintenance of wastewater treatment plants (WWTPs) by the private sector, which represents only approximately 3 to 5% of the market. This number includes approximately 40 agreements for large facilities greater than 440 L/s (10 mgd) and 350 contracts for mid-size facilities, ranging from 44 to 220 L/s (1 to 5 mgd). Within these projects, there have been approximately 40 agreements for a term of 10 years or longer, with many of them set at 20 years. It is estimated that there are thousands of outsourcing agreements for small or package WWTPs located throughout the country.

These numbers do not take into account the multitude of moonlighting or technical supervision jobs typically performed by licensed municipal operators, which are also valid operations contracts. These figures also exclude the hundreds of outsourcings agreements in place for the operation of components of WWTPs and for private-sector service arrangements for functional activities, such as meter reading, customer billing, meter repair, and testing.

The current trend toward outsourcings and other P3 service delivery options might well be a result of the enhanced regulatory environment in which utilities operate. The requirements of the Clean Water Act, the Safe Drinking Water Act, and other environmental regulations are forcing utility providers to make significant capital investments in more complex and technologically challenging facilities, to attract and retain qualified staff to operate these facilities, and to do so with the ongoing pressures of cost control and concerns for customer rate increases. In the past, when such pressures existed, the local government sector had a federal partner in the form of a grant-funding program available for wastewater facilities. With the demise of this program and the increasing competition for state revolving fund monies, the economic effect of the new facilities designed to meet federal environmental mandates falls squarely on the shoulders of the local government. All these factors point to the increased need and involvement, in many situations, of professional service providers to assist communities in meeting the increasingly complex challenges associated with water and wastewater service.

The services delivery industry has undergone a significant transition since the enactment of 97-13, which enabled a broader scope service delivery and greater risk transfer to the service provider. There has been a consolidation of the companies, with a number of the smaller providers being merged with larger companies. This was in response to the need for stronger financial resources to accept a larger risk transfer and support financing of capital projects or asset transfer and an emerging recognition that the demand for privatization capability would continue to develop. In addition, the

company size brings added benefit to the municipal entity, with their leveraged buying position in the marketplace for chemicals, supplies, and support services. Core competencies, such as training, standard operating procedures (SOPs), operating system support, and performance optimization all benefit from a larger operating base. The pairing of either engineering or construction and/or process equipment capability has also emerged to respond to the broader scope encountered in the full-service P3 contracts.

The outsourcings industry provides core services along a variety of lines, including the following:

- Full system operation;
- Management oversight;
- Laboratory analysis;
- Plant startup and testing;
- Operator training;
- Emergency maintenance;
- Contract management;
- Diagnostic operational reviews;
- Billing, collection, and customer services;
- Groundwater remediation;
- Predictive and preventive maintenance;
- Pipeline inspections and repair; and
- Facility design, construction, and commissioning.

Under full-system operation, the private sector may be retained to design, build, operate, maintain, and repair an entire water or wastewater utility system or portions thereof. What is often more common is to segment system components or functional activities for outsourcings, typically referred to as *inside-the-fence* or *outside-the-fence* operations. Inside-the-fence operations include all or part of the functional responsibilities of the treatment plant processes performed within the confines of the treatment facility. Outside-the-fence operations include operation of the water distribution or wastewater collection system, pumping stations, well fields, or biosolids disposal sites.

Depending on the services for which a service provider is retained, companies can range from small local firms to large operators working on national and international projects. The industry might be divided into three categories: international/national, regional/national, and regional/local. This division is somewhat subjective, but can be useful in assessing the capabilities of the various providers to undertake projects of varying complexity and size. Issues that are relevant when considering service providers include past performance, operations experience in similarly sized projects, financial

stability, bonding capability, environmental compliance history, support capability, and successful completion of similar capital projects.

National firms may be affiliated with large domestic or foreign engineering design firms operating on a national or international scale. Regional/national providers are often well-established firms providing services within a broad region of the United States. New entrants in this area include foreign-outsourcings firms that have just begun to provide services or acquired the capability in the United States. The third set of providers includes regional or local firms that may be well-established in a specific geographic region and perhaps even in a specific functional area, such as pumping station maintenance and repair.

ADVANTAGES AVAILABLE IN OUTSOURCING

The issues that lead municipal entities to consider outsourcing their wastewater system operations are diverse. However, there are a number of key elements that include continually increasing environmental regulations and standards, increased pressure from served constituents to maintain rates, competition for a continually decreasing tax/rate base, aging infrastructure, and general operational challenges. Outsourcing these services can be viewed as an economical, effective alternative to the traditional service-delivery options of local government ownership and operation. Typical reasons that a municipality considers outsourcing either operations or project delivery include the following:

- Solve compliance problems or address increasing regulatory requirements,
- Resolve labor relations problems,
- Reduce operating costs and/or capital project costs,
- Expedite capital upgrade delivery,
- Access capital project funding,
- Assure availability of qualified staff,
- Respond to capital and/or capacity upgrades, and
- Transfer risk to private service provider.

While these are often cited as the reasons for evaluating outsourcing as a service-delivery option, they may also serve as hurdles or barriers to the outsourcing process. For example, labor relations might be a positive or negative factor. The presence of a strong union or organization may be a significant obstacle to implementation. While this issue has precluded outsourcing from serious consideration in some communities, it has also been dealt with effectively in many situations by local government leaders

and service providers. A key component in successfully addressing labor-related issues is the development and distribution of a well-structured employee transition plan. The uncertainty of existing employees when outsourcing operations is being considered can often be dealt with by timely and informative communication. For example, employees want assurance that, if they decide to accept employment with the service provider, they will do so with some security and certainty regarding wages and benefits. Employees typically look for security in provisions that prohibit their termination, without cause, within a specified period of time or put limits on the ability of the service provider to transfer employees to other facilities during a given time frame. However, it is not a good idea to impose employment terms in the contract beyond five years. These issues can be addressed effectively in the operations agreement discussed later in this chapter. At the same time, the local government must plan for those employees wishing to stay with the local government. This plan can include the development of retraining programs for former utility employees for a smooth transition to other local government duties.

In a practical sense, cost savings must be achieved if a local government is to accept and implement a privatization action. A contractor is able to avoid considerable expense in the procurement of goods and services because of its freedom from the bidding requirements of most public agencies. The avoided expense is primarily in the cost of the purchasing procedures and the time lost while complying with them in addition to their leveraged size in the marketplace. Contractors may also be able to avoid union restrictions (closed shop, work jurisdictional claims, and feather bedding) and can respond more readily to market forces affecting their ability to maintain a workforce to meet their needs. Other areas that contractors leverage is focused operations expertise, standardization of operational systems, multiskill employee development, and introducing automated systems and controls.

Perhaps the only exception is a situation where the U.S. Environmental Protection Agency (U.S. EPA) or a state agency has issued a compliance order. In this case, the local government may have no choice but to retain private-sector services to ensure compliance. Even in this situation, however, cost savings are likely to be achieved over time.

The element of risk and the apportionment of it in the contractual relationship are not as tangible as other items cited previously, but are just as valuable to the municipal entity and should be carefully evaluated when considering a privatization action. The main risk areas to be considered include environmental compliance, cost of operation, cost of maintenance, cost of major capital projects, and general project performance. These risks can all be quantified and equitably transferred or shared in a carefully crafted contract that balances them equitably and assigns them to the correct party in the best position to manage them.

ECONOMIC FEASIBILITY OF OUTSOURCING

Certainly, one of the foremost reasons for considering outsourced operations or a P3 is the potential for cost savings. The opportunities for cost savings through outsourced operations might depend on the following:

- Complexity of the facility process and/or operation;
- Size of the facility or system;
- Complexity of capital project or upgrade;
- Method of contracting for capital projects (BOOT/DBO);
- Location of the facility (proximity to other operated facilities);
- Regulatory compliance history and potential;
- Opportunities for rationalization; and
- Labor history and condition.

Individually, these factors influence the ability of a service provider to achieve both cost savings for the local government and acceptable internal profit margins. In situations where services are provided for a small facility employing only a few people, cost-saving opportunities may be quite different from those in larger facilities with a significant operating staff and budget.

The facility's location (remote versus urban) can influence the ability of the service provider to achieve the necessary economies of scale in management and operational areas to produce material cost savings. A remote facility with only one or two employees presents a much different set of circumstances and opportunities for cost savings compared with a larger facility or system in an urban area. With the presence of other communities in close proximity, all of which might also have WWTPs or similar facilities, the contractor may be able to achieve economies of scale for the benefit of all involved parties through a regionalization approach.

Projects that include a capital upgrade or new facility BOOT/DBO approach will generally benefit from a more performance-based contract as opposed to one that is highly prescriptive in defining the ultimate technical project solution. Flexibility in the contract will create the opportunity for the provider to apply maximum creativity in delivering the project capital solution.

The design standards incorporated to a BOOT/DBO project are not necessarily consistent with those found in a typical municipally based traditional project. The municipal standard is one that has its roots in many elements, not the least of which are those applied by U.S. EPA in the early grant programs, which funded much of the wastewater infrastructure and, in some cases, actually rewarded participating parties for escalating project costs. That is not to say these standards were not good ones. How-

ever, the product delivered by a typical DBO project will be configured more closely to general industrial standards found in practice today in private industry. These standards are driven by life-cycle cost considerations, reasonable levels of fit and finish for the facility, and acceptable equipment redundancies governed by practical standards. When configuring the contract, the owner should consider what level of standards in the project he or she would like. If there are certain "must haves" in construction materials, types, or configuration, or equipment selection and redundancy, then they should be identified in the request for proposals (RFP) package. However, the more closely constrained the DBO contractor is in this regard, the less benefit the owner may derive in project delivery and cost effectiveness. It is also recommended that the owner be flexible in accepting alternatives that may be offered to the standards prescribed and resist the temptation to universally apply standards used in the past. This approach will deliver the greatest economic benefit in a DBO solution.

Aside from the cost savings often associated with outsourcing, a local government may not be able to comply with the regulations affecting the WWTP under the current operational mode. This situation may provide the incentive and motivation for the local government to consider outsourcings. It is also likely that, in complying with requirements, cost savings may be achieved.

In attempting to quantify cost savings, a local government should take care when comparing the projected private-sector costs and costs of service provided by the local government utility. All too often, significant costs are not included in determining the costs of local government operations. Many indirect costs, such as those associated with the local government's finance and legal departments or the full capture of benefits and other related costs, are often excluded from the analysis. To make an appropriate comparison between an outsourcing proposal and the current cost of service, it is vital to capture all service-related costs. Furthermore, whether under outsourcing or under continued local government ownership, there will be costs associated with administering and overseeing the respective services. These costs may be significantly different under either option and an attempt should be made to estimate them before comparing current operations with the private sector.

In comparing local government service and the outsourcing provider, there is often a failure to compare precise service levels. This problem can be remedied by carefully examining the services currently provided under local government operation and, as appropriate, adjusting those services before issuing a request for qualifications or request for proposals. A local government must thoroughly understand the current services it provides, assess the need for those services, and develop a comparable scope of services for prospective service providers. In estimating the cost of current service delivery by a local government, costs should reflect the scope of services or service lev-

els to be included in the request for proposal. This means that the local government must carefully analyze its current method of providing service and make the necessary adjustments to ensure that service is provided as effectively and efficiently as possible. This internal examination or management/performance review will enhance the ability of the local government to remain competitive with the private sector. Even if the local government decides not to pursue outsourcing, the exercise will benefit the municipality by providing the required services more efficiently and effectively.

Comparing current local government costs is one step in the evaluation process. Another step is to have the local government division or section submit a bid to continue the service being considered for outside bid. This form of managed competition has been used by several local governments when considering outsourcing and affords existing employees the opportunity to compete objectively against the private sector. To assist employees in the preparation of their bid, the local government can provide internal support services or retain outside consulting services. However, this form of managed competition will not be viewed positively by outsourcing companies and will likely discourage enthusiastic participation in the procurement.

Managed competition has produced mixed results in the ability of existing employees to win the competitive bid process. Services awarded to the local government group through this process should carry the same contract provisions and be held to the same standards that would be imposed on the private sector, such as performance measures and reporting, fixed fee arrangements, and cost savings and sharing incentives. Issues that must be considered for an accurate comparison include the availability of performance bonds, liability insurance, permit compliance, technical support, and the accompanying costs associated with these. An evaluation should also consider if the employees are unable to operate the utility within the bid price; the local government will incur the added costs. With an outsourced provider, the inability to operate within the bid price is absorbed by the shareholders of the company. If economic pressures are too great, there is a risk the contractor may petition for fee increases, file contract claims, or pursue litigation to obtain relief.

PROCUREMENT PROCESS

The procurement process for selecting an outsourcing contractor, regardless of the scope of service, must be carefully crafted to assure delivery of a complete service responding to the project requirements. In addition, the process must be consistent with procurement laws, which vary greatly from state to state.

In many locations, communities have the option of going directly to an RFP or taking the intermediate step of issuing a request for qualifications (RFQ) statement from

service providers. The two approaches may require different amounts of time and may influence the number and quality of submitted proposals. Vendors typically prefer a two-step RFQ/RFP process, because the cost of preparing a proposal can be significant. It may range from tens to hundreds of thousands, if not millions, of dollars, depending on the size of the operating contract. Accordingly, most vendors prefer to initially submit qualifications statements, from which the municipality can develop a short list of qualified bidders and ask only those bidders (typically three to five firms) to submit formal, detailed proposals. This approach will enhance the procurement opportunity, narrowing the competitive field. However, a limiting factor may be state or local laws governing the procurement of services by a municipality or public agency. These laws can relate to the bid process associated with procuring either construction or professional services. In some instances, the procurement requirements associated with professional services provide the latitude needed to undertake a two-step RFQ/RFP process.

Having received statements of qualification and technical and cost proposals from vendors, the next step is evaluation and selection. Listed below are several broad evaluation categories that can be used in reviewing submissions:

- Corporate profile,
- Financial strength,
- `Corporate experience,
- Key project staffing,
- Project performance references,
- Proposed project pricing, and
- Project technical approach.

Corporate profile is a general criterion requesting vendors to submit information on the background and primary nature of the company, such as who the proposer is, what services it provides, and where it is located. Knowledge of affiliated companies and organizations can be important in evaluating the experience of the proposer. It is also important to understand the financial resources available to the company and its ability to undertake the project. Requiring such information as annual financial statements and reports can provide this kind of information. The goal is to evaluate the ability of the vendor to undertake the project, provide certain performance guarantees, and ascertain historical data on any past bankruptcy filings or past and pending litigation.

The corporate experience of the proposer is probably the most important criterion in selecting a vendor. Corporate experience typically includes a description of similar projects that the proposer has undertaken in terms of size, climate, regulatory environ-

ment, and technology. The proposer's ability to provide evidence of its capability to supply the full range of requested services is important. When soliciting proposals for a WWTP requiring a particular treatment technology or process, it is important to ascertain whether the proposer has successfully operated that technology or process. The project or plant manager to be assigned is also important. As with corporate experience, proposers should provide information on the experience of the key operators and plant manager in working with processes in similar climates and conditions.

The key to ascertaining the qualifications and experience of the proposer is primarily through the reference check and, if the community can afford it, visiting one or more facilities currently being operated by the proposer. Reference checks should involve more than a cursory telephone call soliciting general information. Questions should be asked about the vendor's ability to meet project schedules, the success of its safety program (i.e., www.osha.gov, U.S. Occupational Safety and Health Administration citations and days lost ratio), and its ability to work with the municipality under extraordinary or extenuating circumstances, such as natural disasters. The amount of cooperation exhibited by the service provider in dealing with customer problems and the ability to work with local, state, and federal regulatory agencies are also important considerations. Through this process, it is important to identify failed or problem projects. Why a project failed or did not meet the client's expectations is important. Lastly, and of significant importance to elected officials, is the price of the service provider's proposed services.

The proposal structure required for a BOOT/DBO project will include submittal of information beyond the normal scope for either a traditional engineering design package or a typical municipal public construction or operations proposal. As previously discussed, the cost structure can be configured to respond to the project requirements. If project financing were included, then details of how the financing will be accomplished would be included. This would identify the debt issuing structure and entity, redemption schedule of the debt, risk apportionment for interest rates, and sale of bonds, if appropriate.

In addressing the technical requirements for a BOOT/DBO, the proposer will typically include design development drawings representing approximately a 40% design as part of the proposal package. These would include basic drawing information depicting site layout, facility plan, process and instrumentation diagrams, process flow diagrams, primary process equipment layout, building elevations, standard finish and hardware schedules, and others, depending on the project. The supervisory control and data acquisition (SCADA) system will be depicted to a planning level key element schedule. It is not unusual to have a submittal that includes up to 100 drawings for a major project. In addition, there will be process descriptions identifying process function, sizing of primary equipment, manufacturer, and basic standards of fabrication.

The proposer will typically include a project schedule that will cover from the "Notice to Proceed" through commissioning. The design/permitting process is an important one and should be depicted in enough detail to demonstrate a reasonable understanding of the process. As part of a BOOT/DBO project, the design effort is compressed, with time frames of eight months considered normal. Project permitting efforts occur concurrently with the design effort.

In addition to technical requirements, it is typical for the RFQ/RFP to require submittal of DBO team qualifications, including project execution history, financial condition, bonding capability, and experience specifically relevant to the project. These criteria should be quantitatively evaluated to rank the proposers in the selection process. A process that involves "scoring" and "weighing" to reflect the importance of each criterion, given equal weight with the project cost, is advisable to formalize the process and protect the owner's interest. Equal weighting assigned between price and the full technical considerations in the ranking of a team is suggested for the owner to select the best-qualified, most cost-effective proposer providing the best value to the owner.

While no single evaluation method is universally accepted, a numerical matrix that assigns points to the various evaluation parameters is typical. Using the previously discussed evaluation categories, a matrix that expands or reduces the categories into smaller, definable items and assigns maximum points to each one allows the proposal reviewers to assign a numerical score. Totaling the scores of each vendor establishes the ranking. The development of a completely objective evaluation process is a noteworthy, but often impractical, goal. Some element of subjectivity is acceptable and important to reflect specific local issues and goals and complete the process in a timely manner. Table 15.1 is a sample evaluation matrix.

KEY CONTRACT TERMS

The outsourcing agreement is the foundation upon which the relationship between a local government and a service provider is built. One of the most frequent criticisms of outsourcing, and P3 service-delivery operations in general, is that the community loses control of the contracted operation. The operations agreement can provide greater levels of control and accountability than may currently exist under the traditional service option. Specifically, the contract can definitively outline the scope of services to be provided and compensation to be paid and provide for periodic (monthly, quarterly, or annual) performance reviews. Performance reviews require strict guidelines and standards to measure results. These reviews may also include the state regulatory body responsible for enforcing permit requirements. In many cases, these are standards of per-

TABLE 15.1 Example of a Sample Evaluation Matrix. (*continued on next page*)

Criteria		Ranking[a] and description	Rank	Assigned value	Assessed value	Comments
(1) Number of years providing relevant services	HA	5 or more		10		
	A	3				
	NA	2				
	U	None				
(2) Client references	HA	100% positive reference checks		20		
	A	80 to 100% positive				
	NA	50 to 80% positive				
	U	>50% positive				
(3) Experience with services of similar capacity and/or process (design, construction, startup, and operations services)	HA	3 or more		5		
	A	2				
	NA	1				
	U	None				
(4) Number of projects with similar treatment technology in operation	HA	3 or more		10		
	A	2				
	NA	1				
	U	None				
(5) Number of projects or resources in proximity capable of providing technical and staff support	HA	3 or more		10		
	A	2				
	NA	1				
	U	None				
(6) Litigation, permit enforcement actions, and/or fines from similar projects	HA	None in last 3 years		5		
	A	None in last 2 years				
	NA	None in last 1 year				
	U					
(7) Detailed project plan	HA	Addresses all project requirements		10		
	A					
	NA					
	U	Incomplete				
(8) Detailed corporate safety program addressing operations and construction	HA	Comprehensive program		5		
	A					
	NA					
	U	Incomplete				

(*continued*)

TABLE 15.1 Example of a Sample Evaluation Matrix. (*continued from previous page*)

Criteria	Ranking[a] and description	Rank	Assigned value	Assessed value	Comments
(9) Identifies strategy for providing operations support: SOPs, operations and maintenance manuals, facility evaluation, maintenance management approach	HA Comprehensive program A NA U Incomplete		5		
(10) Provides in-house specialized support: process control, instrumentation and control, SCADA, and power management	HA Comprehensive program A NA U Incomplete		5		
(11) Corporate training programs	HA Comprehensive program A NA U Incomplete		5		
(12) Financial resources and stability	HA Meets all RFP requirements A NA U Incomplete		5		
(13) Completeness of proposal	HA Meets all RFP requirements A NA U Incomplete		5		
Total			100		

[a]Ranking: HA = highly advantageous = 100% of point value; A = advantageous = 75% of point value; NA = not advantageous = 50% of point value; and U = unacceptable = 0% of point value.

formance or criteria that a municipality does not currently use to evaluate its own employees and operations.

A carefully crafted outsourcing agreement provides the framework under which services are to be provided. It clearly delineates the scope of services, the extent to which the operator has responsibility and authority to act, and the compensation provided to the service provider. Contracts need a certain degree of specificity; however, they also need flexibility because they are often long-term agreements. Figure 15.1 illustrates the components of an outsourcing agreement.

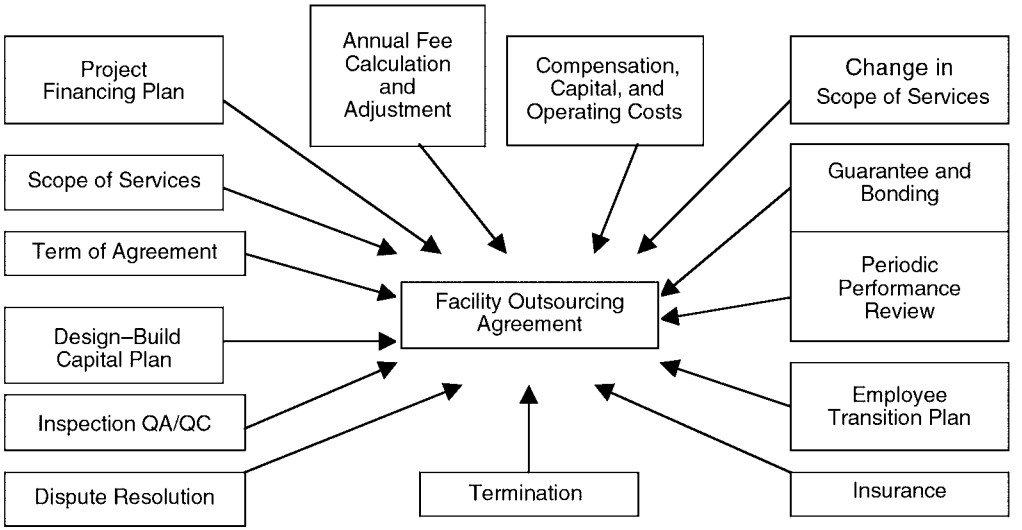


FIGURE 15.1 Sections of an outsourcing agreement (QA/QC = quality assurance/quality control).

Employee issues are critical to the success of outsourcing operations. Thus, the agreement must clearly address transition issues for existing employees. A formal transition plan typically includes provisions for addressing termination, transfer, compensation, and benefits. This is particularly true in union situations, but is important in any situation where existing employees are involved. The transition plan should define how employees can potentially be re-employed with the service provider's company, provide for employee counseling, and provide for economic analysis associated with pension plans and the like.

As was previously identified, the IRS changed the tax code, and it is now possible for private contractors to operate facilities for extended contract periods. This approach, incorporated to an outsourcing agreement, enhances the ability of the contractor to participate in the funding of capital facilities and the amortizing of such costs over an extended period of time. This situation can work to the benefit of the local government by mitigating rate increases and providing a financing source.

Most outsourcing agreements provide for a fixed payment by the local government to the service provider. The amount is generally paid on a monthly or quarterly basis and relates to a baseline service level and associated operation and maintenance costs based on a predetermined production level. The fixed payment also contains

certain baseline costs for utilities, such as electricity or natural gas, with the utility rates adjusted on an annual basis. Annual adjustments can be allowed, based on a predetermined consumer price or general inflation index. Care should be taken when establishing a cost-adjustment index to ensure that it properly reflects local conditions and the effect inflation would have on the costs involved. A national consumer index may have little relation to the cost of chemicals, materials, and supplies in a particular region. The past performance of the index and how it correlates with changes in actual costs over a period of time are important to assessing the relevance of a particular index.

In addition to general inflation adjustments, the compensation amount can be adjusted to the extent that flows to the facility are more than or less than pre-established ranges. Such adjustments can also involve price increases or decreases for utilities or other production-related expenditures.

In crafting the compensation portion of the agreement, care should be taken to ensure that the service provider has adequate incentive to reduce costs, while still effectively operating the facilities. The incentive can be in the form of allowing the service provider to retain a portion of the savings achieved, with the balance accruing to the benefit of the local government. It should also be recognized that the proponent might have incorporated these anticipated savings to the base proposal.

Another key component of the compensation agreement is an annual maintenance fund, funded by the local government and agreed to and planned by both parties. This component ensures that a maintenance program is established and funded. The plan should have monitoring or reporting requirements associated with it, and, at the end of the year, any remaining funds should revert to the local government. To the extent there were no out-of-scope activities performed and maintenance costs exceeded the fund allowance, those excess costs would typically be borne by the service provider. This approach should also be applied to capital replacement, which includes the major equipment replacement as it reaches the end of its useful life. In a 20-year term, the new replacement assets will remain the property of the owner. Requiring the contractor to finance these major replacements throughout the contract will force accelerated depreciation of these costs against the contract in time frames significantly reduced below normal useful life. The result will be higher-than-necessary operating costs.

In projects involving capital improvements, certain considerations must be included. In an owner-financed project, payment schedules are typically tied to the project critical path schedule and may be milestone-based, which provides a relatively easy system to verify payment progress on a project. In the case of a contractor-financed project, the contractor and trustee will control the release of funds.

To have expedient project negotiations and award, it is strongly recommended the owner include contract terms and conditions in the RFQ/RFP and request comments from the proposer. An approach that establishes a fair and reasonable contractual relationship, without creating any unnecessary risk assignment, will provide the greatest benefit to the owner. There are many issues to consider when crafting a contract that would warrant a much broader review, but the following sections are points that are either unique to the DBO process or provide special challenges.

LIABILITY. The nature of a DBO procurement combines three categories of liability that require some form of resolution and assignment. The first is in the design category, which would typically be addressed through professional liability insurance for errors and omissions. This coverage is typically required of a DBO contractor, and, depending on the teaming arrangement, may be provided by an engineering subcontract into the project. Construction liability is generally addressed through the normal performance and payment bonds and typical builder's risk and general umbrella liability insurances associated with any public works project. Operations liability is readily addressed through general liability insurance and a performance bond or letter of credit typically reflecting the value of one or two years of the facility's operating cost. In addition, it may be appropriate to require that the operator carry hazard insurance on the facility assets, depending on which party is the facility owner during the course of the contract. Care should be taken to assign values to each individual coverage, reflecting the relative value of the associated risk, and not simply the total value of the project, which encompasses all three elements.

The long-term nature of these contracts merits consideration of additional liability coverage reflecting the scope of the services provided. This requirement should not be unlimited in nature, but should provide a value that reflects the real-world cost effects for project failure. An unlimited guarantee can really only be pledged once by a corporation to have a real value and is obviously subject to the net worth of the corporation. Requiring acceptance of unlimited liability is not acceptable to large corporations, as it requires "betting the bank", and is not a responsible action to owners and shareholders of the corporation. In addition, it places an unreasonable burden on the company, with an accompanying extraordinary cost. However, a bonded guarantee that pledges, as an example, $20,000,000 from a $3 billion corporation has a real and intrinsic value and is one to which underwriters can subscribe. This approach provides absolute quantification of the protection afforded the owner and removes any exposure associated with corporate success, bankruptcy, or ownership change of the company.

CONTRACT BUYOUT. It is sometimes deemed desirable to the owner to provide for contract buyout or call provisions. If this is included, the terms for the buyout must

recognize the value of expenditures associated with project startup, ongoing operations, and lost opportunity for the contractor. In addition to these issues, the inclusion of call provisions has an effect on the ability to finance the project. If a bond issue is anticipated to finance the project, the marketability of the bonds and their accompanying discount rate will be negatively affected. It is suggested that, if the contractor is performing properly under the contract, there is really no need for the contract buyout provision. If performance does not meet requirements, then the owner may act on contract breach terms and exercise termination options.

PROJECT FINANCING. If the contractor is to provide project financing, the issue of interest rates is an important one. Given the time it often takes between the bid of a project and the award, it is not possible to lock in a bond issue interest rate for this duration. It is recommended that the interest rate used in the bid basis be adjusted at the contract award to provide the best value to the owner in terms of project financing. This also reduces the risk the proposer must assume with regard to project financing and therefore the cost passed on to the owner.

CONTRACT TERMINATION. The conditions for contract termination should be based on nonperformance or breach. Termination for convenience is not reflective of the long-term partnering relationship, which is desired in a DBO contract, and can be a disincentive for proposers to consider committing resources to the development of the project.

BONDING REQUIREMENTS. Bonds are an instrument used to mitigate project risk for the owner in the project. As previously discussed, the bonding requirements for a DBO are not overly different from typical contracting requirements; they are just combined in one contract body, as opposed to separate contract actions. Care should be exercised in determining the individual bond value requirements to avoid unnecessarily escalating bonding costs and duplication of coverage.

SERVICE PROVIDER/OWNER INTERFACE

Once a facility is under contract operation, the degree and frequency of owner participation can have a direct effect on the success of the venture. A review of privatized or contract-operated facilities will reveal both success stories and failures. The success or failure can typically be related to the effectiveness of the contract and the type and degree of owner participation.

The type and degree of owner participation varies widely from contract to contract. It is incumbent on the owner not to under- or over-manage. The owner should not take

an out-of-sight, out-of-mind attitude just because a contractor operates the facility, unless it has, in fact, transferred the permitting requirements and ownership of the facility. The owner is still ultimately responsible to the customers and state and federal regulators. Sufficient detail must be provided to verify that the facility is being operated within permit requirements and in accordance with the contract provisions and should be based on objective criteria established in the contract. It is also of utmost importance that the owner verifies that contract conditions are met with respect to maintenance and replacement of equipment and facilities to ensure protection of the owner's original investment. The other extreme is overmanagement, where overzealous owner involvement borders on harassment. Overmanagement is more likely to occur at facilities where employees strenuously opposed the move to privatization. Often, the facility owner will attempt to placate dissenting factions by establishing onerous reporting mechanisms, placing owner employees in the facilities as inspectors, or establishing oversight committees to ensure performance of the contract. In most cases, these actions serve only to increase the cost to the owner and limit effectiveness of the contract operator.

The unique requirements of a BOOT/DBO project also extend to the owner and the owner's project execution team. An approach enlisting the same procedures found in traditional municipal capital projects will not suit a DBO project and will likely cause significant problems in its execution. The owner's team must be project-specific, including all necessary disciplines, and be empowered to make project decisions. As the project moves from proposal through negotiations and award to actual execution, the requirements for interface and exchange will continue. It is typical for the BOOT/DBO team to meet with the owner on at least a biweekly basis beginning in negotiations; transition to review progress in the design effort; and share information on products, equipment, hardware, and other project details. In this process, it must be recognized that the contractor has already selected much of the project material at the time of proposal, and this "design" effort is a refining and coalescing process. As such, the level of "submittals" typically seen for approval is, in fact, submitted for the owner's information and record. Should a product prove objectionable to the owner, depending on its significance, the owner should be prepared to absorb any significant cost effect through a project-change order. An important coordination requirement exists for the owner's team with regard to other existing infrastructure or ongoing projects. This will continue throughout the project's duration.

As the project moves from the design and permitting phase to actual construction, the owner may wish to assign a full-time, on-site representative. This will provide direct interface with the contractor and enable quick response to project requirements and issues. In addition, this entity may serve as the quality assurance/quality control (QA/QC) oversight for the owner in assuring a project is constructed to those stan-

dards originally presented. Maintaining project records, as-built drawings, and recording progress are typically accomplished by the DBO contractor, and the owner's agent can serve as an active affirmation of this. The owner's representative should have a detailed list of responsibilities and a clear definition of role and authority in the project. He or she would participate in project meetings and keep the owner's management informed of project progress and involve them in ongoing key project decisions. Typically, the contractor provides services of an independent testing agency to provide QA/QC on construction materials, such as concrete or pressure vessel welding and painting, with the results made available to the owner.

The key to a successful public–private partnership is letting the contractor do his or her job and having a contract that clearly identifies the scope of the project and the role of the owner. Privatization, to whatever level accomplished, is a partnership between the owner and the service provider and will work only through establishing clear, reasonable expectations and cooperation by both parties.

Chapter 16

Training

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INTRODUCTION

Training is part of a well-run organization, and it can be a great asset or a great liability. The difference between success and failure typically depends on a utility's attitude toward training as a part of its culture. The wrong approach can nearly guarantee failure, despite a large budget and a skilled, determined training staff. The right approach can lead to success, even when means and personnel are limited.

THE ORGANIZATION AND THE TRAINER

Trainers occupy a special place in any organization, and any trainer or training group should be organized to preserve and capitalize on this separate status. Training deci-

sions must be made without undue constraint or direction from laypeople, so the trainer should operate as freely within the organization as its culture can allow. There are several reasons for this separation, the most important of which is that if training personnel lack the freedom to identify and address training needs and to refuse to address what other staff mistakenly believe to be training needs, training inevitably becomes a subset of the organization's management, to the detriment of both training and management.

Ideally, a trainer or training group would report to the head of the organization so they have reasonable access to the resources of all departments and freedom from any competing pressures in the organization.

THE STARTING POINT: SUPPORT

It is easy to identify an organization that does not support its training team. Even if the training budget is large and training policies exist, the organization has managerial stresses and inefficiencies, poor or spotty job performance in important departments, too-frequent equipment breakdowns, and stress fractures in the organization itself. If an organization supports a vibrantly effective training group, such problems will shrink (though they never entirely disappear from any organization).

Support means more than a program budget and policy statements. The people responsible for training should be free to design, develop, and deliver training that meets the group's actual needs, and they should have access to the human and physical resources necessary for the job. More important, the training group must have a voice in the organization, be seen as a vital part of it, and have a defining role in its future direction.

THE REAL GOALS

Any modern training system should create a learning culture in the organization. In a learning culture, all participants share the responsibility for their own development, and they have a responsibility to help their fellow employees develop.

To achieve this goal, the training team must implement a technical training system that is project- rather than curriculum-based. Such a system allows the trainers to focus on "just-in-time" training, in which instruction is available when needed and delivered only to those who truly need it. This process maximizes results and provides the most training flexibility. Each training need is a separate project rather than a step in a regimented system.

Project-based training also eliminates the need to create, maintain, and update a large body of seldom-used curricular material, relying instead on the trainer's ability to develop material for immediate, clearly defined needs. This is both a benefit and a disadvantage. Without an overall curriculum, trainers need a comprehensive reference system of standard operating procedures and other job aids to ensure that appropriate information is available to guide employees whenever needed.

Ideally, an effective, project-based training program would only provide information that is fully relevant to both the job and the participant. It also would consistently use the training media best suited to the material and the participants' skills and knowledge.

A project-based training program may require a higher standard for trainers than one that uses a set curriculum, but because training is need-specific, personnel will spend fewer total hours being trained. So, trainers should be proficient in all aspects of training-program development and delivery, and they must either have expertise in the jobs they are teaching or have access to employees who do.

This approach to technical training is driven by the organization's performance needs and tied to bottom-line results rather than predetermined course material. If analysis shows that training is not the solution to a performance deficit, trainers can help find other cost-effective solutions.

WHAT IS TRAINING?

A trainer's real job is to identify deficiencies in skill and knowledge sets that could cause poor performance or nonperformance and correct them as quickly and inexpensively as possible. Training is *not* presenting a set curriculum via prespecified methods to groups of people identified by administrative policies and procedures. Rather, training provides the information people need to do the organization's work, when and where they need it, in ways that can be easily assimilated and put to use.

Of course, each participant should be expected to demonstrate that they have mastered the material, and each training class on a topic should match others on the same topic. Supervisors also should monitor employees' work to ensure that they are implementing what they learned.

Outside authorities may issue requirements that conflict with the local approach to training. This is particularly true of safety training, where state and federal safety agencies often dictate periodic repetition of many topics and local legal counsel may require retraining for various reasons. These variances are typical at governmental or quasigovernmental organizations, and training personnel routinely accommodate them.

Sometimes repetition of training can be useful. For example, periodic "refreshers" on key duties can help keep people sharp. If an important part of the job is only done during one season (e.g., cold-weather operations in northern states or rainy-season-flow emergencies in southern states) retraining may be the only workable solution. This kind of repetition is valid training, because skills will lapse through disuse during the seasons when they are not needed.

THE TRAINER'S ROLE

Trainers are vital to utility operations. They may simultaneously implement new administrative policies, help test and start up new facilities, create new work methods for existing jobs, maintain a central compendium of job-related information, introduce new people to the workplace, determine soft-skill training needs, and prospect for outside trainers to meet them. The job requires range and versatility, as well as freedom within the organization and administrative support.

Too often, training is assigned to the person who is most proficient at a given job, who may or may not have the skills needed to train others. This approach works well for straightforward tasks that can be taught via demonstration. However, the most skilled person may not communicate well with trainees, and ongoing personal relationships also may affect the results.

Trainers should be proficient at the specific job or able to learn it from experts. They should know how to organize a presentation and adapt it to their trainees' abilities while delivering it.

THE TRAINER AS SURGEON

Surgeons do not outline the hospital's food-service menus, sterilize laboratory equipment, or administer daily doses of medication. They perform a specific set of functions—ones only they can do and have experience with. Surgeons are not called on to do things outside their area of expertise, but are the only ones considered when a patient has internal problems to correct.

In an ideal organization, trainers look for deficiencies in employee performance and devise ways to improve them. The goal is to make the entire organization work better by finding and fixing specific problems. This organization does not use trainers as a substitute for managerial solutions, but over time, finds it has fewer management problems because people are more confident and motivated on the job. The problems that may have prevented them from performing well (or even rewarded poor performance) are disappearing and the entire workplace functions more effectively.

Just as surgery is not the solution to all of a patient's problems, trainers may be vitally important in solving some performance deficiencies and irrelevant in correcting others.

WHEN TRAINING WILL SUCCEED— WHEN TRAINING WILL FAIL

Training will succeed when given as close to the actual need as possible. If delivered so far in advance that the participants will not retain the information or cannot see an immediate advantage, it will fail. If given so late that the participants already believe they know the material, it will fail.

Training will succeed when the material is fresh and new. It will fail when it duplicates previous training.

Training will succeed when it addresses one topic. It will fail when it attempts to cover multiple topics at once.

Training will succeed when the participants believe the new material will help them do a better job or make the job easier by solving a problem, teaching a useful new technique, or otherwise improving life in the workplace. If participants think the training has no immediate payback, it will fail.

Training will succeed when responding to participants' need for skills and knowledge that they currently do not have. It will fail when it is a substitute for more appropriate forms of performance feedback or punishment for a job failure.

In other words, training will succeed when it gives the participants an immediate advantage on the job (e.g., training on new facilities, process equipment changes, policy changes, and safety). If the topic has no immediate benefit and does not address a known deficiency, it will fail.

Trainers can help ensure training success by ensuring that participants know from the start that their needs will be met. They should begin by explaining why the training is being given and what advantages it will provide in the workplace.

PROGRAM DEVELOPMENT

When developing a training program, trainers should consult both rank-and-file employees and subject-matter experts.

Logically, the first step in developing a training curriculum is to break down every job into its overall responsibilities, then into individual duties, and then into the specific steps to follow when performing those duties. Once the job analysis, task analysis, and standard operating procedures are completed for every aspect of every job, train-

ers would develop a training package for each job and deliver it to everyone who may be required to perform those duties. However, at wastewater utilities, the analysis and procedural development alone could take years, the delivery more years, and maintaining the file library required for it would be a bureaucratic nightmare. One large wastewater utility began such an effort in 1993, only to discover that it would take more than 8000 work hours just to develop the procedures for plant operations alone. If that program had been continued, the utility would have discovered that, once the training was finished, much of the material would seldom be needed. The program would have been valid, but too cumbersome to use in the real world.

Training needs to be more practical. A project-based training system is simpler and more valid because it delivers the training that is actually needed, when it is needed, and in the form that is most effective for the subject matter.

This is not to say that other methods should be excluded. Each has its place, and the emphasis should be on using the most practical methods available for any part of a training program. Although the emphasis should be on project-based training, sometimes general training may be necessary. For example, when operators are preparing for state certification tests, necessarily the training is based on a curriculum because the required topics are known in advance and everyone must learn all the material whether or not it is relevant to their facility.

PROGRAM ELEMENTS

No two training programs are alike, but there are elements common to all. Among these are the basic methods and approaches proven successful in training adults, the policy and procedural documents developed before training is given, skill verification after every training, and the use of onsite expertise when developing both training and procedures.

BASELINE. The initial introduction to utility rules and practices that all new employees receive no matter what their job duties, may or may not be part of the training program. For the purposes of this chapter, operations and maintenance training begins by introducing employees to specific equipment and how it operates. This is an area in which peer training can be particularly valuable, though most larger utilities develop a system in which trainees are initially supervised by a trainer. This training enables new employees to have direct, hands-on experience with the equipment in a setting that does not require adherence to specific routines. Either individually or as a group, they will learn startup, shutdown, control methods, and other duties (e.g., sampling and reporting).

An easy way to outline this new-hire program, while giving ownership to experienced employees, is to do the following:

- Call together a group of employees for a 30-minute meeting, preferably without a supervisor present. Bring the following tools: a marker and either paper and tape or a self-sticking note pad.
- Ask someone to name any job duty, write it down, and then stick the paper to the wall.
- As other duties are named, write them down and stick them up too. At the same time, ask for the main parts of each duty. For example, after the plant headworks is named, notes for bar screens and grit chambers would be placed below it. More specific duties (e.g., clearing grit piping) would be placed with the grit chamber note.

An outline will emerge and be fleshed out so rapidly that a second note-taker may be needed.

After the session, put the outline on paper and ask a lead worker or supervisor to review it and note any details that may have been missed. Invariably, this outline will be a list of every job duty that a new person needs to learn, produced by the people who know the job best, and every item on the list can be taught peer-to-peer in the plant.

This technique can be used to outline any job in the organization, including those of its board of directors.

SAFETY. Safety cannot be handled simply or by a person who is not thoroughly versed in both safety methods and the applicable state and federal laws. The legal consequences of an on-the-job injury or death are too great to allow anything but the utility's best effort. At the very least, the training should be developed and delivered by skilled vendors who specialize in safety training.

Following are some of the topics that a comprehensive safety program might include. A safety professional will add others that are plant-specific.

- Safety and health policies;
- Basic safety and health for wastewater professionals;
- First aid and cardiopulmonary resuscitation;
- Wastewater hazards;
- Industrial hygiene;
- Respiratory protective equipment;
- Hand and power tool safety;

- Fire prevention and control;
- Accident and illness reporting;
- Accident investigation;
- Hazardous energy control (lockout-and-tagout) procedures;
- Confined space entry;
- Safe work permitting procedures;
- Emergency response;
- Safety for hydrogen sulfide and other gases;
- Chemical handling;
- Hazard communication and labeling (material safety data sheets);
- Hearing, eye, and face protection;
- Right-to-know laws for employees and the community;
- Housekeeping and safe equipment storage; and
- Electrical hazards (e.g., hot work and basic awareness).

For more safety information, see Chapter 5.

OTHER. While baseline training and safety are the two largest concerns, an overall training program also may include the following:

- Cross-training and rotational job assignments.
- Individual training goals for employees seeking to advance into other positions in the utility.
- Professional organizations (e.g., the Water Environment Federation and its state and local affiliates). Many utilities pay employee dues for participation in such organizations.
- An operator certification training program, either locally developed or using the accredited certification training courses available in most states.
- Formal education, which can be limited to courses brought to the plant or extended to local colleges and regional occupational programs.

THE TRAINING SYSTEM

Training begins with management. A system must be in place to manage training development, maintain complete records of every employee's training, and allocate training resources (money and time) throughout the organization.

People matter; the policies and procedures for developing and delivering training are as important as those for operating and maintaining the plant. These standards

should include organizing and maintaining training materials and courses, and standard formats for training documents (e.g., work procedures, lesson plans, certifications, qualification guides, and attendance rosters).

Many organizations now find that training has become such a complex discipline that they need training information management software. Such software can allow small and large utilities to manage their training programs efficiently and maintain all the necessary employee-development records.

Just as a critical assessment of a training session helps to improve later classes, an audit of the training program can help identify its weaknesses and strengths. Such audits should be done periodically (typically at 5-year intervals). An audit will include an overview of the personnel and money allocated for training and how it is divided among the utility's departments. Auditors will scrutinize the methods and standards currently in use and attempt to gauge the utilitity's satisfaction (or dissatisfaction) with the program. The audit may also include benchmarking visits to other utilities to see their training facilities and compare them to those of the utility being audited.

CHOOSING TRAINERS

The best trainer is not necessarily the one who knows the subject best (although subject-matter experts should be part of the training development process). Just as architects probably would not write travel brochures for the hotels they designed, subject-matter experts are more likely to be resources for the trainer rather than trainers themselves. In today's workplace, when a training need is identified, the trainer will seek appropriate experts inside or outside the organization and mold their knowledge into an effective package.

Formally educated trainers tend to have certain characteristics in common. For example, versatility—the ability to gain competence quickly in unfamiliar surroundings—is very important. A modern trainer must adapt to new developments in the workplace, because technology rapidly changes the nature of the job. Versatility in delivery is also necessary. A class can be turned from failure to success by the trainer's ability to alter the presentation while giving it so it better matches the needs and expectations of a particular group of participants. Technical competence is highly desirable in a technically complex workplace (e.g., operations and maintenance work). Experience in the organization helps give potential trainers familiarity with existing systems, personnel, and methods.

TRAINING DOCUMENTS

Hard-skill (and most soft-skill) training is pointless if the presentation is not backed by descriptive documents. In a complex work environment, participants simply cannot

retain all the information that is pertinent to the job, and these documents provide both reinforcement and references.

Consider, for example, a newly installed activated sludge influent pumping station with variable-speed drives, a constant-speed backup pump, and controls that can govern pump operation via wet-well level, flow, or manual adjustment. It has local and some limited remote control, plus automated alarm and emergency shutdown sequences. Power is available through the plant grid or from a backup generator that can autostart or be run manually. Operators must be able to "black start" this station, run it in any mode, switch between modes or shut down as needed, and recognize the conditions that trigger each activity. Years from now, incoming personnel will need to attain the same proficiency.

Because no one, including the trainer, knows how to operate this station, the utility must create an operating manual and specific operating procedures for every activity associated with its operation. It would be impossible to develop meaningful training for the station without them. After startup, these documents will serve as a reference that will guide operators for as long as the station exists. Training for the maintenance staff will require the same level of diligence and its own backup documentation.

Also, all contents of training presentations and documents must be official requirements of the organization, backed by management approval. If the organization does not have a stated policy or procedure for the training subject (especially those with potential for equipment damage, personal injury, or resulting public hazards), the trainer may be held legally liable for any negative results. No trainer should have to accept that level of responsibility, and no organization should require it.

POLICY. ***Definition.*** A policy is an administrative document governing a single phase of a facility's, department's, or work group's operations. It outlines management and workplace practices, sets performance expectations, assigns responsibilities, and describes the processes to be followed in fulfilling them. A policy should deal with one particular topic—not a range of topics. If more than one topic will be addressed, a policy should be written for each. Policies must be easily recognizable, clearly written, and well-organized. A written policy may have legal implications, so it should not be open to misinterpretation and released only after administrative approval.

Content. Almost any written policy must include the following items:

- Title,
- Issue and revision dates,
- Summary,

- Purpose,
- Objectives,
- Definitions,
- Criteria and constraints,
- Enforcement and penalties,
- Statement, and
- Authority.

A given policy may not require all these items, but the following guidelines should be considered when composing policy and all required items should be included. Minimum standards would require the title, applicable dates, purpose and objectives, policy statement, and issuing authority. (The headings shown in this section are used for demonstration purposes only.)

Title. The title is short, preferably five words or less. It describes the policy and should include any policy numbering system in effect. A revision number should be added when applicable.

Issue and Revision Dates. The policy must be dated, because some are issued before their effective dates. If the issue and effective dates are not identical, however, the effective date should be included in the text.

Summary. The summary is a concise description of the policy, intended for executive use. It is equivalent to the executive summary in a staff report. This item should only be included in extended policy documents.

Purpose. The purpose is a statement listing the reason(s) why a formal policy is necessary. For example, "These written policies should increase our mutual understanding of [utility] expectations, minimize the need for personal decisions on matters of [utility-wide] policy, and help to assure uniformity in program administration."

Objectives. Each objective should be a simple, declarative sentence (in active voice) stating what the policy is intended to accomplish. If a policy has several objectives, they should be written as a list, and each objective should begin with an active verb. For example, "This policy is intended to do the following:

- Establish parking enforcement authority within plant boundaries,
- Designate parking areas for each employee group,
- Provide guidelines for the use of handicapped parking spaces, and
- Delineate zones for rideshare parking."

Definitions. Any terms that are not in common use should be identified and defined. For example, "*Sunset*—a provision that limits the effective life of a policy by providing a specific end date or other terminating criteria, such as the end of a construction project."

Criteria and Constraints. Criteria and constraints explain when the policy is in effect and when it is not. They also should list affected departments or employee groups, as well as any limitations, special cases, or exclusions. Following are examples of criteria and constraints:

- Criteria: "This policy will apply to selected employees who have completed more than 15 years of service, without respect to age, health, or job position. It will not apply to employees who have already retired or who have filed retirement documents."
- Constraints: "This policy will apply to laboratory personnel and operations personnel taking samples from plant process streams."
- Limitations: "This policy will not apply to contract personnel doing approved work on agency property."
- Special cases or exclusions: "Employees currently under disciplinary suspension are not eligible for the early retirement option."

Enforcements and Penalties. Monitoring requirements and noncompliance penalties should be clearly stated. For example, "Employees violating this policy will be subject to disciplinary action by the agency, including, but not limited to, termination of employment."

Statement. A policy statement describes the process to be followed to fulfill the policy, including any details required to clarify the utility's intentions. Delegations of responsibility and authority should be made clear (to departments and job positions, not to individuals by name). For example, "The senior operations supervisor will have the power to set work schedules for plant operations personnel, under direction of the chief operator."

Also, the required compliance standards should be given. For example, "Results of the calculation will be expressed in standard engineering units."

Reporting responsibility and frequency, along with a description of the reporting process, should be included. For example, "The operations engineer will develop plans to train supervisors in all areas of the plant and will submit an outline and recommendations to the director of operations in December of each year."

The specific policy requirements should be stated. For example, "Employees may not copy or duplicate, or permit anyone else to copy or duplicate, any physical or magnetic version of the computer programs, documentation, or information ."

All critical dates should be included. If there are sunset provisions [review dates, expiration dates, or other criteria (e.g., completion of a project or issuance of another document)], these should be included in the text. Also, the effective date should be provided. For example, "This policy's limitations on aeration deck access will be terminated upon completion of the P1-36-2 construction project."

Any new policy statement may affect or even eliminate existing policies. Any necessary eclipse provision for other affected policies should be included; if other policies are changed or eliminated, this should be made clear. For example, "Any policy issued previous to this statement, or any portion thereof, which conflicts with this document, is hereby repealed." or "This policy supersedes Policy SP-003, 'Use of Respiratory Protection Equipment by Agency Employees'."

The administrative authority under which the policy is issued should be stated. A policy is not valid without the organization's sanction. The person under whose authority the policy is issued must sign the final draft of the policy statement.

PROCEDURE. The procedure is an organized set of instructions used to accomplish a particular task. The task may be as simple as the series of calls to be made and information taken if an odor complaint occurs, or as complex as black-starting an activated sludge plant. The hallmark of a procedure is its limitation to the completion of a single item. Related items are handled in separate documents.

Procedures are written in active voice, with direct instructions on performing each step. Conditional references (e.g., "could", "should", "may", and "ought") must be avoided; these steps are mandated, not suggested.

A procedure should include the following items.

Ordination. The ordination should include

- The procedure name and reference number (and revision number, if appropriate);
- The effective date and latest revision date; and
- The signature of the responsible manager (keep this signed document as a legal requirement of the organization).

Purpose and Scope. This is a succinct statement of why the procedure was written and the exact circumstance it is meant to cover. This should be no more than one or two sentences.

Definitions. Any term, title, or organization that a competent but inexperienced person may not know should be defined.

Responsibilities. This is a listing (by position or department, not individual name) of the exact responsibilities that everyone affected by the procedure will have. If an entire

department is affected, it and all affected positions should be listed. This includes a statement of the utility's expectations for action by outside organizations.

Procedure. This is a chronological, extended outline detailing each step, from the initiating event (phone call, alarm, supervisory decision, etc.) through the final disposition of all people, materials, and necessary documentation. However, if any stage of the procedure includes safety considerations, they must be stated before that portion of the procedure so personnel will be prepared.

References. The references should include the titles of all regulations, policies, or laws that reasonably have a bearing on the performance of the procedure or that may have created the need for it.

Attachments. Items that may help staff perform the procedure (e.g., sample documents, maps, blueprints, and contact listings) are included in the attachments.

OPERATING MANUAL. The operating manual is a compilation of information on primary equipment or unit processes, with all the policies and procedures needed for both normal and irregular operations. The following list of items is commonly, but not necessarily, included. An operating manual should address the topics needed to provide a complete operational guide for the equipment or process.

(1) Unit description
   (a) Basic process principles
   (b) Operational features
   (c) Capacities
   (d) Location
   (e) Utilities
   (f) Drawings or schematics
(2) Relationship to adjacent units
   (a) Influent sources
   (b) Effluent receivers
   (c) Byproduct removal
   (d) Effects on overall process
(3) Classification and control
   (a) Mechanical operations
   (b) Basis of control
   (c) How control is exerted
   (d) Automatic changes

(4) How equipment responds to conditions
  (a) Standard conditions
  (b) Operator changes
(5) Items that are operator-controllable (how to make control changes)
(6) Major components
  (a) Tanks, piping, channels
  (b) Robotic functions (conveyors, flights, sweeps, etc.)
  (c) Control panels
  (d) Motors and drives
  (e) Chemical systems
(7) Chemicals used
  (a) Schematics and isometrics
  (b) Auxiliary systems
(8) Common operating problems (troubleshooting)
(9) Laboratory controls
  (a) Samples
  (b) Expected quality control results
  (c) Quality control during startup and shutdown
(10) Startup and shutdown
  (a) Black startup
  (b) In-service startup
  (c) Emergency shutdown
  (d) In-service shutdown
  (e) Isolation and lockout
(11) Normal operations
  (a) Recommended rounds
  (b) Expected readings
  (c) Standard settings (gates, valves, switches, etc.)
  (d) Making process adjustments
  (e) Safety
(12) Alarms
  (a) Alarm conditions
  (b) Alarm points
  (c) Where alarms are received
(13) Alternate operations
  (a) Emergency operations
  (b) Secondary operating modes
  (c) Methods for changing modes
  (d) Fail-safes

OTHER DOCUMENTS. A simple job aid that can make life easier in the workplace is a "picture procedure"—a printed document posted at the work site. It provides both written instructions and pictures of an individual performing the major steps of the task. A well-done picture procedure can take the place of some training and eliminate the need for refreshers. It places a visual reminder at the employee's disposal, exactly when needed. Some agencies laminate, frame, and hang these documents permanently at the equipment site.

TRAINING TYPES, ISSUES, AND STYLES

There are several styles of training, and no one method works well in every situation. Also, no matter what the method, the agency must provide sufficient resources and time for the trainee to complete the training.

INSTRUCTOR-LED VERSUS SELF-PACED. The most basic choice is whether to have an instructor deliver the training or create a package—either online or a printed document—that will allow participants to train at their own pace. This sounds like a simple choice, but it is not. Using an instructor to deliver training better controls the training process, but takes personnel away from other duties for set periods of time and creates other scheduling problems (e.g., makeup presentations and training for new employees).

A self-directed training package overcomes these problems, but may create others. If an instructor is not present, the training package must contain all the information and reference materials that the trainee will need. This means many hours of preparation for even a simple package. However, once created, the package can be used by large numbers of people and kept as a resource.

Self-directed training can be an excellent tool for specific technical material presented to a large audience (e.g., a new air-monitoring device that will be routinely used in several ways by plant operators and maintenance workers, confined-space entry teams, laboratory personnel, outside construction crews, and air-quality workers). Proper training is a vital safety concern, and staff changes would require many classes to be given later. So, a study package that employees can use at their own pace, and a qualification guide that can help supervisors verify that employees know how to use the equipment properly enables training to be handled without formal classes.

SITE-SPECIFIC VERSUS VENDOR. A training vendor is an individual or company that develops and sells training packages on various topics. Because this training is sold to multiple buyers, it must be general and has limited use in operations or maintenance training. Some training (for the most common types of equipment) can be

purchased this way, but typically vendor training is best for soft skills, which are more applicable to the utility's office workers.

In the plant, there is no substitute for site-specific training developed onsite, and delivered when needed. A vendor may be able to develop such a package with supervision, but typically this training will be created and delivered by utility staff.

For new facilities and equipment, the equipment manufacturer can be another valuable source for training. This training must be adapted to the facility and the utility's own operating requirements or supported by locally developed training containing this information.

PEER- AND SUPERVISOR-GUIDED. The differences between peer- and supervisor-guided training are real but not large. Each can be a real asset, but neither is a cure-all. If a supervisor is doing the instruction, there is the advantage of authority and familiarity with the participant, but there may also be frictions from other sources that carry over into the training session and mar the result. With peer training, personal relationships and the trust of an equal are big advantages; however, because the trainer is an equal, the lack of authority can sometimes lead to trouble.

This type of training is useful but cannot be allowed to proceed piecemeal. The utility is responsible for the outcome of this training, as it is for any other. The peer trainer or supervisor should be provided with all needed reference documents and performance guides that will be completed and retained as part of training-program documentation.

INTERVAL-BASED. Training repeated verbatim, year after year, is rarely effective. So, interval-based training is not recommended, because it invariably leads to training people who already know the material, damaging morale and leaving participants with a nonchalant attitude toward the overall training process. Remember, training should improve work performance in areas where the job is not done well because of something the workers do not know. It should not be done merely to put a check mark in an employee record.

Unfortunately, most state and federal requirements—particularly safety requirements—do require retraining at stated intervals, and utilities must comply with them.

AD HOC. This is a brief (30 minutes or less) class developed on short notice in response to a new, important piece of equipment or change in utility work methods. Sometimes called a "tailgate training session", its goal is training key personnel on a relatively simple topic quickly.

CONSTRUCTION. Construction training is often the most difficult to arrange because it involves new facilities. Design specifications should call for training on installed equipment, for every affected department. The contractor should provide the initial operations and maintenance manuals in cooperation with the facility's design engineer. However, this training is not equipment-specific; the overall facility is a training challenge of its own. Staff also must verify that every operating procedure provided by the manufacturer works under local conditions using the actual equipment installed. This verification is part of normal startup procedures, and includes the trainer as an active participant.

BASELINE. Baseline training is given to new hires to bring them up to basic competence. It should be maintained as a separate package and updated as changes in equipment and procedures are implemented. This training is curriculum-based because there are basic duties that every new employee must learn. This is the area in which peer- and supervisor-guided training can be most effective.

THE JOB AS A TRAINING FACTOR

Operations and maintenance staff face opposing sets of job stresses, which the trainer must take into account when developing and delivering training. Although largely hired and largely promoted based on their ability to recognize and respond to breakdowns and emergencies, operations and maintenance staff have job duties that are mostly routine. An operator may make the same checks on a piece of equipment and observe the same readouts from its instrumentation for years before a problem occurs. These people are justifiably proud of their ability to maintain this kind of vigilance and to use virtually all of their senses as tools of the trade, but such routine takes its toll and eventually can lead to fatigue and burnout. At milder levels, it may reduce the resources an individual has to invest in a training session.

SHIFT WORK. The job itself places constraints on training. Ten- and 12-hour shifts are now common, and round-the-clock operation means people must work through the night. Longer shifts and night shifts mean more fatigue, particularly at the end of a workweek, and less tolerance for any training that is not directly job-related. Scheduling training during the appropriate shift helps but is often impractical because of the hours and expense involved. Also, staffing may be too thin to break people free for extended training, even when it can be delivered during their shift.

Shift work also means staggered days off, which further limits the days when training can be scheduled. Staffing limitations can be a psychological barrier to training because employees do not want to leave their colleagues shorthanded. While this sentiment may be commendable, the result is not.

The plant also can be an impediment to certain kinds of training. Process equipment must run and be monitored 24 hours per day, and operators must respond to any irregularities, despite other scheduled activities. Training is further constrained by work rules that discourage the use of overtime to cover training.

These roadblocks cannot be eliminated, but their effects can be reduced by keeping training sessions short, holding them onsite whenever possible, and giving makeup classes.

SPECIALIZATION AND SKILL STRATIFICATION. As wastewater collection and treatment facilities incorporate modern operating techniques, department sizes will change. This restructuring can lead to skill stratification, particularly among operators. Such strong variations in skill and knowledge levels within a work group can reduce the organization's ability to adapt to further changes but increases efficiency in the short term. Stratification stems from three causes.

First, reducing the overall group size can lead to specialization and a tendency to make the day shift the central talent pool and carrier of most responsibilities. Then, the off-shifts are considered caretakers whose duty is simply to maintain the operational status quo. This changes the organization's expectations of each group's performance and estimation of their training needs and job-mastery requirements.

Second, larger facilities tend to create area work teams that each focus on a specific process area and the related job skills rather than maintaining proficiency in all areas of plant operation. While area work teams improve overall plant performance in the short term, they promote specialization and change each individual's perceived training needs. Team members gain some skills and lose others.

Third, reinvention often results in "department hopping", typically from maintenance operations. Maintenance specialists enter operations with highly developed skill sets that often can be directly applied to operations work and that experienced operators often lack. So, a trainee may be precociously effective at certain aspects of the work, outperforming his more experienced colleagues. Such individuals will bypass their experienced coworkers because of skills and knowledge that the "old hands" have not had the opportunity to acquire.

It is a trainer's duty to see such trends and find ways to minimize their negative effects and optimize their positive ones.

POSSIBLE SOLUTIONS. Individually, any personnel and job-related constraint can be overcome without a debilitating effect on the training program. Collectively, however, they can be problematic. To keep training effective, trainers should do the following:

- Train only in response to a clear and immediate need;
- Help managers assess and solve organizational problems;
- Limit training to topics that will give the trainee an immediate advantage on the job;
- Avoid duplication;
- Keep sessions brief and informal;
- Make maximum use of hands-on training;
- Keep groups small and provide as many makeup sessions as the training budget will allow;
- Focus on quick, familiar training methods and easy-to-use job aids;
- Carefully screen trainers and their training plans before approval;
- Obtain as much rank-and-file participation in session content and planning as time and security will allow;
- Present policy-related training as help for the employee, not as a "decree from above";
- Provide training during a shift when it offers a clear advantage;
- Offer maintenance training to operators;
- Include as many off-shift personnel as possible in all training opportunities;
- Give training in the plant whenever practical; and
- Create and maintain a practical, positive image of the job and the training organization.

TRAINING DESIGN AND DEVELOPMENT

The following rules should be followed in training design and development:

RULE 1. Train only in response to a clear and immediate need. Avoid the trap of delivering training that is not supportable by routine training analysis. Such training may be a substitute for supervisory remedies or a previously established, repeating schedule that does not reflect current training needs. Training time is too valuable to be wasted on unnecessary classes.

RULE 2. Decide whether training is the proper response to the perceived need. While not completely independent, trainers must have enough control to be able to insist on

training when needed and refuse to provide inappropriate training. Because trainers analyze perceived needs as if they were outsiders, they can help the organization's managers find appropriate solutions, even if they do not involve training.

RULE 3. Use practical methods. Training technology can be an integral part of a program's success or a needless expense. Trainers should stay informed of training-technology developments and use the most cost-effective methods that are appropriate to the subject matter.

RULE 4. Training builds skills and knowledge; it does not solve organizational problems. Trainers can be a helpful observer and resource in situations that do not lead directly to training, but training cannot substitute for necessary changes in supervisory or management practices.

ASSESSMENT TOOLS

Training assessment often reveals the need for management changes. In these instances, trainers may help supervisors deal with the problem but typically will not have the authority to make or enforce policy changes. When training is needed, the exact need should be defined so training can be developed simply and logically.

Following are some common methods used to determine whether a performance problem can be repaired by training or if another solution may be more appropriate.

First, trainers should ask the following question: Could the employees in question do this if they had to? If the answer is "yes", then training is not the answer. Something in the workplace is rewarding poor performance or nonperformance. This situation could be caused by one of the following reasons:

- Employees may not have the opportunity to do the task often enough to stay proficient.
- Poor intrastaff relationships or attitudes could cause job duties to be left undone.
- There may be no visible consequences for doing the task poorly or not at all. "It does not matter" is a perfect excuse for inaction.
- Supervisors may not be responding adequately to substandard performance, or working with employees who need coaching.

These situations cannot be corrected by training. If attitudes are the problem, training may actually make things worse by temporarily masking the real source of the trouble.

If the answer to the first question is "no, they would not be able to do this if they had to", answer the second question: "Are they willing to do the task?"

If the employees cannot do the task and are willing to learn how, arrange for either training or coaching by the supervisor or lead worker, depending on the severity of the problem and the number of people affected. Adults in a workplace seldom refuse or resist job duties without a reason. If members of the group cannot do the task and are unwilling to learn how, find out why. Training will fail if the resistance is not eliminated first. Following are some possible reasons for such resistance:

- Attitudes. Some individuals may have poor attitudes toward the task or the job in general. If the attitudes are culturally based, training will not solve them; the only solution may be to excuse those people from doing the task or reassign them to other jobs. Alternatively, the group may feel strongly that the task should be done by someone else, not the group to which it has been assigned. Do not automatically reject this thought; they may be right.
- Poor supervision. Supervisors may disagree on how, or whether the job should be done, causing confusion and discord among the staff. Follow-up on poor performance may be weak, inconsistent, or overly harsh. This may indicate that supervisory training is needed, rather than skill training for the rank-and-file employees.
- The task is not valued. If doing the task poorly or leaving it undone does not have negative consequences, perhaps it does not need to be done at all, and the whole staff knows it. Inspect the advantages and disadvantages of the task, and work with supervisors to eliminate it if unnecessary. If a task needs to be performed, the trainer's first job may be to teach the employees why and then teach them how, if necessary.
- Built-in resistance. Something in the overall job duties may cause resistance to this particular task. For example, it may be so time-consuming that more important duties cannot be done properly, or it may negatively affect another part of the operation.

TRAINING ADULTS: IT IS NOT A SCHOOL

Adults learn for different reasons than children, and they learn in different ways. While a child may learn for the joy of it, most adults do not. The typical adult approaches a training situation with one goal: to ease some aspect of the job that causes distress or makes the participant feel inadequate. Something affects that individual in an immediate and perceptible way, and he or she is there to fix it.

Because training is geared toward adults, they will have little interest in training to maintain skills unrelated to their current problem(s). This is not lack of motivation or poor attitude; it is simply a facet of the adult mind. So, each person in every session must be reminded how the material will make work-life better for the person who learns it and puts it to use.

THE IMPORTANCE OF VERIFICATION

Until a new skill can be demonstrated, it has not been learned. This fact has several ramifications for both participants and the organization in which they work.

Demonstrating new skills or knowledge gives an individual immediate confidence and a strong impetus to use them. This obviously helps the organization by increasing workplace efficiency and safety, and it improves the individual's attitude toward the job. Employees who know they can do their jobs well are happier and more motivated than those who have reservations about their performance.

For the utility, skill verification lets supervisors know that their crews can do what is needed. Also, if an operating error results in damage or injury, there may be serious financial and even criminal liabilities if the utility cannot show that those involved were fully competent.

A simple step-by-step qualification guide can eliminate such negative outcomes, help ensure positive ones, and serve as a checklist of employee skills. Rather than repeating classes periodically, employees can work through the related qualification guide with a supervisor or instructor and demonstrate competence without wasting job time and training expenses. In a classroom, the qualification guide could be a written quiz that covers the central points of the class. In the field, it could be a simple checklist of skills that the employee would demonstrate in a "dry run". Each guide should be dated and signed by both the participant and the trainer when the test is complete.

While it may be simple, the qualification guide is a vital record. It should be kept on file along with other important employee records.

THE IMPORTANCE OF TIMELINESS

The importance of timeliness cannot be overstated when dealing with an adult workforce. Training that is forgotten before it can be put to use is wasted and could damage both equipment and workplace morale.

Even worse is training given after workers have groped their way through hands-on learning of unfamiliar systems. Aside from the obvious problems of potential equipment damage and personal injury, they must unlearn bad practices and replace them

with correct operating procedures. This will never completely succeed, and the negative effects may last for years.

It is difficult to develop and deliver "just-in-time" training, but the rewards are clear. It is particularly hard to provide this kind of training in a new facility or process, where nobody has full knowledge of or experience in using it. Trainers must work with available resources and be full participants in the activities of any startup team assigned to work out proper methods.

ANALYSIS, NOT PARALYSIS

If not carefully governed, the analysis portion of training development can be wasteful and time-consuming. Many utilities have had their training programs grind to a halt while training personnel performed increasingly detailed task analysis of every facet of every job. A practical look at the level of detail required can avoid this problem.

Training development takes as much analysis as that used to create standard operating procedures for trained personnel on the job. The same people do both tasks, and need the same level of support for each. The target audience in each case is an intelligent employee competent in using other plant equipment but unfamiliar with the equipment in question. The level of detail that will let such a person work through the task is appropriate for both procedure and training development.

WRITING OBJECTIVES

Training objectives are deceptively simple. An objective is a statement specifying the task that the participant will be expected to be able to perform after the training (i.e., "At the end of this training, each participant will demonstrate the ability to . . ."). Objectives are written in the same form every time to facilitate their use in developing training and to help ensure that each is appropriate. Each objective describes only one item, not a list of related items, and notes the level of competence expected. If a percentage of correct performance is required, it should be stated in the objective.

Objectives are the first thing written when creating a training package. When the training package is completed, the performance guide or examination should be written directly from the objectives. This ensures that the objectives are met, and it helps the trainer confirm that the training document is complete.

BLOOM'S TAXONOMY

During the late 1940s and early 1950s, B. S. Bloom organized and described the levels of cognition that are part of learning (Table 16.1). These levels proceed from the most

TABLE 16.1 Bloom's taxonomy guidelines.

Level	Definition	Sample verbs
Knowledge	Remembers previously learned material; recalls or recognizes information, ideas, and principles in the approximate form in which they were learned.	Write, list, label, name, state, define, describe, identify, and match
Comprehension	Grasps the meaning and explains or interprets the material; predicts outcomes and effects; estimates trends.	Explain, summarize, paraphrase, describe, illustrate, convert, defend, distinguish, estimate, generalize, and rewrite
Application	Applies learned material to a new situation; uses rules, methods, theories, or principles to complete problems or tasks with little direction.	Use, compute, solve, demonstrate, apply, construct, change, compute, operate, and show
Analysis	Understands the organization of material and the relationship of its parts; makes independent conclusions and hypotheses.	Analyze, categorize, compare, contrast, separate, distinguish, diagram, outline, relate, break down, discriminate, and subdivide
Synthesis	Combines and integrates learned ideas to create new products, plans, or proposals.	Create, design, hypothesize, invent, develop, combine, comply, compose, and rearrange
Evaluation	Appraises, assesses, or critiques on a basis of specific standards and criteria, judges relative values, and supports conclusions with facts.	Judge, recommend, critique, justify, appraise, criticize, compare, support, conclude, discriminate, and contrast

rudimentary learning (recall of facts) to the most complex (evaluation and assessment based on derived standards and criteria).

When analyzing a potential training package, trainers should first assess the level of mastery required to do the portion of the job covered by the training. Then, they should write appropriate training objectives. By incorporating Bloom's sample verbs into the

written objectives, trainers can easily define the competency level that will be achieved. For example, if the application level is desired, an objective might read as follows:

"At the conclusion of this training, each participant will demonstrate the ability to:

- Compute digester efficiency, given laboratory analyses of volatile and non-volatile solids."

If the knowledge level is desired, the objective might state:

- "List the readings taken during rounds of the gas compressor building."

PITFALLS

Many pitfalls can harm, or even doom, a training program. Following are the most common and the most serious.

DUPLICATION. Duplication can creep into a training program in several ways. Most common is simply lax development. If an agency uses a particular type of equipment in several parts of its plant, staff do not need to be trained on that equipment in every instance of its use (including new installations).

Another form of duplication involves multiple topics centered on one piece of equipment. It may be necessary to teach the operation of that equipment once, but not repeatedly for every new operation that requires its use. Only the new material should be taught.

REPETITION. Repetition is a drag on a training program. Many utilities require personnel to be trained at stated intervals (typically every year) on the operation or maintenance of certain equipment. This sounds good, but it is not. For example, participants have been pulled in for training on the operation of equipment that they would have been using successfully had they not been interrupted by the training. Such an occurrence may amuse those with an eye for irony, but it damages the training program.

Interval-based training is a grossly inefficient way to run a training organization and should be eliminated wherever possible. One way to achieve the same effect is to use the qualification guide that was part of the original training package. A trainer or lead worker can take each employee through the guide and fix any performance deficiencies on the spot. This eliminates the need to take time off the job for unnecessary training.

SCATTERSHOT. Fighting brushfires can render a training organization ineffective. While trainers must respond quickly to some training needs, such responses must not

become a pattern that will eventually choke off productive activity. If trainers spend their time responding to one emergency after another, they will not be able to push the program forward. Items start to be handled as training issues, that simple analysis—had there been time for it—would have indicated they were not training issues.

This overload leads to more emergencies, as items that would have been scheduled and developed normally are pushed back until they too become emergencies. In the end, the utility sees its training organization as a response to random emergencies, not a structured group moving toward a goal. When this happens, the training organization ceases to be an asset to the utility and may stop being an organization at all.

FAILING TO LEAD. Leadership is necessary and difficult. This is especially true when training has been done for a long time without any overarching plan. Department leaders are accustomed to having their needs met without question and will not respond well when a trainer says "no" to a training request. Nonetheless, to meet the utility's needs the training organization must be able to refuse a request and to insist on training over management disapproval.

Trainers should be free to identify and assess training needs, deliver training when and where needed, and refuse to let training be used as a substitute for more appropriate solutions to the utility's problems.

SUBSTITUTION FOR MANAGERIAL REMEDIES. At least 50% of the training at typical utilities is unnecessary, and some of it aggravates the very problems it was intended to correct. This is because training is often used as a substitute for more appropriate, but personally unpleasant, managerial action. If an employee (or group of employees) is failing to perform as needed, training is only appropriate if that person or group actually does not know how to do the job.

Most such failures do not result from a lack of knowledge. More often, they are the result of a situation that fails to reward good performance and may reward poor performance. This reward can be anything that makes life on the job easier or more enjoyable (e.g., a longer break time, relief from the need to climb flights of stairs, or less paperwork). When analyzing a training request, trainers should look for such punishments (anything that produces any kind of discomfort in the workplace) and rewards (anything that adds any sort of comfort). A manager who uses training to avoid the more unpleasant task of changing workplace methods also has fallen victim to this feedback loop.

Trainers can help managers find and permanently correct these problems, or they can fall into the trap of using retraining sessions to flog people into doing things differently, only to watch them fall back into pre-training performance levels.

TOO EARLY OR TOO LATE. This pitfall both renders training ineffective and damages the training organization's reputation. It can be difficult to avoid. Scheduling training at the exact time it is needed can be challenging, especially when there are multiple needs. Still, it must be done.

UNNECESSARY. Few things damage a training organization's effectiveness more than giving unnecessary training. If most employees already know the material, do not train them. Concentrate on only those who need it. This applies to both locally developed and vendor training. (It is tempting to let vendor training be delivered, especially when offered without charge by a company that does business with the utility.) The effect can be softened by making it optional, so employees do not feel constrained to participate. Overall, though, trainers should evaluate the content of the training and turn it down if it is not needed.

RECOMMENDED READING

There are thousands of texts on training and adult education, and the degree of repetition within them can be daunting. However, Robert F. Mager's books contain virtually everything truly necessary to build a training program. Sometimes called the "manager six-pack," these books are simple, direct, and often sold as a bound unit. They are a valuable addition to any training organization's library. Their titles are as follows (Mager, 1997a to e; Mager and Pipe, 1997):

- *Analyzing Performance Problems*,
- *Preparing Instructional Objectives*,
- *Measuring Instructional Results*,
- *How To Turn Learners On . . . Without Turning Them Off*,
- *Goal Analysis*, and
- *Making Instruction Work*.

For anyone charged with procedure writing, *Fundamentals of Procedure Writing*, by Carolyn Zimmerman and John J. Campbell (1988), is an excellent resource.

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Sixth Edition

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Task Force

Prepared by the Operation of Municipal Wastewater Treatment Plants Task Force of the Water Environment Federation

Michael D. Nelson, *Chair*

Douglas R. Abbott
George Abbott
Mohammad Abu-Orf
Howard Analla
Thomas E. Arn
Richard G. Atoulikian, PMP, P.E.
John F. Austin, P.E.
Elena Bailey, M.S., P.E.
Frank D. Barosky
Zafar I. Bhatti, Ph.D., P. Eng.
John Boyle
William C. Boyle
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C. Michael Bullard, P.E.
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Kathleen M. Cook
James L. Daugherty
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John Donnellon
Gene Emanuel
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Joanne Fagan
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Samuel S. Jeyanayagam, Ph.D., P.E., BCEE
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Sandeep Karkal
Gregory M. Kemp, P.E.

Justyna Kempa-Teper
Salil M. Kharkar, P.E.
Farzin Kiani, P.E., DEE
Thomas P. Krueger, P.E.
Peter L. LaMontagne, P.E.
Wayne Laraway
Jong Soull Lee
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Chung-Lyu Liu
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Pam Schweitzer
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Andrew Shaw
Timothy H. Sullivan, P.E.
Michael W. Sweeney, Ph.D., P.E.
Chi-Chung Tang, P.E., DEE, Ph.D.
Prakasam Tata, Ph.D., QEP
Gordon Thompson, P. Eng.
Holly Tryon
Steve Walker
Cindy L. Wallis-Lage
Martin Weiss
Gregory B. White, P.E.
George Wilson
Willis J. Wilson
Usama E. Zaher, Ph.D.
Peter D. Zanoni

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For information on membership, publications, and conferences, contact

Water Environment Federation
601 Wythe Street
Alexandria, VA 22314-1994 USA
(703) 684-2400
http://www.wef.org

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Chapters 11, 23, and 32 were not updated for this edition of MOP 11. Chapters 11, 23, and 32 included herein are taken from the 5th edition of the manual, which was published in 1996.

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J. A. Brown, *Vice-Chair*
S. Biesterfeld-Innerebner
R. Fernandez
S. S. Jeyanayagam
Z. Li
M. D. Nelson
S. Rangarajan
E. P. Rothstein
A. T. Sandy
A. K. Umble
T. O. Williams
J. Witherspoon

Acknowledgments

This manual was produced under the direction of Michael D. Nelson, *Chair*.

The principal authors and the chapters for which they were responsible are

George Abbott (2)
Thomas P. Krueger, P.E. (2)
Thomas E. Arn (3)
Greg Ramon (3)
Gregory M. Kemp (4)
Roger A. Migchelbrink (5)
Melanie Rettie (6)
Michael W. Sweeney, Ph.D., P.E. (6)
David Olson (7)
Russell E. Mau, Ph.D., P.E. (8)
Peter Zanoni (9)
Louis R. Germanotta, P.E. (10)
Norman Jadczak (10)
James Kelly (11)
Richard Sutton, P.E. (12)
Alicia D. Gilley, P.E. (13)
Jorj Long (14)
Keavin L. Nelson, P.E. (15)
Ed Ratledge (16)
Kathleen M. Cook (17)
Frank D. Barosky (17)
Jerry C. Bish, P.E., DEE (18)
Ken Schnaars (19)
Donald J. Thiel (20, Section One)
William C. Boyle (20, Section Two)
Donald M. Gabb (20, Section Three)
Samuel S. Jeyanayagam (20, Section Four)
Kenneth Schnaars (20, Section Five)
Alan J. Callier (20, Section Six)
Jorj Long (20, Appendices)
Howard Analla (21)
John R. Harrison (22)
Anthony Bouchard (23)
Sandeep Karkal, P.E. (24)
Daniel A. Nolasco, M. Eng., M. Sc., P. Eng. (25)
Donald F. Cuthbert, P.E., MSEE (26)
Carole A. Shanahan (27)
Kim R. Riddell (28)
Peter L. LaMontagne, P.E. (29)
Patricia Scanlan (30)
Webster Hoener (30)
Gary Neun (30)
Jim Rowan (30)
Hari Santha (30)
Elena Bailey, M.S., P.E. (31)
Rhonda E. Harris (32)
Peter L. LaMontagne, P.E. (33)
Wayne Laraway (33)

Contributing authors and the chapters to which they contributed are

David M. Mason (3)
David W. Garrett (9)
Earnest F. Gloyna (23)
Roy A. Lembcke (23)
Jerry Miles (23)
Michael Richard (23)
John Bratby, Ph.D., P.E. (29)
Curtis L. Smalley (32)

Michael D. Nelson served as the Technical Editor of Chapters 10 and 25.

Tony Ho; Dr. Mano Manoharan, Standards Development Branch, Ontario Ministry of the Environment, Canada; and Dr. Glen Daigger, CH2M HILL collaborated in the successful development of the methodologies presented in Chapter 25.

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CTE Engineers, Spokane, Washington
David A. Flowers, Cedarburg, Wisconsin
DCWASA, Washington, D.C.
Department of Biological Systems Engineering, Washington State University, Pullman, Washington
Earth Tech Canada, Inc., Markham, Ontario, Canada
Earth Tech, Sheboygan, Wisconsin
East Norriton-Plymouth-Whitpain Joint Sewer Authority, Plymouth Meeting, Pennsylvania

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MAGK Environmental Consultants, Manchester, New Hampshire
Malcolm Pirnie, Inc., Columbus, Ohio
Massachusetts Institute of Technology, Cambridge, Massachusetts
Metcalf & Eddy, Inc., Philadelphia, Pennsylvania
Metro Wastewater Reclamation District, Denver, Colorado
Mike Nelson Consulting Services LLC, Churchville, Pennsylvania
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Peter LaMontagne, P.E., New Britain, Pennsylvania
Philadelphia City Government, Philadelphia, Pennsylvania
Philadelphia Water Department, Philadelphia, Pennsylvania
PSG, Inc., Twin Falls, Idaho
R.V. Anderson Associates, Limited, Toronto, Ontario, Canada
Red Oak Consulting—A Division of Malcolm Pirnie, Inc., Phoenix, Arizona
Research and Development Department, Metropolitan Water Reclamation District of Greater Chicago, Cicero, Illinois
Rock River Water Reclamation District, Rockford, Illinois
Rohm and Haas Co., Croydon, Pennsylvania
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Chapter 17

Characterization and Sampling of Wastewater

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INTRODUCTION

Effective operation and control of a wastewater treatment plant (WWTP) requires that the operator possess thorough knowledge of the composition of the influent, effluent, and internal process streams. To obtain that knowledge, the operator determines the characteristics of the raw wastewater and streams by collecting and analyzing representative samples throughout the plant. This chapter provides the operator with a basic understanding of wastewater characterization and sampling necessary to operate the plant effectively.

CHARACTERIZATION OF WASTEWATER

Characterization of plant influent, effluent, and internal process streams provides plant operations personnel the information they need to properly control treatment processes. Depending on the size of the WWTP and the composition of the influent, wastewater characterization may require a few simple tests or several more complex tests in a well-equipped laboratory. As an alternative to maintaining a plant laboratory, an outside agency or private laboratory approved by the regulatory agency may

provide the necessary analytical services. In either case, the operator must determine the specific information needed for each sample site. The following sections describe the various data that might be needed for process control and influent and effluent monitoring. The facility's National Pollutant Discharge Elimination System (NPDES) permit lists many of the pollutants to be tested.

SOURCES. Wastewater can typically be categorized as originating from domestic, commercial, or industrial sources. Wastewater is conveyed to the treatment facility in a collection system isolated from the stormwater collection system. There are also combined sewer systems that carry both stormwater and wastewater. The combination of wastewater and stormwater can alter wastewater characteristics. As a result, plant treatment processes are affected.

Domestic. Domestic wastewater comes primarily from residential, nonindustrial business, and institutional sources. Except for small treatment plants serving residential communities, most plants treat some commercial and industrial wastewater. Wastewater with a predominantly domestic origin tends to be fairly uniform in composition. Composition varies somewhat among communities because of differing social, economic, geographic, and climatic conditions. Composition and quantities of domestic wastewater in some systems vary seasonally because of contributions from large institutions, such as colleges, or from resort areas where the population fluctuates widely.

Industrial and Commercial. Most municipal sewers convey wastewater from industrial and commercial sources and from domestic sanitary sources. Industrial wastewater typically contains substances derived from raw materials, intermediate products, byproducts, and end products of the industry manufacturing or production processes. Industrial wastewater changes with changing production mixes and schedules. This wastewater is more variable than domestic wastewater. Food-processing wastes, which typically contain high concentrations of soluble organic constituents, often cause extreme variations in plant loading because of the seasonal production associated with crop harvests. Food-processing wastes may also be nutrient-deficient (i.e., low in nitrogen), which can have an adverse effect on the activated sludge process at the WWTP. Airports discharging significant amounts of glycol during the winter months may also affect plant secondary processes. Glycol is high in biochemical oxygen demand (BOD) and contributes to phosphorus nutrient deficiency. Commercial sources, such as retail businesses, contribute primarily domestic wastewater; other commercial sources, such as warehouses and distribution centers, may contribute variable wastewater from washing and other operations.

Infiltration and Inflow. Infiltration and inflow can affect hydraulic loadings. Infiltration enters sewers through leaky joints, cracks, or holes in pipes. Groundwater is a common source of infiltration, particularly when the ground is saturated. Inflow results when storm or runoff water enters the system through leaky manhole covers or cracked casings. Illegal roof gutter and sump pump connections are also a source of inflow.

FLOW VARIATIONS. The plant operator needs to know whether the wastewater influent comes from separate or combined collection systems, because stormwater flows from combined systems can adversely affect plant hydraulics. Even plants served by separate sanitary sewer systems receive some extraneous water from inflow of surface runoff and infiltration of groundwater. Infiltration and inflow cause seasonal flow variations. These effects are influenced by the age, condition, and type of the collection system. Combined systems cause major changes in wastewater flow from runoff of stormwater or snowmelt. In addition to the hydraulic effects on the plant, changes may result from the organic matter and dissolved contaminants contained in runoff flushed from streets and other impervious surfaces. The effects of hydraulic and pollutant loadings from combined sewers are especially pronounced during the first hours of a storm following a dry period.

Wastewater flows typically vary consistently during days, weeks, seasons, and years. Daily (diurnal) flow variation depends largely on the size and shape of the collection system; in general, the smaller the collection system, the greater the diurnal variation. Other influences on flow variation include the number and type of pumping stations, types of industries served, and population characteristics.

Daily flows for treatment plants typically peak between 8:00 and 10:00 a.m., between 12:00 and 2:00 p.m., and between 4:00 and 7:00 p.m. Minimum flows typically occur late in the evening and early in the morning. The flow peaks and minimums tend to smooth out as the length of the collection system increases. Depending on the system size, the typical daily peak flow exceeds the daily average flow by 50 to 200%.

Although characterization of wastewater by source provides some general information about plant influent, such information is insufficient for either process control or permit compliance. Most of the necessary data depend on testing the influent, effluent, and plant process streams to determine their physical, biological, and chemical characteristics. Biomonitoring of the plant effluent can determine its toxicity.

PHYSICAL CHARACTERISTICS. The physical characteristics of wastewater include temperature, color, odor, and turbidity. Of these, color, odor, and turbidity can quickly be checked by sight and smell before actual testing is done.

Temperature. The temperature of wastewater indicates the amount of thermal energy it contains. It is measured in degrees Celsius or degrees Fahrenheit. The two scales are interrelated by the following equations:

$$°C = 0.5556\ (°F - 32) = 5/9\ (°F - 32) \quad (17.1)$$

$$°F = 1.8000\ (°C) + 32 = 9/5\ (°C) + 32 \quad (17.2)$$

Wastewater is typically somewhat warmer than unheated tap water, because wastewater contains heated water from dwellings and other sources. As buried pipes convey wastewater long distances to the plant, the influent temperature typically approaches the temperature of the ground. Accordingly, summer wastewater temperatures exceed winter temperatures. The annual mean wastewater temperature typically ranges between 10 and 20°C (50 and 70°F).

In general, the rate of biological activity depends on temperature. As temperature increases, microorganisms accelerate consumption of organics and use of oxygen in the wastewater. The reaction rates approximately double with every 10°C (18°F) increase in temperature until higher temperatures begin to inhibit biological activity.

A significant increase in temperature for a short period typically indicates the presence of an industrial discharge. A significant drop in temperature often indicates intrusion of stormwater.

Wastewater treatment plant operators, in areas of the country subject to wide temperature swings between summer and winter, must be aware of the effect that changes in temperature will have on the activity of the microorganisms; the warmer the temperature, the higher the activity.

Color. The color of wastewater depends on the amounts and types of dissolved, suspended, and colloidal matter present. Normal raw wastewater is gray. Wastewater becoming septic will be darker, providing an excellent indication of the need for further aeration. Other colors typically indicate the presence of industrial discharges. For example, green, blue, or orange discharges may emanate from plating operations; red, blue, or yellow discharges are often dyes; and white, opaque discharges often come from dairy wastes or latex paint. Knowledge of the types of industries contributing to the collection system and the colors of their discharges is of great value to the operator.

Odor. Odor, a highly subjective parameter, can nonetheless offer valuable information. The human nose, a sensitive odor-detecting system, can often smell wastewater constituents. Fresh wastewater typically produces a musty odor. Other wastewater odors, such as petroleum, solvents, or other abnormal scents, indicate an industrial spill.

Because some of the compounds present in wastewater may be toxic, caution must be used when smelling wastewater, especially when smelling bottled samples. Detection of unusual odors in a plant, particularly in confined areas, requires exercising caution and strict adherence to safety procedures.

Anaerobic decomposition of wastewater produces hydrogen sulfide, which has a distinctive, rotten-egg odor. When hydrogen sulfide is present, measures to increase the oxygen content of the liquid stream must be taken. In addition to indicating process problems, the presence of hydrogen sulfide raises concerns for other reasons. It is poisonous at relatively low levels, corrosive to concrete, and potentially explosive. It is also important to note that hydrogen sulfide is particularly dangerous because it essentially paralyzes one's sense of smell when present at high concentrations. In this situation, one would initially note the rotten-egg odor, but it would seem to quickly go away. If one interprets this lack of a rotten-egg odor as no hydrogen sulfide present, it could quickly lead to one or more fatalities. Methane gas, which is even more explosive, may accompany hydrogen sulfide. The conditions that produce methane and hydrogen sulfide demand oxygen, often resulting in an oxygen-deficient atmosphere. Therefore, the presence of hydrogen sulfide and methane demand extreme caution and rigorous application of established safety procedures. This includes using appropriate gas detection equipment before entering a confined space and turning on ventilation equipment, if available. For more information regarding hydrogen sulfide, refer to *Water Supply and Sewerage* (Steele, 1979).

Turbidity. Turbidity, measured with a device called a turbidimeter, indicates the quantity of suspended and colloidal material in the flow stream, particularly at low solids concentrations. Turbidity is measured in nephelometric turbidity units, which have to do with the type instrument used to measure turbidity—in this case, a nephelometer. Turbidity does not directly correlate with suspended solids concentrations, because color can interfere with the turbidity measurement. However, it is easy to determine a relationship between turbidity and suspended solids for any given system. To determine the relationship, take multiple grab samples and analyze for suspended solids over a suitable range of turbidity values, as shown in the graph in Figure 17.1. Then use a linear regression to determine the relationship.

The graph shows an "estimated" suspended solids to turbidity relationship based on the relationship between suspended solids and turbidity from Metcalf & Eddy (2003). The "actual" line is from a WWTP and was obtained by collecting samples at different turbidity values and analyzing for the corresponding suspended solids values.

Because online turbidity meters located at the outlets of the secondary clarifiers can rapidly indicate solids carry-over, allowing quick corrective actions, operators may find it useful to establish such a relationship for their particular system to provide a

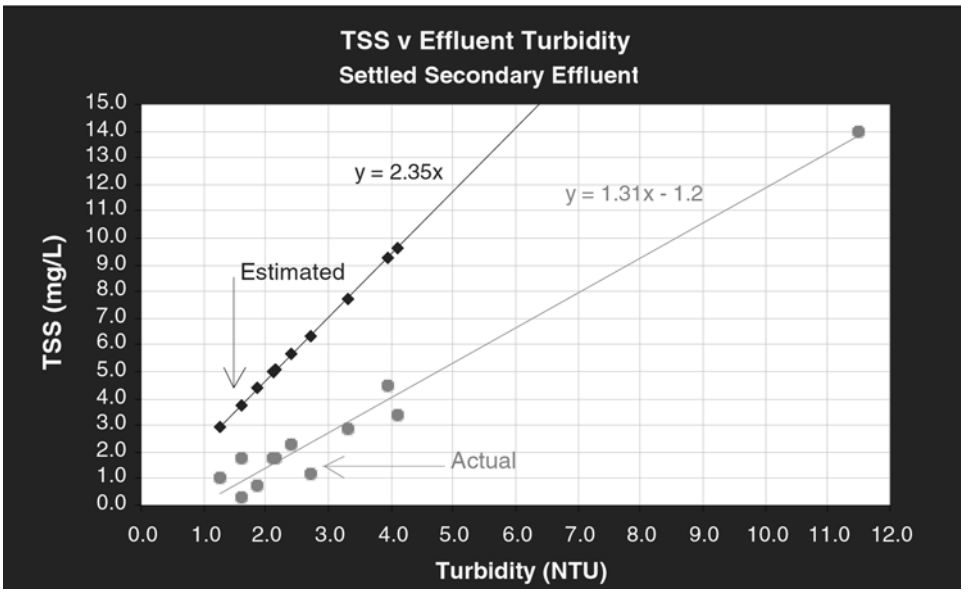


FIGURE 17.1 Example of an estimated suspended solids to turbidity relationship (TSS = total suspended solids).

quick indication of suspended solids trends that may assist with timely process control decisions. On the down side, turbidimeters typically require extensive maintenance to ensure they maintain accurate readings as solids have a tendency to foul the units.

CHEMICAL CHARACTERISTICS. The chemical characteristics of wastewater include alkalinity, chemical oxygen demand (COD), conductivity, oxidation–reduction potential (ORP), and pH.

Alkalinity. Alkalinity is a measure of the ability of the wastewater to neutralize acid. Alkalinity is reported as milligrams per liter of calcium carbonate. However, other compounds also contribute to alkalinity. The characteristics of the raw water supply influence alkalinity, which can be high in areas having hard water (typically associated with groundwater sources) or extremely low in areas having soft water.

High-alkalinity wastewater allows a WWTP to better survive an acidic industrial discharge. Some process conditions, such as nitrification in the secondary units, will consume alkalinity and may lower pH. Thus, a reduction in alkalinity across the secondary process units denotes nitrification in the secondary process. Conversely, denitrification will generate alkalinity and may increase pH; therefore, a treatment system that supports both denitrification and nitrification can regain some of the lost alkalinity;

that is, denitrification will return approximately 40% of the alkalinity lost to nitrification (0.76 mol alkalinity as carbonic acid regained for every 1.98 mol alkalinity as bicarbonate consumed).

Chemical Oxygen Demand. *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 1998) defines COD as the amount of a specified oxidant that reacts with the sample under controlled conditions (where the quantity of oxidant consumed is expressed in terms of its oxygen equivalence). In short, it provides a measure of how much oxygen a sample will consume (oxygen demand), and it does so in three or four hours. The COD test, therefore, provides a means to quickly estimate the five-day BOD (BOD_5) of a sample.

The correlation between BOD and COD varies from plant to plant. However, COD results are typically higher than BOD results because all the organics are oxidized. Use of the COD test for process control requires that the BOD tests must first be run in parallel with the COD tests to determine this correlation. This allows BOD-to-COD ratios to be developed for each plant. These ratios vary across the plant from influent to effluent. The BOD-to-COD ratio is typically 0.5:1 for raw wastewater and may drop to as low as 0.1:1 for well-stabilized secondary effluent. Normal COD ranges for raw wastewater are 200 to 600 mg/L. The graphs in Figures 17.2 and 17.3 illustrate the results of actual measurements to determine this relationship for a particular plant.

Another test, known as the total organic carbon test, provides an alternative means of estimating BOD.

Conductivity. Conductivity measures the ability of an aqueous solution to carry an electrical current. The conductivity of domestic wastewater generally ranges from 50 to 1500 μS/cm, although some industrial wastewaters have conductivities higher than 10 000 μS/cm.

The conductivity of wastewater indicates the quantity of dissolved inorganic material present in the water. Wastewater has a normal range of conductivity associated with the dissolved solids concentrations in the water supply. A significant increase in the conductivity of the wastewater indicates an abnormal discharge, probably from an industrial source.

Conductivity measurements can be used to determine flow time between pump stations or between other points in the collection system. This procedure involves injecting a solution of conductive material, such as salt, to the flow and noting the elapsed time until conductivity increases at the downstream point.

Obtaining reliable data with conductivity-monitoring equipment requires care of electrodes to prevent fouling and adequate sample circulation. Conductivities greater than 10 000 to 50 000 μS/cm or less than 10 μS/cm can be difficult to measure.

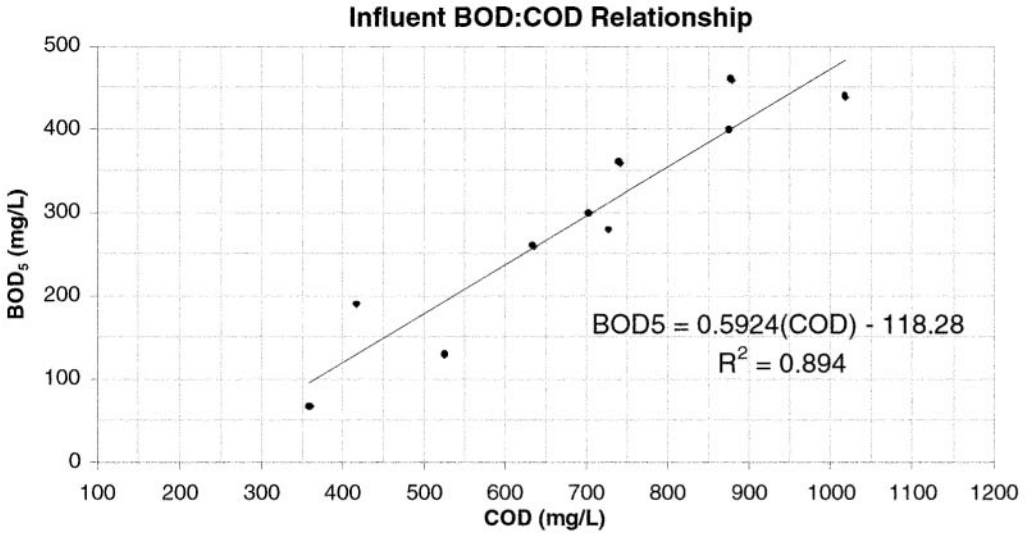


FIGURE 17.2 Example of the results of actual measurements to determine the influent BOD-to-COD relationship for a particular plant (R^2 is the "coefficient of determination", which, in linear regression, is a measure of how well the line approximating the points represents the data. Values exceeding 0.85 indicate very good representation).

Dissolved Oxygen. Dissolved oxygen is simply the molecular oxygen present in water or wastewater. The maximum amount of oxygen in water or wastewater is temperature-dependent. Colder water is capable of containing more dissolved oxygen than warmer water. However, colder water may actually contain less dissolved oxygen than warmer water, depending on conditions in the water.

The dissolved oxygen in a particular section of a wastewater treatment system is one of the determinants of what type organisms will live and thrive. As dissolved oxygen concentrations decrease, aerobic organisms slow down. Low dissolved oxygen concentrations favor filamentous organisms that may cause sludge bulking. Excess dissolved oxygen concentrations may result in pinpoint flocs that will not clump and settle. Therefore, dissolved oxygen concentration is an essential control factor in wastewater treatment. The dissolved oxygen concentration must be maintained in a range that favors the desired organisms.

Oxidation–Reduction Potential. Certain substances release or take up electrons when these substances are dissolved in solution. The intensity or ease of electron loss (oxidation) or electron gain (reduction) is the ORP. An example of this is shown in Table 17.1. It is commonly referred to as the *redox potential* and is measured in millivolts.

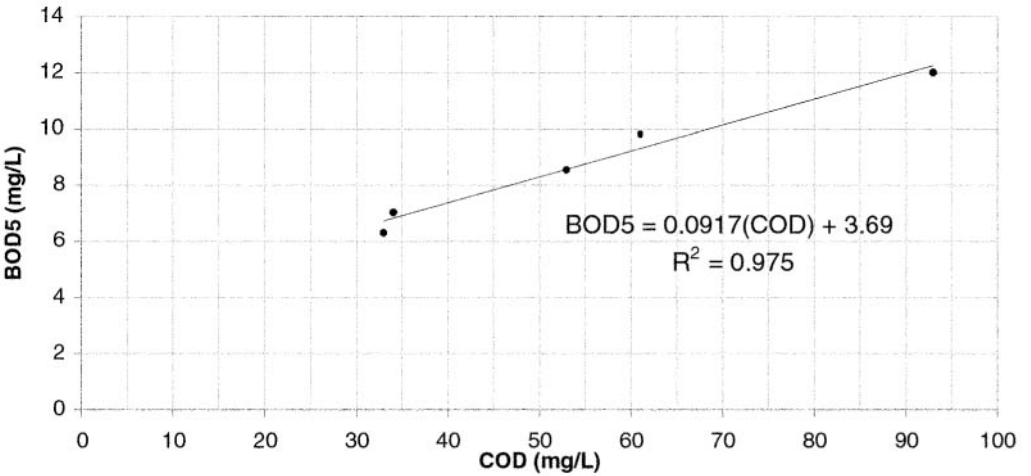


FIGURE 17.3 Example of the results of actual measurements to determine the effluent BOD-to-COD relationship for a particular plant (R^2 is the "coefficient of determination", which, in linear regression, is a measure of how well the line approximating the points represents the data. Values exceeding 0.85 indicate very good representation).

The ORP measures the potential of the treatment system. It can identify current operational conditions, a weak link of the treatment train, and if operational conditions improved a system. It provides an immediate response to critical controls.

Redox potential is measured using a data logging meter and an ORP submersible probe. It can be used to monitor incoming raw wastewater, primary effluent, suspended growth systems, fixed-film systems, and aerobic digesters.

TABLE 17.1 Example of the ORP.

Oxidation–reduction potential			
Electrical Activity Found in Biological Systems			
Anaerobic			
Fermentation	−200 mV	to	−50 mV
Anoxic			
Denitrification	−50 mV	to	+50 mV
Aerobic			
Carbonaceous BOD	+50 mV	to	+225 mV
Nitrification	+100 mV	to	+325 mV

Raw wastewater influent has a typical ORP of −200 mV. A strong influent measures approximately −400 mV, and weak influents (such as those containing infiltration and inflow) measure −50 mV.

Ideally, ORP values of a system's primary effluent should be the same as that of its raw influent. A decrease may indicate a need to increase removal of primary sludge or indicate sidestream interference, as from a supernatant recycle.

In the suspended growth system, a well-oxidized sludge can be affected by a strong organic waste load. An ORP test can indicate the reserve capacity available to maintain treatment. The ORP for suspended growth systems should be monitored between aeration basins and within the basins.

In a fixed-film system, such as a trickling filter, the slime (zoogleal) growth layer becomes thick enough to develop an anaerobic layer. A decrease in potential across the filter indicates a loss of treatment and a need to flush the filter.

The ORP can be used to effectively operate aerobic digesters to reduce sludge yield and reduce electricity costs; that is, aerobic conditions generate nitrates and stable potential values. Anoxic conditions, controlled by the ORP, use nitrates instead of oxygen, thereby reducing blower usage. Cells are destroyed, which reduces sludge yield. The ORP is used to prevent slipping from anoxic to anaerobic conditions, which would generate odors.

pH. The term *pH* is traditionally used as a convenient representation of the concentration of hydrogen ions in a solution, where pH is determined by the following:

$$\text{pH} = -\log[\text{H}^+] \tag{17.3}$$

Where: $[\text{H}^+]$ = actual hydrogen ion concentration in a solution.

For example, neutral water has a pH of 7, which means that the hydrogen ion concentration is 10^{-7} mol/L.

The pH scale ranges from 1 to 14, with a neutral reading of 7. Readings below 7 indicate an acidic condition, and those above 7 indicate a basic condition. The pH is extremely important in biological wastewater treatment, because the microorganisms remain sufficiently active only within a narrow range, generally between pH 6.5 and 8. Outside this range, pH can inhibit or completely stop biological activity. Nitrification reactions are especially pH-sensitive. Biological activity declines to near zero at a pH below 6.0 in unacclimated systems.

Raw wastewater typically has a pH near 7. Although significant departures may indicate industrial or other nondomestic discharges, there are other conditions that can

cause pH to deviate from the norm. Anaerobic conditions lower the pH of a wastewater. Low pH values, coupled with other observations, such as sulfide odors and black color, provide evidence of septic conditions in the collection system or within the treatment process. Only nitrification reactions in the secondary aeration basins may reduce the pH enough to inhibit biological activity in some low-alkalinity systems. Conversely, denitrification reactions (by themselves) will increase pH. Covered high-purity oxidation systems can also lower pH as a result of the buildup of carbonic acid.

BIOLOGICAL CHARACTERISTICS. Bacteriological testing determines the presence of pathogenic (disease-causing) organisms or indicator bacteria for such organisms in the raw wastewater, process streams, and treated effluent. As testing for all of the possible pathogens is impossible, accepted procedures involve testing for what are called *indicator bacteria*. Their presence signals the likely presence of pathogens.

Tests to determine biological activity include BOD, pathogen, and microscopic examination.

Biochemical Oxygen Demand. The BOD test measures the amount of oxygen needed to biologically oxidize material in wastewater. Because the rate of biological activity depends on temperature and complete stabilization may require as long as 20 days, the BOD_5 test has been standardized to conditions of 20°C for five days. This test provides a relative measure of the amount of food material available to the biological system, degree of stabilization of the wastewater, and prospective effect of the effluent on the receiving water.

The measurement of BOD_5 is a significant parameter and provides an important basis for determining plant loading and design considerations. As designed, the BOD_5 test typically measures the amount of oxygen required to oxidize the organic matter in the sample. The amount of oxygen required to oxidize only the carbonaceous organic matter (not nitrogen) is referred to as *carbonaceous BOD* (CBOD). If the sample is allowed to react further, a second phase of biological oxidation, known as *nitrification*, begins to occur. During this phase, a different group of bacteria convert ammonia to nitrite and nitrate, consuming oxygen. The time required for transition from carbonaceous to nitrogenous reactions varies, depending on the sample. If nitrifying organisms are initially present at background levels, an appreciable nitrogenous oxygen demand may sometimes be exerted before five days have elapsed.

Secondary treatment plants are typically designed to remove CBOD, but not nitrogenous BOD; nonetheless, nitrogenous reactions frequently occur in some well-stabilized secondary effluents during the five-day test period. The BOD_5 of domestic wastewater in the United States typically ranges from 100 to 250 mg/L, but is more

likely to be higher. United Kingdom plants served by newer collection systems with low inflow and infiltration rates may have wastewater with BOD_5 near the higher end of the above range.

Because nitrogenous oxidation can sometimes result in substantially higher BOD_5 test results than those from oxidation of organic substances, U.S. Environmental Protection Agency (U.S. EPA) has approved the use of a modified BOD test, in which a nitrification inhibitor is used to suppress the nitrification reaction. Use of the CBOD test for permit reporting must be approved by each state regulatory agency.

Pathogens. Pathogens are disease-causing organisms and are present in large numbers in raw wastewater, process streams, and treated effluent. The presence of pathogens can be determined by testing for indicator organisms, including total and fecal coliform, *Escherichia coli*, enterococci, and, in a few cases, fecal streptococcus.

Total and fecal coliform bacteria are not themselves pathogens, but are used as indicator organisms because they tend to resist the effects of disinfection better than most pathogens, are much more numerous than pathogens, and are easily counted. Therefore, a low coliform count suggests that few, if any, pathogenic organisms survive. Both total and fecal coliform bacteria are reported in units of colonies per 100 mL, if the membrane filter technique is used, or as the most probable number per 100 mL, if the multiple-tube method is used. Because most permits contain a coliform limit, some means of disinfection, such as chlorination, UV light, or ozone, is typically needed.

A U.S. EPA water quality criteria document (U.S. EPA, 1986a) concerning bacteria recommends the use of *E. coli* or enterococci as the indicator microorganisms for establishing freshwater bacterial criteria. Enterococci levels are recommended for marine water bacterial criteria, based on the strong correlation between the incidence of gastroenteritis and the numerical densities of these microorganisms. Analytical methods using membrane filter techniques (U.S. EPA, 1986b) have been published for the *E. coli* and enterococci tests.

Fecal streptococcus testing resembles that for coliforms, but uses different conditions for selecting the bacteria. Fecal streptococcus bacteria are pathogens that are more prevalent in the feces of animals than of humans. The ratio between fecal coliforms and fecal streptococcus is sometimes used to determine whether bacterial contamination originates from humans or animals. A ratio greater than 1 typically indicates an animal source as a result of a nonpoint source.

Viruses. Viruses excreted with feces, urine, blood, or any other body fluids or secretions from any species of animals may pollute water. Especially numerous, and of particular importance to health, are the viruses that infect the gastrointestinal tract of humans and are excreted with the feces of infected individuals.

Because viruses multiply only within susceptible living cells, their numbers cannot increase in wastewater. Wastewater treatment, dilution, natural inactivation, and water treatment further reduce viral numbers

In municipal wastewater, viruses occur less frequently than bacteria and are much more difficult to measure. Routine examination of water and wastewater for viruses is not performed. If testing is required, it should be done only by competent and specially trained water virologists.

Microscopic Examination. Microscopic examination of wastewater and process streams can provide valuable information on the biological characteristics of the system and is a powerful tool for process control, particularly for activated sludge. Examination of sludge under a microscope can reveal sludge conditions and warn of impending process problems. Microscopic examination can show floc appearance, clarity of supernatant liquid, types and distribution of protozoa, and presence or absence of filamentous bacteria. The information obtained from microscopic examination is described more completely in *Activated Sludge* (WEF, 2002a).

SOLIDS. Treatment plant operators use mechanical devices and microbiology (a population of naturally occurring microorganisms) to remove or condition solids such that the system effluent meets regulatory requirements. Operators use screening, skimming, pumping, and filtering devices to remove the large solids (or macrosolids) and any floating solids. They primarily use microbiology to condition the remaining smaller or microsolids, such that they will settle to the bottom of undisturbed water or be converted to gas or water. The treatment is not perfect. Consequently, operators must compare the amount of solids in the water entering the treatment system with the amount in the water leaving the treatment system to measure the treatment's effectiveness and efficiency and assess whether the system is in compliance with applicable regulations. They can also measure changes in the different solids types at various stages in the treatment process to assess treatment effectiveness so that they can make necessary changes.

It is, therefore, important that operators understand the different types of solids and be able to determine the quantities of each type. This knowledge of solids, coupled with collecting the appropriate data, provides information operators need to effectively operate and control wastewater treatment systems.

Total Solids. Total solids are all the solids in wastewater. They can be grouped based on what they "do" in water: those that settle (i.e., sink); those that do not settle (i.e., nonsettleable; they float or stay dispersed throughout the water); or those that dissolve.

That is,

$$\text{Total Solids} = \text{Settleable Solids} + \text{Nonsettleable Solids} + \text{Dissolved Solids} \quad (17.4)$$

All solids that are not dissolved are considered to be suspended solids, so

$$\text{Suspended Solids} = \text{Settleable Solids} + \text{Nonsettleable Solids} \quad (17.5)$$

Then,

$$\text{Total Solids} = \text{Suspended Solids} + \text{Dissolved Solids} \quad (17.6)$$

To determine the total solids concentration, first determine the mass of total solids per unit volume as follows:

1. Measure the mass of an oven-dried container,
2. Fill it with a known volume of wastewater,
3. Put the filled container in an oven,
4. Leave it in the oven until the water evaporates, and
5. Remeasure the mass of the dry container with the remaining solids residue.

Subtracting the original mass of the empty dry container leaves the mass of the total solids. Dividing the mass of total solids by the volume of wastewater used at the start then gives the total solids concentration in terms of mass per unit volume (e.g., mg/L). See *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 1998) for more detailed information.

It is important to measure the total solids entering the treatment system, because they can serve as an indicator as to whether something unusual is occurring in the collection system (i.e., the sanitary sewers feeding into the treatment system). For example, if an influent total solids database has been established, and there is a significant change relative to historical data, this may be an indication of illegal discharges or some sort of failure in the collection system. This change from historical data may provide early indications of a problem and allow for timely corrective action to prevent an upset of the treatment system.

Suspended and Dissolved Solids. Total solids can also be grouped based on whether they will pass through a filter of a particular pore size. The dissolved solids pass through the filter with the water. The solids caught by the filter are called *suspended*

solids. They can be thought of as "suspended" by the filter because they cannot pass through it with the water.

Suspended solids are typically those that are visible in water and give it a dirty, unpleasing appearance. They consist of solids that settle on the bottom, float throughout, or float on top of the water.

The solids that float throughout the water as opposed to sinking to the bottom or floating to the top are generally relatively small particles, referred to as *colloidal solids*. They stay dispersed throughout the water because of their small size, a specific gravity approximately equal to that of the wastewater, and/or an electric charge that tends to repel them from each other and keeps them from settling.

Suspended solids are particularly important in wastewater treatment, because this is one of the criteria used by regulatory agencies to assess regulatory compliance. For example, U.S. EPA defines *secondary treatment*, with certain exceptions, as being capable of producing an effluent having a monthly average suspended solids concentration not exceeding 30 mg/L and a weekly average not exceeding 45 mg/L. In addition, treatment systems must achieve 85% removal of suspended solids from the system's influent to its effluent.

Unless they color the water or are present in very high concentrations, dissolved solids are typically not visible in water. Sugar or salt dissolved in water are examples of dissolved solids. In general, dissolved solids and their effect on wastewater treatment are assessed via other tests and will not be discussed further in this section.

To determine the suspended solids concentration, determine the mass of suspended solids per unit volume as follows:

1. Measure the mass of a suitable oven-dried filter,
2. Filter a measured volume of wastewater through the filter,
3. Put the filter with the trapped solids in an oven,
4. Leave it in the oven until the water evaporates, and
5. Remeasure the mass of the dry filter with the remaining solids residue.

Subtracting the original mass of the dry filter leaves the mass of the suspended solids. Dividing the mass of suspended solids by the volume of wastewater used at the start then gives the suspended solids concentration in terms of mass per unit volume (e.g., mg/L). See *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 1998) for more detailed information.

Volatile and Fixed Solids. Solids can also be grouped based on whether they burn off (or volatize) at a certain temperature. Those solids that burn off are called *volatile solids*

because they "volatize" when subjected to the heat, and those that remain are *fixed solids* because they remain "fixed" in spite of the heat treatment. That is,

$$\text{Total Solids} = \text{Volatile Total Solids} + \text{Fixed Total Solids} \quad (17.7)$$

$$\text{Suspended Solids} = \text{Volatile Suspended Solids} + \text{Fixed Suspended Solids} \quad (17.8)$$

In general, wastewater operators are more interested in the volatile solids because volatile solids provide a good approximation of how much organic matter is present in wastewater. It is primarily organic matter that can be converted and/or conditioned by the microorganisms. Accordingly, before and after treatment, volatile solids determinations may provide an indication of the treatment's effectiveness.

See *Standard Methods* (APHA et al., 1998) for instructions to determine volatile or fixed solids concentrations.

Settling Characteristics. One of the primary means of removing solids from wastewater is to simply let them settle to the bottom of tanks called *clarifiers* and let the clarified water overflow weirs at the top. The effectiveness of this settling depends on how well the operators control the treatment system to grow the best mix of microorganisms that will produce or condition solids that will settle and how well they manage the solids inventory (i.e., the total amount of suspended solids in the treatment system).

If the microorganism-conditioned solids are too heavy, they sink too fast and leave many of the very small particles dispersed throughout the water, which then go out with the treated water. If the microorganism-conditioned solids are too light, they settle too slowly or not at all and go out with the treated water.

The operators can assess settleability via tests described in *Standard Methods* (APHA et al., 1998) or the 30-minute settled sludge volume (SSV) test described below.

Settled Sludge Volume Test. The 30-minute settling procedure for activated sludge processes provides data on the settling characteristics of suspended solids. The test results depend on the suspended solids concentration (the solids inventory) and the health and mix of microorganisms. The testing equipment uses a settleometer (a 2 L cylindrical transparent container graduated to 1 L). The test measurements, expressed as milliliters per liter, for the SSV typically range from 100 to 300 mL/L. If the SSV is in this range, it is a good indication that the solids inventory, microorganism health, and microorganism mix are where they should be. Poorly settled sludge may have test values significantly higher than that range, an indication of potential operational problems. The 30-minute settling data, when combined with the mixed liquor suspended

solids (MLSS) concentration data, can be used to calculate a parameter called the sludge volume index (SVI). The SVI is defined as follows:

$$SVI = SSV \times 1000/MLSS \tag{17.9}$$

The normal SVI range is 50 to 150 mL/g. Further information about the sludge volume test is contained in Chapter 20.

CHEMICAL COMPOSITION. Chemical analysis of wastewater and internal process streams, according to *Standard Methods* (APHA et al., 1998) or the U.S. EPA manual *Methods for Chemical Analysis of Water and Wastes* (U.S. EPA, 1983), provides a wide variety of information concerning the characteristics of the wastewater and the condition of treatment processes. Chemical testing provides information on the concentrations of the specific substances for which the tests are designed. This information, especially when coupled with flow to calculate mass loading, allows the operator to monitor and control the treatment processes.

Compliance with the plant's NPDES permit may require several chemical analyses. Chemical constituents can be separated into numerous categories, depending on the purpose of the classification.

Chlorine. Free chlorine is not typically found in raw wastewater because of its extreme reactivity. However, it can be present in less reactive forms, such as chloramines. Chlorine is commonly used for disinfection. Measuring the chlorine residual and understanding the meaning of the results can provide an effective means of controlling the disinfection process. Approaches for measuring chlorine residual include several manual techniques and online instrumentation. The online instruments can be incorporated to a mechanism for controlling the chlorination process automatically by constantly measuring total chlorine residual. Although automatic instrumentation may need frequent calibration, it provides a continuous feed rate and eliminates the need for frequent manual adjustments.

Nitrogen. In wastewater, nitrogen occurs in four basic forms: organic nitrogen, ammonia (both ionized and free ammonia), nitrite, and nitrate. The forms of nitrogen present in a wastewater indicate the level of organic stabilization. Raw wastewater has higher concentrations of organic nitrogen and ammonia and contains little or no nitrite and nitrate (APHA et al., 1998). As the organic nitrogen is metabolized, it changes first to ammonia and then, if conditions are suitable, to nitrite and nitrate. In addition, the biological mass assimilates nitrogen for cell growth and thus removes some of the nitrogen.

Changes in the distribution of nitrogen can provide excellent information on process conditions in treatment units. An increase in the ammonia concentration across primary clarifiers often signals developing septic conditions from excessive sludge accumulation. An increase in nitrite and nitrate across the secondary units indicates nitrification. Conversely, a decrease in nitrate indicates denitrification, which may be desirable if it occurs in the activated sludge process (before the secondary clarifiers). It will most likely be undesirable if it occurs in the secondary clarifiers because the released nitrogen gas tends to float solids to the surface. Floating solids in the secondary clarifiers can also be the result of "bulking" sludge. If there is a question as to the cause of the floating solids, testing for nitrates provides a relatively quick check to distinguish between denitrification and bulking sludge.

Typical ranges of nitrogen concentrations in raw domestic wastewater are 20 to 85 mg/L for total nitrogen (the sum of organic nitrogen, ammonia, nitrate, and nitrite-nitrogen); 8 to 35 mg/L organic nitrogen; and 12 to 50 mg/L ammonia-nitrogen. Much lower nitrite- and nitrate-nitrogen concentrations are present. If the plant treats industrial flows with high BOD and low nitrogen levels, the wastewater may become nitrogen-limited. If so, complete stabilization of the BOD would require nitrogen addition from another source.

An analysis of nitrogen in wastewater involves several procedures and techniques. The organic nitrogen level is determined by performing a Kjeldahl nitrogen analysis, which measures both the organic nitrogen and ammonia, and then subtracting the ammonia value, which is measured separately. Nitrite-nitrogen is measured directly. The nitrate concentration is determined by a procedure that measures total nitrate and nitrite and then subtracts nitrite. Ammonia-nitrogen may also be measured directly using an electrode.

The nitrogen analysis throughout the nitrifying treatment system indicates whether or not the process is performing correctly. If ammonia is not being metabolized into nitrate and/or nitrite, the system is not processing wastewater effectively. In this case, other tests should be done to determine the problem.

Phosphorus. Phosphorus, like nitrogen, assumes different forms in wastewater and serves as an essential element for biological growth and reproduction. Phosphorus can be present as orthophosphate, polyphosphate, and organic phosphate. They are often measured in combination, as total phosphate. Orthophosphate, the form most available to biota, sometimes requires control. Some of the polyphosphate compounds, called hydrolyzable compounds, convert to orthophosphate under acidic conditions.

Normal domestic total phosphorus levels range from 2 to 20 mg/L, including 1 to 5 mg/L of organic phosphorus and 1 to 15 mg/L of inorganic phosphorus.

An oversupply of phosphorus in surface waters leads to excessive algae blooms and eutrophication. As a result of these adverse effects to effluent streams, many plants have effluent limits for phosphorus. Thus, in a biological nutrient removal (BNR) system, conditions are created to favor phosphorus-accumulating organisms (PAOs). These PAOs uptake excess phosphorus under aerobic conditions and release it under anaerobic conditions. Consequently, phosphorus measurements can vary within the system. To preclude phosphorus release resulting from long detention times and low dissolved oxygen, some BNR systems have simple aeration systems at the effluent end to provide a small dissolved oxygen boost. Operators need to be aware of the effects of dissolved oxygen to ensure that they do not cause an inadvertent release of phosphorus by shutting off blowers in a misguided attempt to reduce operating costs.

Sulfur. Hydrogen sulfide, frequently associated with adverse health effects and corrosion of sewer pipes and plant equipment, requires control. It is the "rotten-egg" odor of septic wastewater and is best controlled at its source, before being discharged to the collection system or treatment plant. Measurement of the sulfide concentration can indicate the severity of potential corrosion and the effectiveness of sulfide control programs. It can be differentiated as total versus soluble sulfide and requires concurrent measurement of pH to accurately quantify.

Hydrogen sulfide can be neutralized in lift stations with the addition of commercially available products. Peroxide, permanganate and ferrous or ferric chloride can also be used.

Fats, Oils, and Greases. Fats, oils, and greases (FOG) in plant effluent can result in floating material in the receiving water. The FOG can enter the plant as discrete floatable particles, as emulsified material, or as a solution. The FOG can also be classified as polar or nonpolar. Polar FOG, typically biodegradable, originates from animals; nonpolar FOG, much less readily biodegraded, typically comes from petroleum products. The FOG measurements upstream and downstream from the treatment units provide data on removal efficiencies. If excessive levels of FOG enter a secondary system, the low-density FOG constituents merge with the biomass. This merge can cause poor settleability of the biological solids with a resultant excessive solids loss to the effluent.

A representative sample of FOG is almost impossible to obtain because of the surface concentration of FOG and its adherence to the surfaces of the sampling device and storage container. Consequently, grab samples are used, and the entire sampling container is rinsed with solvent to capture the attached oil and grease.

Elimination of FOG at the source using grease traps or other recovery technology is the best method for control of what enters the collection system and treatment plant.

Priority Pollutants. *Priority pollutants* is a general term applied originally to a list of chemical compounds identified by U.S. EPA as being of significant concern because of their wide use and toxicity. This list has since been expanded and modified to include a listing of toxic pollutants and hazardous substances. U.S. EPA frequently revises this list based on its expanding knowledge of toxic compounds. The specific listing of these compounds is contained in 40 *CFR*, Part 122, Appendix D, "Tables of Toxic Pollutant and Hazardous Substances". Copies of the document can be obtained from U.S. EPA and should be retained in each plant's reference library. On request, U.S. EPA typically will include the plant on its mailing list to receive any updated listings.

The compounds on the toxic pollutant list typically come from industrial sources. The toxic compounds can be divided into two categories: toxic organic compounds (including organic solvents and many pesticides) and other toxic compounds (including heavy metals, cyanide, and phenols). Analyses of most of the listed compounds require sophisticated instrumentation. Further, their concentrations in domestic wastewater are typically low (measured in parts per billion). Special sampling equipment may be required to prevent sample contamination.

Many of the listed toxic compounds, if they reach sufficient concentrations, inhibit biological activity. Industrial discharges of heavy metals, such as chromium, can result in process upsets or failure and can adversely affect the biosolids quality and process performance.

The discharge of toxic compounds can impair receiving water environments because of their immediate toxicity and because many, such as mercury and polychlorinated biphenyls, are bioaccumulative. This means that biological organisms remove the toxic substances from the water and concentrate them within their biomass. The concentration effect typically progresses up the food chain until high and possibly toxic levels are reached at the end of the chain in more complex organisms, including humans.

BIOASSAY TOXICITY TESTING. U.S. EPA has recently begun to require that reissued permits include a more generic type of toxicity analysis called *bioassay toxicity testing*. These two testing procedures are sometimes referred to in the NPDES permit as *whole effluent toxicity testing* and *acute toxicity testing*. Instead of identifying specific constituents in the wastewater, the new testing approach addresses the overall toxicity of plant effluents. The rationale of this toxicity approach recognizes the impossibility of identifying and measuring all toxic substances in the plant effluent, from either analytical or financial viewpoints. Even if testing each compound were possible, combinations of compounds may behave synergistically (that is, the actual effect of the combination may exceed, or fall short of, that predicted for the individual component concentrations).

Bioassay toxicity testing exposes selected organisms to the plant effluent and identifies no-effect concentrations for each organism selected. The no-effect concentration represents the highest continuous concentration of effluent at which there is no observable effect. Generally, three species are tested, and toxicity is statistically evaluated (U.S. EPA, 1989). If effluent is found to be toxic, the plant will be required to attempt to identify and reduce or eliminate the cause. To do this, U.S. EPA has developed a comprehensive protocol, called a *toxicity reduction evaluation* (TRE), and supplemental procedural guidance (U.S. EPA, 1989). Because carrying out a TRE program involves complex tasks, contractual support may be needed.

SAMPLING

The design and implementation of an effective sampling program requires consideration of the specific reasons for sampling, manner in which samples are to be collected, sampling locations, analyses to be performed on the samples, and specific methods of sample collection and preservation. An effective sampling program is the cornerstone of a good process monitoring and control program. The following sections review the major issues to be considered in developing a sampling program.

REASONS FOR SAMPLING. The reasons for developing a sampling and characterization program for a treatment plant include compliance with legal requirements, process monitoring and control, and historical data collection. All are discussed below and should be part of the sampling and analytical program.

Legal Requirements. All WWTPs operating under the NPDES permit are required to conduct a sampling and analysis program. This program focuses primarily on monitoring effluent quality for evaluation of plant compliance with the permit's effluent limits. Each plant's NPDES permit specifies sampling location, type, and frequency; analyses to be performed at each sampling location; and frequency of reporting the analytical results to the regulatory agency. These permits also specify that the sampling and analysis must comply with either U.S. EPA's *Methods for Chemical Analysis of Water and Wastes* (U.S. EPA, 1983) or *Standard Methods* (APHA et al., 1998), as specified in 40 *CFR* Part 136 of the *Federal Register* (Guidelines Establishing Test Procedures for the Analysis of Pollutants, 1999). Failure to conduct the required program as specified in the permit could subject the plant and its personnel to criminal and civil penalties, including incarceration and fines.

Process Monitoring and Control. The sampling and analyses required for NPDES permit compliance provide data on the quality of the plant effluent. Evaluation and

control of the treatment unit processes require additional sampling and analyses. An effective sampling program provides information on loading and performance of each unit process. These data allow the operator to anticipate the need for operational adjustments based on changes in process performance and on review of past operating records. Visual inspection, coupled with online instrumentation, such as pH and conductivity, also provides data on system discharges that can affect treatment systems. Processes can be adjusted before they affect the plant's biological systems.

Historical Data Collection. A historical database for the WWTP benefits both the plant operators and design engineers. In general, the same data collected for process monitoring and control can be retained for the database. Examination will show trends in plant loading and performance that can be used to predict when plant expansion or upgrading is needed. The operator may also examine the historical record to determine whether repetitive or seasonal conditions indicate successful control actions. A regular review of these data helps the operator develop an understanding of the plant's operational characteristics. Although some records are required to be kept for only three to five years, it is wise to retain all data, if possible. The statue of limitations for some U.S. EPA permits can be as long as seven years.

Types of Sampling. The purpose of a sampling program is to provide samples of wastewater, sludges, and receiving streams for analyses. If the samples collected do not accurately reflect the composition of the stream or process to be analyzed, decisions to make system changes based on the analyses of these samples may be erroneous.

Samples can be collected in several different ways, depending on the types of information required and the nature of the process to be analyzed. Samples can be collected manually or automatically, and, once collected, individual samples can be retained or composited to form a single sample. Online analyzers provide continuous operating data for some parameters, such as pH, conductivity, temperature, and dissolved oxygen. The plant's NPDES permit specifies the sample type to be collected for each required analysis. U.S. EPA has specific definitions for composite and grab samples and sample preservation techniques. Discussions of the various sample types and their appropriate uses follow.

Grab Samples. A grab sample is a discrete sample that is collected manually. Grab samples are used if the operator must know the characteristics of the process stream soon after the sample's collection. Grab samples serve to characterize variations of the waste stream over time. They also allow analysis of unstable parameters soon after sample collection and are required for many permit constituents. Examples of such parameters include pH, dissolved oxygen, chlorine residual, soluble sulfide, FOG,

hexavalent chromium, and indicator bacteria. Other situations appropriate for grab sampling are

- A "slug" discharge's composition must be determined to identify its source and potential effects on the treatment processes.
- The flow to be sampled occurs intermittently and during short periods.
- Intensive sampling would not be justified because the process stream's composition is reasonably constant. That assumption should be periodically verified by the collection of multiple samples during a time period long enough to determine the variations of wastewater characteristics.
- The operator checks whether the composite sample masks short-term variations in the wastewater characteristics. For example, a short-term, high-BOD discharge may affect a biological system and yet be hidden by the dilution effects of the composite sample. Wide variations in parameters such as BOD or pH could bar adequate treatment without equalization, pretreatment, or neutralization. Sequential grab samples offer the only means of measuring these variations. Online analyzers, however, may alert the operators when grab samples are needed.
- The constituents to be analyzed (i.e., purgable organic compounds, phenols, and cyanide) are unstable or extremely difficult to preserve; the samples must therefore be analyzed immediately or be stored under special conditions to prevent loss of the unstable constituents.

Composite Samples. A composite sample is a single sample prepared by combining or compositing a number of grab samples during a specific period, typically 24 hours. A composite sample, prepared either manually or with automatic sampling equipment, provides information on the average characteristics of the sample over the specified period. The specific conditions appropriate for composite sampling include

- The plant's permit requires collection of a composite sample.
- The test data will be used to calculate plant removal efficiencies.
- Average data are needed to adjust plant processes. If extreme variations in waste characteristics occur, grab data should supplement the composite data, as discussed previously.

For a 24-hour composite, the sample holding time begins after the last grab sample is added to the samples collected and combined during the previous 24-hour period.

Composite samples include two general categories: time-composite (fixed-volume or simple composites) and flow-proportioned.

Time composite. To create a time-composite sample, the operator collects a fixed-volume sample at specific time intervals and combines them. Such sampling is appropriate for process streams with a composition not strongly flow-dependent, such as the contents of activated sludge aeration tanks. Time-composite samples can be collected either manually or automatically. The total volume of the composite sample depends on the number and type of analyses to be performed. After the 24-hour composite sample volume and grab sample frequencies are determined, the volume of each grab sample can be calculated as follows:

$$\text{Number of samples/d} = 24\ \text{h/d} \times \text{number of samples/h} \tag{17.10}$$

$$\text{Volume of each sample} = \text{composite sample volume/number of grab samples} \tag{17.11}$$

For example, if a final sample volume of approximately 4 L (1 gal) is required for a 24-hour composite sample and individual samples are to be collected every 2 hours, the individual sample volume is calculated as follows:

$$\text{Number of samples/d} = 24\ \text{h/d} \times (1\ \text{sample/2 h}) = 12\ \text{samples/d}$$
$$\text{Volume of each sample} = (4\ \text{L} \times 1000\ \text{mL/L})/(12\ \text{samples}) = 333\ \text{mL/sample}$$

A grab sample must be transferred quickly while mixing, first from the collection to the measuring device and then to the composite container. Such handling prevents settling and minimizes sampling error.

The sampling frequency capability of automatic samplers far exceeds the capability possible with manual sampling. Automatic sampling reduces the probability of missing short-term variations in the process stream. As a general sample frequency guideline, one sample every four hours is sufficient; however, variable processes may demand more frequent sampling.

Flow-proportioned composite. A flow-proportioned composite sample requires varying either the volumes among the grab samples or the sampling frequency, to weight the final sample in proportion to the several flowrates measured during the composite sample period. Such a composite contains wastewater reasonably equivalent to the flow-weighted average composition of the process stream during the composite sampling period. In effect, the total composite volume collected is proportional to the total flow volume past the sampling point. Accordingly, flow-proportioned composite sampling demands accurate measurements of the varying flowrates of the process stream.

A flow-proportioned composite, typically required by the plant's NPDES permit, is a more representative sample than a fixed-volume composite for a varying process

stream. The former type of sampling is often required for plant influent, effluent, and many internal process streams.

A variable-volume technique for forming the flow-proportioned composite is the most practical with manual sampling. In this technique, samples are taken at equal time intervals, but the sample volume, named an *aliquot*, varies directly with the flowrate at the moment of sampling. A simple step-by-step procedure for the variable volume technique is as follows:

1. Determine the desired composite sample volume (in milliliters) based on the analyses to be performed. *Standard Methods* (APHA et al., 1998) contains required sample volumes.
2. Divide the composite sample volume by the average flow during the sampling period.
3. Divide the resulting value in step 2 by the number of samples to be collected during the sample period.
4. Multiply the result in step 3 by the lowest readable flow unit for the flow stream and round to a whole number. This number represents the number of milliliters to be collected per unit of flow at each sample time.
5. Develop a table showing the volume to be collected at each of several flowrates within the probable flow range during the composite period by multiplying each flowrate by the number calculated in step 4. Alternatively, the desired volume can be calculated directly at each sampling time by multiplying the measured flow by the milliliters per unit flowrate figure calculated in step 4.

If plant flowrates vary significantly on a seasonal basis, repeating the above process seasonally may be necessary as the flowrates change. In this way, seasonal sample volume to flow factors can be developed.

A numerical example of the above five-step procedure follows:

1. Assume a final sample volume of approximately 5000 mL (1.3 gal) is required. Assume that samples will be collected hourly and that the average plant flow is 2.5 mgd, with a minimum reading of 0.1 mgd.
2. Divide 5000 mL by 2.5 mgd, which gives 2000 mL/mgd.
3. Divide 2000 mL/mgd by 24 samples, which gives 83.33 mL/mgd/sample.
4. Round 83.3 to 80 and multiply by the minimum measurable flow of 0.1 mgd to get 8 mL/0.1 mgd/sample.
5. If a proportional table is to be prepared, it should span the diurnal range of flow. Alternatively, use a factor of 80 mL/mgd. For example, at a flow of 4.1 mgd, the sample volume to be collected is 4.1 mgd $\times$ 80 mL/mgd = 328 mL.

If the flow is unknown when sampling, samples of equal volume may be taken during the composite sampling period and then stored. After the hourly flowrates are obtained, a composite sample can be prepared by varying each sample's volume in proportion to the corresponding measured flow. This procedure applies best to online sequential sampling with hourly collection of samples in discrete sample bottles.

A variable-frequency, flow-proportioned composite sample is composed of fixed-volume samples with variable intervals between the times of sample collection. The intervals between samples are proportional to the measured flows. This technique, often used with automatic sampling, can result in accurate composite samples. Basically, the sampler, coupled to the flow meter, collects a sample when a specific volume of flow passes the sampling point. That volume depends on the average plant flow, individual sample volume, and total composite sample volume needed for the analyses. The procedure used to determine the flow volume for each sample follows:

1. Determine the final composite sample volume needed for all analyses.
2. Divide the composite sample volume by the volume of each sample to be collected. This gives the number of samples to be collected each day.
3. Divide the average daily flow by the number of samples to be collected. This gives the volume of flow that must pass through the flow meter before each sample is collected.

The method of setting the volume of each sample depends on the type of sampler used. The instruction manual for the automatic sampler provides guidance.

Continuous. A continuous sample is one whose parameters are measured continuously. This method requires instrumentation with a sensor(s) (e.g., an electrode) that is in constant contact with the sample source. The sensor(s) sends signals to a recording device (e.g., a computer), which constantly records data. To function properly, instrumentation must be serviced regularly. The instrument manual provides guidance. Common parameters subject to continuous sampling include pH, dissolved oxygen, temperature, conductivity, and flowrate.

SAMPLING EQUIPMENT. Sampling equipment encompasses sophisticated devices, such as automatic samplers; simple devices, such as weighted buckets attached to a rope, beakers, and other containers attached to extension rods; and valved taps in flowing pipelines. The simple devices are typically constructed by plant operations personnel to fit the plant's physical conditions. Of course, their construction must

avoid use of materials that could contaminate the sample. For example, brass or galvanized sampling devices will result in significant heavy metals contamination of samples. Such contamination could inhibit bacterial activity in the BOD test. In general, plastic sampling devices are the least likely to contaminate samples. However, glass devices must be used for FOG.

In some cases, the operator may need a vertical profile of the wastewater contained in a treatment unit. To achieve this, a coring device can provide a continuous top-to-bottom core sample, or a discrete sampling device can be actuated to take a sample at the desired depth. An example of a coring device is the "sludge judge". It provides a core sample that can be visually examined before analysis. The Van Dorn sampler, a discrete sampling device, is triggered at the desired depth to collect a sample. Other types of sampling devices are described in *Standard Methods* (APHA et al., 1998).

Many types of automatic sampling devices are marketed. Before any of these devices are purchased, their proposed use and installation require careful consideration. *Instrumentation in Wastewater Treatment Facilities* (WEF, 1993) discusses the selection and installation of automatic sampling devices. Plant personnel, when choosing the sample piping that feeds the samplers, should avoid pipe material that could contaminate the sample. Generally, polyvinyl chloride pipe is the best for sample piping.

Often, automatic sampling devices are ignored until a problem develops, simply because they function without operator attention. Ensuring reliable operation of the devices requires an ongoing maintenance and surveillance program. Routine monitoring of the sampler operation throughout the day allows timely detection of malfunctions and prompt correction.

Operations personnel should know the expected volumes of samples collected at various times throughout the day so that departures can be detected. When a problem is detected with an automatic sampling device, manual sampling should be substituted until the automatic sampling unit is repaired and put back online. All sampling equipment, including intakes and supply lines, need regular inspection and cleaning to allow representative sampling.

Regular cleaning of the samplers and the lines leading to them is necessary to prevent biological fouling and alteration of the sample. To avoid sample contamination, conduct the following:

- Clean the sampling equipment and containers before the sampling event.
- Place samples in a tightly sealed container to eliminate contamination from the environment or from other samples.

- Ensure that sample collection bottles have been acid-washed (when appropriate) and rinsed with distilled water and dried before sampling.
- Use freshly prepared preservatives.
- Analyze preservative blanks to check for contamination of the chemical preservatives.
- Identify sample containers properly with labels to avoid mix up or confusion of the samples collected.
- Analyze blanks on automatic sampling equipment to determine whether or not the equipment is causing contamination.

Because most samplers are equipped with built-in refrigerators, sample temperature should be monitored regularly to ensure the proper temperature for sample storage. Samplers that are located outside during freezing weather may require heating to prevent freezing of the sample and sample lines.

Several types of online analyzers are used in WWTPs. Such analyzers are best applied to influent monitoring of potential toxic slug discharges and to some online control functions. Meters placed online can measure temperature, conductivity, total organic carbon, phosphorus, nitrogen, and pH. Such measurements offer reliable, early warnings of industrial slug discharges as they enter the plant. These meters require extensive maintenance to ensure that they remain in operation. The warnings can sometimes allow the plant operator to take the steps necessary to protect the plant from the industrial discharge. Online analyzers can also monitor the effluent discharge on a continuous basis as required by some plants' discharge permits.

Online analyzers for dissolved oxygen and respiration rate provide the capability of automatically controlling dissolved oxygen in the activated sludge system and continuously monitoring dissolved oxygen concentrations in the effluent or any other process streams. Chlorine residual analyzers provide a means of automatically monitoring and controlling the chlorination rate. Online control systems, which combine dissolved oxygen and chlorine residual analyzers, offer the capabilities of optimizing dissolved oxygen and chlorine control systems, both to minimize treatment costs and improve process stability. Reliable performance of online control systems demands a routine (sometimes extensive) maintenance and calibration program. Analyzers measuring nutrients such as phosphorus or nitrogen can be used by operational staff to help control chemical feed systems.

REPRESENTATIVE SAMPLING. The primary goal of sampling is to ensure that the sample obtained will be representative of the flow stream to be analyzed. Because

the sample represents only a small portion of the flow, both sample site selection and sampling techniques are crucial. Failure to obtain a representative sample can produce invalid data, leading to erroneous process control decisions. Several guidelines to ensure representative sampling include the following:

- Collect samples at points where the sample stream is well-mixed, such as in aerated channels or at locations of hydraulic turbulence, such as downstream from a Parshall flume.
- Avoid taking samples where settling occurs or where large chunks of floating debris exist.
- Avoid areas with nonrepresentative deposits or solids accumulated on channel walls.
- Collect influent samples at a point upstream of any recycle stream discharge.
- Collect solids samples at the tank discharge point.
- After choosing the sample sites, mark them with paint or some other means and always sample at those locations.
- Where samples are to be collected from flowing pipes, keep the sample line as short as possible. Excessively long sample lines risk inadequate flushing before taking the sample and consequently sample alteration from chemical and biological activity within the sample pipe. Use the appropriate container and material for the collection.
- Clearly mark sample containers for each sample location. Do not rotate containers from site to site.
- Keep the sampling devices at each sampling site. Use of the same sampling device at multiple sites risks cross-contamination of samples. Rinse sampling and measuring devices with the sample before transferring the sample to the sample container.
- Keep samples thoroughly mixed throughout the collection and measuring procedure to prevent settling.
- After collection, store the samples so that their composition will not change before testing. Refrigeration at 4°C is typically appropriate. Check *Standard Methods* (APHA et al., 1998) for specific storage requirements.

SAMPLING LOCATIONS. The scope and frequency of sampling and analyses at a treatment plant depend on regulatory requirements, plant size and complexity, plant design, and process control needs, including the variability of influent characteristics. Table 17.2 presents suggested sampling locations, sampling frequencies, and analytical schedules for various unit treatment processes.

TABLE 17.2 Suggested sampling locations, typical analyses performed, sampling frequencies, and type of sample required for wastewater treatment unit processes.

			Sample		
Unit processes	**Sampling location**	**Analysis**	**Use[a]**	**Frequency[a]**	**Type[a]**
Single-stage waste stabilization lagoon	Plant influent	BOD	PP	W	C
		TSS	PP	W	C
		pH	PC	D	G
	Pond	pH	PC	D	G
		DO	PC	D	G
		Temperature	PC	D	G
	Plant effluent	BOD	PP	D	C
		TSS	PP	W	C
		pH	PP	W	G
		DO	PP	D	G
		Fecal coliform	PP	D	G
		Chlorine residual	PP	D	G
Primary treatment	Primary influent	BOD	PP	D	C
		TSS	PP	W	C
	`	pH	PC	W	G
		TKN	PP	D	G
		NH_3	PP	W	G
	Primary effluent	BOD	PP	W	C
		TSS	PP	W	C
		DO	PP	W	G
		pH	PP	D	G
	Primary sludge	TS	PC	D	C
		VS	PC	W	C
Trickling filter and rotating biological contactor	Effluent from primary treatment (filter influent)	BOD	PP	D[b]	C
		TSS	PP	D[b]	C
		pH	PC	D[b]	G
	Filter effluent	DO	PC	D	G
		Temperature	PC	D	G
		NH_3	PC	W	G
		NO_3	PC	W	G
	Final settling tank effluent	BOD	PP	D[b]	C
		TSS	PP	D[b]	C
		DO	PP	D[b]	G
		Fecal coliform	PP	D	G
		Chlorine residual	PP	D[b]	G
		pH	PP	D[b]	G
		NO_3	PP	W	G
		NH_3	PC	W	G

TABLE 17.2 Suggested sampling locations, typical analyses performed, sampling frequencies, and type of sample required for wastewater treatment unit processes (*continued*).

			Sample		
Unit processes	**Sampling location**	**Analysis**	**Use[a]**	**Frequency[a]**	**Type[a]**
	Final settling tank sludge (secondary sludge)	TS	PC	D[b]	C
		VS	PC	D[b]	C
Activated sludge	Primary effluent	BOD	PP	D[b]	C
		TSS	PP	D[b]	C
		pH	PC	D[b]	G
	Mixed liquor	DO	PC	D	G
		Temperature	PC	D	G
		TSS	PC	D[b]	C
		VSS	PC	D[b]	C
		NO_3	PC	W	G
	Return sludge	TSS	PC	D[b]	C
	Final settling tank effluent	BOD	PP	D[b]	C
		TSS	PP	D[b]	C
		DO	PP	D	G
		Fecal coliform	PP	D[b]	G
		Chlorine residual	PP	D	G
		pH	PP	D	G
		TKN	PP	W	G
		NH_3	PP	W	G
		NO_2	PP	W	G
	`	NO_3	PP	W	G
Anaerobic digestion	Digester feed	TS	PP	D	C
		VS	PP	D	C
		pH	PC	D	G
		Alkalinity	PC	W	G
	Digester contents	Temperature	PC	D	G
		Volatile acids	PC	W	G
		Alkalinity	PC	W	G
		pH	PC	D	G
		Heavy metals	PC	M	G
	Digested sludge	Volatile acids	PC	W	G
		TS	PP	D	G
		VS	PP	D	G
		TKN	PC	W	G
	Supernatant	TS	PP	D	C
		TSS	PC	D	C
		BOD	PC	D	C
	Digester gas	CH_4 or CO_2	PC	D	G

TABLE 17.2 Suggested sampling locations, typical analyses performed, sampling frequencies, and type of sample required for wastewater treatment unit processes (*continued*).

			Sample		
Unit processes	**Sampling location**	**Analysis**	**Use[a]**	**Frequency[a]**	**Type[a]**
Aerobic digestion	Digester influent	TS	PP	D	C
		VS	PP	D	C
		pH	PC	D	G
		NO_3, NH_4	PP	W	G
		Alkalinity	PC	W	G
	Digester contents	pH	PC	D	G
		Temperature	PC	D	G
		DO	PC	D	G
		NO_3, NH_4	PP	W	G
		TS	PP	D	C
		VS	PP	D	C
		Alkalinity	PC	W	G
	Settled digested sludge	Volatile acids	PC	W	G
		TS	PP	D	C
		VS	PP	D	C
		NO_3, NH_4	PP	W	G
		pH	PC	D	G
	Supernatant	TS	PP	D	C
		TSS	PP	D	C
		NO_3, NH_4	PP	W	G
		BOD	PC	D	C

[a] D = daily; W = weekly; M = monthly; C = composite sample; G = grab sample; PC = process control; and PP = plant performance.
[b] Frequency could be reduced if the discharge permit allowed and/or process upsets were infrequent.

Table 17.2 serves as a starting point for developing the sampling and analysis program. It includes only suggestions, to be adjusted as necessary, based on each plant's operational and regulatory requirements. At a minimum, Table 17.2 must be expanded to include all tests specified in the plant's NPDES permit.

SAMPLE VOLUME. After determining the specific analyses required for each sample site, the sample volume necessary for those analyses can be calculated.

The total sample volume required represents the sum of the sample volumes listed for each analytical measurement to be performed, plus any additional volume necessary for replicating analyses and analytical reruns. As a general rule, the calculated volume should be increased by 50% to offset possible reduced sample volumes resulting from below-average flows and other losses. The analytical procedure used for each test

generally governs the size of the sample (aliquot). As a general rule, the operator should use the largest practical volume of sample possible, because, as sample volumes decrease, the chance for nonrepresentative results increases because of sampling error. The risk of nonrepresentative results is especially high for heterogeneous samples, such as raw wastewater.

SAMPLE HANDLING. Following collection, samples must be handled properly to ensure that they remain unchanged. Handling requires proper preservation before analysis, proper labeling, and proper transportation to the testing site.

Preservation. As the best analytical policy, analyses should closely follow sample collection, even with recommended sample preservation procedures, to reduce storage effects on sample composition. When possible, immediate analysis is best. Because immediate analysis is not always practical, storage of the samples must adhere rigorously to procedures that will prevent chemical and biological reactions from changing the sample characteristics. Table 17.3 lists the volume required, container type, preservation method, and holding times for most analytical measurements. Although Table 17.3 includes a broad array of preservation techniques, refrigeration to 4°C is sufficient for most grab and composite samples that are to be held no longer than 24 hours. Further preservation, and possibly sample splitting, may be required for longer-term storage (APHA et al., 1998; U.S. EPA, 1983). For those analyses with indicated holding times of less than 24 hours, samples cannot be composited.

Chain of Custody. *Chain of custody* is a legal term for an unbroken sequence of possession from sampling through analysis. To prevent any possibility of confusion regarding the sampling location, chain-of-custody procedures should be followed. This requires attaching a special information label to each sample bottle or marking the necessary information on the bottle with a waterproof marker. The information provided on each bottle should include the following:

- Sample source,
- Sample location,
- Sample date and time,
- Sample type (grab or composite),
- Preservative(s) added,
- Required analyses,
- Date submitted to the laboratory, and
- Signature of the person collecting the sample.

TABLE 17.3 Required containers, preservation techniques, and holding times.

Parameter name	Container[a]	Volume required, mL	Preservation[b,c]	Maximum holding time[d]
Bacterial tests				
Coliform, fecal and total	P, G	—	Cool, 4°C, 0.008% $Na_2S_2O_3$[e]	6 hours
Fecal streptococci	P, G	—	Cool, 4°C, 0.008% $Na_2S_2O_3$[e]	6 hours
Inorganic tests				
Acidity	P, G	100	Cool, 4°C	14 days
Alkalinity	P, G	200	Cool, 4°C	14 days
Ammonia	P, G	400	Cool, 4°C, H_2SO_4 to pH < 2	28 days
BOD	P, G	1000	Cool, 4°C	48 hours
Bromide	P, G	100	None required	28 days
CBOD	P, G	1000	Cool, 4°C	48 hours
COD	P, G	100	Cool, 4°C, H_2SO_4 to pH < 2	28 days
Chloride	P, G	50	None required	28 days
Chlorine, total residual	P, G	500	None required	Analyze immediately
Color	P, G	500	Cool, 4°C	48 hours
Cyanide, total and amenable to chlorination	P, G	500	Cool, 4°C, NaOH to pH < 12, 0.6 g ascorbic acid[e]	14 days[f]
Fluoride	P	300	None required	28 days
Hardness	P, G	100	HNO_3 to pH < 2, H_2SO_4 to pH < 2	6 months
pH	P, G	25	None required	Analyze immediately
Kjeldahl and organic nitrogen	P, G	500	Cool, 4°C, H_2SO_4 to pH < 2	28 days
Metals				
Chromium VI	P, G	500	Cool, 4°C	24 hours
Mercury	P, G	500	HNO_3 to pH < 2	28 days
Metals, except chromium and mercury	P, G	200	HNO_3 to pH < 2	6 months
Nonmetals				
Nitrate	P, G	100	Cool, 4°C	48 hours
Nitrate nitrite	P, G	200	Cool, 4°C, H_2SO_4 to pH < 2	28 days
Nitrite	P, G	100	Cool, 4°C	48 hours
Oil and grease	G	1000	Cool, 4°C, H_2SO_4 to pH < 2	28 days
Organic carbon	P, G	100	Cool, 4°C, HCl or H_2SO_4 to pH < 2	28 days
Orthophosphate	P, G	50	Filter immediately, cool, 4°C	48 hours
Oxygen, dissolved, probe	G, BT	300	None required	Analyze immediately
Phenols	G only	500	Cool, 4°C, H_2SO_4 to pH < 2	28 days
Phosphorus, elemental	G	50	Cool, 4°C	48 hours

TABLE 17.3 Required containers, preservation techniques, and holding times.

Parameter name	Container[a]	Volume required, mL	Preservation[b,c]	Maximum holding time[d]
Phosphorus, total	P, G	50	Cool, 4°C, H_2SO_4 to pH < 2	28 days
Residue, total	P, G	100	Cool, 4°C	7 days
Residue, filterable	P, G	100	Cool, 4°C	48 hours
Residue, nonfilterable (TSS)	P, G	100	Cool, 4°C	7 days
Residue, settleable	P, G	1000	Cool, 4°C	48 hours
Residue, volatile	P, G	100	Cool, 4°C	7 days
Silica	P	50	Cool, 4°C	28 days
Specific conductance	P, G	500	Cool, 4°C	28 days
Sulfate	P, G	50	Cool, 4°C	28 days
Sulfide	P, G	500	Cool, 4°C, add zinc acetate plus sodium hydroxide to pH > 9	7 days
Sulfite[g]	P, G	50	None required	Analyze immediately
Surfactants	P, G	—	Cool, 4°C	48 hours
Temperature	P, G	1000	None required	Analyze immediately
Turbidity	P, G	100	Cool, 4°C	48 hours
Winkler	G, BT	300	Fix on sight and store in dark	8 hours
Organic tests[h]				
Purgeable halocarbons	G, PLS	—	Cool, 4°C, 0.008% $Na_2S_2O_3$,[e]	14 days
Purgeable aromatic hydrocarbons	G, PLS	—	Cool, 4°C, 0.008% $Na_2S_2O_3$,[e] HCl to pH = 2	14 days
Acrolein and acrylonitrite	G, PLC	—	Cool, 4°C, 0.008% $Na_2S_2O_3$,[e] adjust pH to 4 to 5[j]	14 days
Phenols[k]	G, PLC	—	Cool, 4°C, 0.008% $Na_2S_2O_3$[e]	7 days until extraction, 40 days after extraction
Benzidines[k]	G, PLC	—	Cool, 4°C, 0.008% $Na_2S_2O_3$[e]	7 days until extraction[l,m]
Phthalate esters	G, PLC	—	Cool, 4°C	7 days until extraction, 40 days after extraction
Nitrosamines[k,n]	G, PLC	—	Cool, 4°C, 0.008% $Na_2S_2O_3$,[e] store in dark	40 days after extraction
PCBs[k] acrylonitrite	G, PLC	—	Cool, 4°C	40 days after extraction
Nitroaromatics and isophorone[k]	G, PLC	—	Cool, 4°C, 0.008% $Na_2S_2O_3$,[e] store in dark	40 days after extraction
Polynuclear aromatic hydrocarbons	G, PLC	—	Cool, 4°C, 0.008% $Na_2S_2O_3$,[e] store in dark	40 days after extraction
Haloethers[k]	G, PLC	—	Cool, 4°C, 0.008% $Na_2S_2O_3$[e]	40 days after extraction
Chlorinated hydrocarbons[k]	G, PLC	—	Cool, 4°C	40 days after extraction
TCDD[k]	G, PLC	—	Cool, 4°C, 0.008% $Na_2S_2O_3$[e]	40 days after extraction

TABLE 17.3 Required containers, preservation techniques, and holding times (*continued*).

Parameter name	Container[a]	Volume required, mL	Preservation[b,c]	Maximum holding time[d]
Pesticide tests				
Pesticides[k]	G, PLC	—	Cool, 4°C, pH = 5 to 9	40 days after extraction
Radiological tests				
Alpha, beta, and radium	P, G	—	HNO_3 to pH < 2	6 months

[a] P = polyethylene; G = glass; BT = bottle and top; PLS = polytetrafluoroethylene-lined septum; and PLC = polytetrafluoroethylene-lined cap.

[b] Sample preservation should be performed immediately after sample collection. For composite chemical samples each aliquot should be preserved at the time of collection. When use of an automated sampler makes it impossible to preserve each aliquot, then chemical samples may be preserved by maintaining them at 4°C until compositing and sample splitting are completed.

[c] When any sample is to be shipped by common carrier or sent through the U.S. mail, it must comply with the U.S Department of Transportation Hazardous Materials Regulations (49 CFR Part 172). The person offering such material for transportation is responsible for ensuring such compliance. The Office of Hazardous Materials, Materials Transportation Bureau, Department of Transportation, has determined that the Hazardous Materials Regulations do not apply to the following materials: hydrochloric acid (HCl) in water solutions at concentrations of 0.04% by weight or less (pH about 1.96 or greater); nitric acid (HNO_3) in water solutions at concentrations of 0.15% by weight or less (pH about 1.62 or greater); sulfuric acid (H_2SO_4) in water solutions at concentrations of 0.35% by weight or less (pH about 1.15 or greater); and sodium hydroxide (NaOH) in water solutions at concentrations of 0.08% by weight or less (pH about 12.30 or less).

[d] Samples should be analyzed as soon as possible after collection. The times listed are the maximum times that samples may be held before analysis and still be considered valid. Samples may be held for longer periods only if the permittee or monitoring laboratory has data on file to show that the specific types of samples under study are stable for the longer time, and has received a variance from the Regional Administrator under § 136.3(e). Some samples may not be stable for the maximum time period given in the table. A permittee or monitoring laboratory is obligated to hold the sample for a shorter time if knowledge exists to show that this is necessary to maintain sample stability. See § 136.3(e) for details.

[e] Should only be used in the presence of residual chlorine.

[f] Maximum holding time is 24 hours when sulfide is present. Optionally all samples may be tested with lead acetate paper before pH adjustments to determine if sulfide is present. If sulfide is present, it can be removed by the addition of cadmium nitrate powder until a negative spot is obtained. The sample is filtered and then NaOH is added until a pH of 12 is reached.

[g] Samples should be filtered immediately on-site before adding preservative for dissolved metals.

[h] Guidance applies to samples to be analyzed by GC, LC, or GC–MS for specific compounds.

[i] Sample receiving no pH adjustment must be analyzed within 7 days of sampling.

[j] The pH adjustment is not required if acrolein will not be measured. A sample for acrolein receiving no pH adjustment must be analyzed within 3 days of sampling.

[k] When the extractable analytes of concern fall within a single chemical category, the specified preservative and maximum holding times should be observed for optimum sample integrity. When the analytes of concern fall within two or more chemical categories, the sample may be preserved by cooling to 4°C, reducing residual chlorine with 0.008% sodium thiosulfate, storing in the dark, and adjusting the pH to 6 to 9; samples preserved in this manner may be held for 7 days before extraction, and 40 days after extraction. Exceptions to this optional preservation and holding time procedure are noted in footnote e (the requirement for thiosulfate reduction of residual chlorine), and footnotes l and m (the analysis of benzidine).

[l] If 1,2-diphenylhydrazine is likely to be present, adjust the pH of the sample to 4.0 ± 0.2 to prevent rearrangement to benzidine.

[m] Extracts may be stored up to 7 days before analysis if storage is conducted under an inert (oxidant-free) atmosphere.

[n] For the analysis of diphenylnitrosamine, add 0.008% $Na_2S_2O_3$ and adjust the pH to 7 to 10 with NaOH within 24 hours of sampling.

[o] The pH adjustment may be performed on receipt at the laboratory and may be omitted if the samples are extracted within 72 hours of collection. For the analysis of aldrin, add 0.008% $Na_2S_2O_3$.

All of the above data are needed for samples transported off-site to an outside analytical laboratory. For routine samples collected and analyzed on-site, the data may be limited to the first four items on the list, but only if there is no possibility of confusion.

The chain-of-custody is important to protect the operating staff and facility owner. For example, if samples are to be used in legal proceedings, they require strict adherence to chain-of-custody procedures. All samples are to be accurately identified and carefully transported from the collection site to the laboratory to avoid sample mixups. After collection, samples are transported to the laboratory immediately and then logged in and stored in a refrigerator at 4°C until they can be analyzed or further preserved.

PROCESS CONTROL SAMPLING. *Standard Methods* (APHA et al., 1998) is a joint publication of the American Public Health Association, American Water Works Association, and Water Environment Federation. Revised and updated every three to five years since 1905, it is designed and written for use by trained laboratory personnel. *Standard Methods* (APHA et al., 1998) or *Methods for Chemical Analysis of Water and Wastes* (U.S. EPA, 1983) provide detailed procedures to be followed when performing analyses required by the NPDES permit because of legal requirements.

Some wastewater treatment plant operators may find *Standards Methods* (APHA et al., 1998) complex and difficult to follow because of its detailed discussions and procedures. In that case, operators may refer to *Basic Laboratory Procedures for Wastewater Examination* (WEF, 2002b). The publication, which is not intended to be a substitute for *Standard Methods* (APHA et al., 1998), is a simplified guide written especially for operators and technicians of smaller plants. The two publications may be used together. As the publication's simplified techniques are mastered, the operator should read the more detailed procedures in *Standard Methods* (APHA et al., 1998) to learn of possible pitfalls and interferences. Use of the simplified methods should be avoided for the examination of wastewaters containing significant industrial waste.

Laboratory results are valuable as a record of plant operation. These data inform the operator how efficiently the plant is operating, provide warning of troubles that may be developing in the processes, and enable timely correction of these troubles.

Plant operation records are also important to the operating staff because they provide the necessary documentation required by the regulatory agency to ensure that certain levels of treatment were achieved and that certain activities occurred. In this age of regulatory enforcement, these records may be the only means by which the operating staff can ensure that they can legally document what happened, when it occurred, and how a problem was corrected. It is important that operators keep well-

maintained, organized, and accurate records to demonstrate to the regulatory agency that their facility is meeting the compliance requirements.

AIRSPACE MONITORING

Monitoring of airspace has become increasingly necessary, both because of safety issues associated with confined space entry and because of a heightened sensitivity of the plant's neighbors and workers to odors and volatile chemicals generated at treatment facilities. Odor control is discussed in Chapter 13. Before entering any confined space, testing of its atmosphere is required to ensure safe working conditions. Sampling typically provides for analyses of hydrogen sulfide, oxygen deficit, and explosivity. Several combined instruments, available through safety supply outlets, can provide this information. Reliable operation of such instruments demands their regular calibration and maintenance. Sensors should be replaced at intervals recommended by the manufacturer of each instrument. Chapter 5 covers confined space entry more thoroughly.

Airspace and offgas sampling may be required to meet National Institute for Occupational Safety and Health (Atlanta, Georgia) criteria or local air pollution control agency requirements. Sampling and analysis may simply involve measurement of specific constituents by drawing an air sample through a chemically treated tube that qualitatively indicates the concentration of a specific compound. At the other extreme, air sampling and analysis may be as complicated as collecting a sample for subsequent analysis with a sophisticated gas chromatograph–mass spectrometer system. This procedure requires expensive, specialized equipment but provides accurate qualitative and quantitative data and is necessary for obtaining data on volatile organic chemicals. Specific details concerning sampling and analysis for atmospheric parameters can be obtained from the procedures manuals provided with the equipment or from the laboratory that will receive the samples.

SAFETY AND HEALTH CONSIDERATIONS

Sampling and analysis activities include a number of aspects requiring special precautions or compliance with federal or state regulations. Sampling and analysis of wastewater samples exposes personnel to a variety of hazards, including risk of infection, if proper safety procedures are not followed. Laboratory work exposes employees to a variety of toxic and corrosive materials that require special handling and protective measures to ensure worker safety.

Chemical suppliers, laboratory manuals, and the plant operation and maintenance manual provide valuable information on the proper use and handling of chemicals and laboratory safety. Failure to follow proper procedures can expose employees to hazardous conditions unnecessarily and also compromise the quality of the data generated. Accordingly, all phases of the sampling and analysis process require careful attention. Employees must be informed of potential hazards associated with all phases of their jobs and the proper procedures for dealing with the hazards.

"Right-to-know" legislation, administered by the Occupational Safety and Health Administration (OSHA), requires employers to train their employees regarding hazard exposure. Each employer must develop a written hazard communication program explaining container labeling, location, and use of the material safety data sheet (MSDS); employee training and information; and related issues. A hazardous chemical inventory must be maintained, and an MSDS (available from suppliers) for all listed chemicals must be available. Plant managers need to learn the specific requirements of their state's program and take the necessary steps to carry them out. Refer to OSHA standards that pertain directly to laboratories and specific chemicals.

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Chapter 18

Preliminary Treatment

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INTRODUCTION

Preliminary treatment of wastewater includes screening, grit removal, odor control (where appropriate), and flow measurement (Figure 18.1). The removal of debris in the screening area and the removal of sand, rocks, gravel, and other inorganics in the grit-removal system protect downstream treatment processes. Should the screening or grit-removal equipment fail, other downstream treatment processes may also fail. Various screening and grit-removal systems exist to properly prepare influent wastewater for advanced treatment later in the plant.

It is important that operations and maintenance personnel follow safety guidelines specified by headworks equipment manufacturers and commonly practiced by the utility. This includes, but is not limited to, procedures describing appropriate equipment lockout, confined space entry, localized power interruption, and standby–rescue personnel during maintenance activities. Operations personnel must familiarize themselves with and respect safe operations guidelines recommended by the equipment manufacturers and maintain a clean, well-ventilated, and well-lit environment to prevent accidents.

Equipment and systems described in this section benefit from planned maintenance procedures. The utility should include the headworks in its program of routine inspection, lubrication, and repair, guided by recommendations of the equipment suppliers.

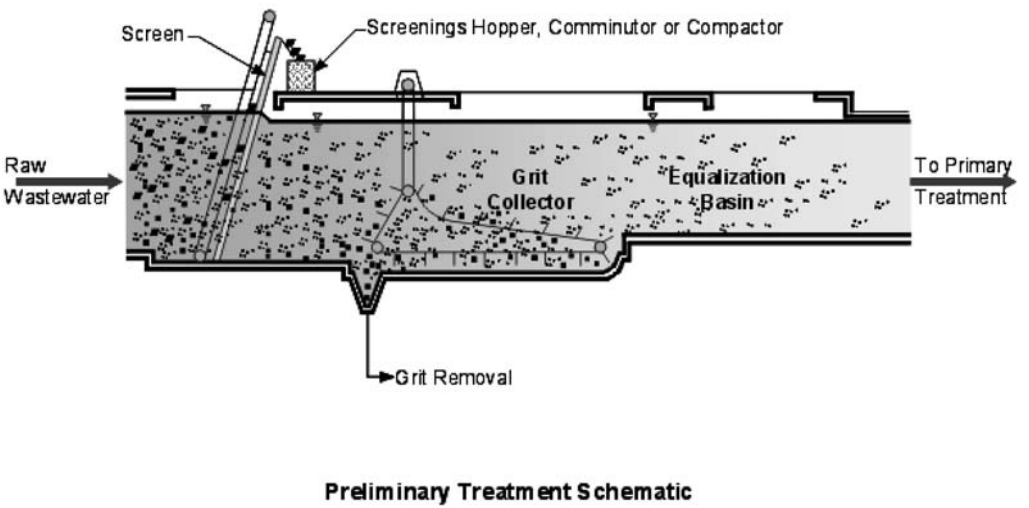


FIGURE 18.1 Preliminary treatment schematic.

SCREENING PROCESS

The screening process removes large solids and trash that could otherwise interfere with the operation of a wastewater treatment plant (WWTP). As the plant's first treatment unit, coarse screens protect plant equipment against damage such as clogging of pipes, pumps, and grit aeration diffusers. Fine screens are being used more frequently in wastewater treatment plants for added removal of debris. The debris captured on the bar screen depends on the bar spacing and the size, configuration, and amount of debris. If the bar spacing is too small, organics that should be treated by subsequent processes will be captured and removed; if too large, much debris will not be captured and will cause downstream difficulties.

Screenings debris accumulated on the screens is removed at appropriate intervals by the use of either manual or automatic control methods. The cleaning rate depends on many variables, including the type of collection system (separate or combined), demographics, diurnal-flow patterns, condition of collection system, and seasonal factors (such as leaves during the fall).

Debris removed from the coarse bar racks typically consists of wood, tree limbs, rocks, and other large items. Debris removed from the bar screens typically includes rags, small plastic objects, leaves, paper, and other small objects. Screenings may be loaded onto conveyors for transport elsewhere in the plant or deposited directly into containers. Ultimately, the screenings are transported for final disposal at a landfill or incinerator. Increasingly, screening presses and vacuum containers are being used at wastewater treatment plants to remove the liquid from the screenings before transport to remove excess water, volume, and weight.

EQUIPMENT. ***Trash/Bar Racks.*** Coarse screens are classified as either trash racks or bar screens, depending on the spacing between the bars. Trash racks, also called bar racks, are constructed of heavy, parallel rectangular or round steel bars with 50–150 mm (2–6 in.) spacing set in a channel. Bars are sloped at an angle ranging from 30 to 45 degrees from the vertical. Bar racks may be cleaned manually or mechanically with robust steel rakes. Some multichannel installations use a single rake mounted on a traveling bridge that moves from channel to channel. Trash racks are mainly used in wastewater plants that see high amounts of large debris.

Trash/bar racks require inspection for visible and audible indications of possible malfunctions, as recommended by the preventive maintenance procedures in the operation and maintenance (O&M) manuals. As a routine practice, the operator needs to observe all moving mechanisms to determine if the components are free of obstructions, properly aligned, moving at constant speeds, and producing no unusual vibrations. The operator must listen to all moving mechanisms and recognize their normal

operational sounds. For example, abnormal screeches could indicate lack of lubrication; thumps could indicate broken or loose components.

Preventive maintenance requires that worn parts and components be replaced before failure and that the proper lubrication of all moving parts be applied at the recommended intervals. The operator should always follow the manufacturer's recommendations on the type of lubricant to use because the lubricant's qualities are selected for the anticipated operating conditions and for compatibility with the materials used in the equipment.

Bar Screens. Bar screens resemble bar racks except that they have smaller clear spacing between the bars, typically 18.75–50 mm (0.75–2 in.). Bar screens are designed as stationary structures built into concrete channels. Some units are designed with cables or cog wheels attached to the submerged end of the screen and a pivot arrangement at the upper end to permit lifting of the submerged end for easy inspection and maintenance.

Bar screens are usually installed in a nearly vertical position, with a mechanical, sturdy steel raking device that cleans the screen. The bar screen is typically positioned at 15 to 30 degrees from the vertical for ease of operation of the raking mechanism. Many mechanically cleaned bar screen designs are currently used in wastewater treatment plants. These designs include cable and rake, continuous chain, catenary, reciprocating rake, and continuous self-cleaning.

The typical overall widths for a screen channel vary from 0.6 to 4.2 m (2 to 14 ft). The straining efficiency (screenings removal) of a screen and the hydraulic flow through the screen depend on the clear spacing between the bars. The smaller the spacing, the more debris is captured and the more head loss is developed across the screen. Sizing the screen opening usually depends on downstream operations and the maximum particle size they can effectively and economically remove. Screens with smaller spacing require wider channels for a given flow to enable flow to pass through the screens.

Most plants include two screening channels, especially when one or both channels are equipped with mechanically cleaned bar screens. Thus, if one unit malfunctions, the other unit and channel may remain in service during repairs. Stop gates for the channels allow diversion of flow to clean, maintain, and repair the screening equipment.

Influent flows should be equally distributed among all of the channels with screens to ensure uniform loading among the screens. Uneven loading will require more frequent cleaning of some screens than others.

A common type of mechanically cleaned bar screen is the front-cleaning unit with the rake mechanism on the upstream side of the bar screen (Figure 18.2). The typical front-cleaning unit includes a toothed hopper (rake) that swings out from the bar

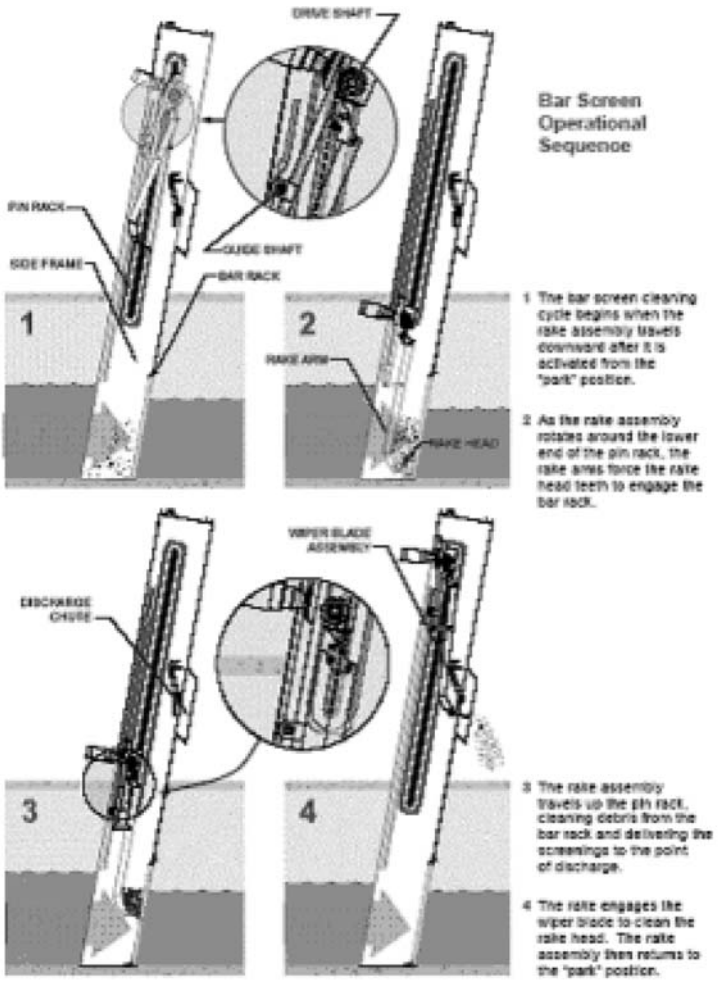


FIGURE 18.2 Front-cleaning bar screen (Courtesy of Vulcan Industries, Inc.).

screen as it travels down to the bottom of the channel. After reaching the bottom of the channel, cables, chains, or cog wheels draw the toothed hopper toward the bar screen. The teeth of the hopper (rake) then slide between the bars and, during the upward movement, drag the screenings out of the wastewater. A variation of this type of screen is the rear-cleaning unit with the rake mechanism on the downstream side of the bar screen and the rake teeth protruding through the bars to the upstream side.

Another type of mechanically cleaned bar screen is the continuous self-cleaning screen. This screen consists of a continuous belt of plastic or stainless steel elements that are pulled through the wastewater to provide screening along the entire length of

the screen. Continuous screens may have openings as small as 1 mm (0.039 in.). Solids are captured on the face of the screen and, as the belt rotates, teeth protrude on the upward movement to collect the screenings. Some of these screens include spray bars or brushes to improve the cleaning of the screening elements.

A reciprocating rake bar screen consists of stationary components (frame, bar rack, dead plate, pin rack) along which the rake assembly travels. The rake assembly consists of drive assembly, rake arms, rake, and cam followers, the latter controlling rake position. Unlike continuous screening devices, the reciprocating rake bar screen usually goes through a single operation cycle (from top rest position, to downward stroke with rake in open position, to upward cleaning stroke with rake engaged in bar screen, to screenings discharge operation, and return to top rest position), when initiated by timer or differential water level signal.

Under normal operation of a mechanically cleaned bar screen, the operator should visually check the equipment several times during a shift to ensure that it functions properly. Use of local manual controls allows immediate observation of the operation of the mechanically cleaned bar screen or other equipment, even though it may be inactive when inspection begins. Screens should be operated with manual switching until the accumulated solids are cleared. While the equipment is running, the operator needs to check for unusual noises, scraping of the screen, jerking motion of the drive mechanisms, over-accumulated screenings, and lubrication of the chain or drive mechanism.

Screenings need to be removed from the face of the screen as often as necessary to ensure a reasonably free flow of wastewater. During rainstorms, the cleaning frequency may have to be increased. In installations with multiple channels, additional screens may be placed into service during a storm event. Uneven loadings among the screens will result in more frequent cleaning of some screens than others, more wear, and subsequently, higher maintenance on those units.

Chains used in chain-driven bar screens tend to stretch from wear. Periodically, removal of a link may be necessary to ensure that the chain rides smoothly on the sprockets. To minimize equipment breakdown and maintain operational efficiency, badly worn parts should be replaced. Chain drives require frequent replacement of chains, sprockets, and other parts. Chain life also depends on how the unit is operated. For example, if the unit is operated continuously, then the chain life could be dramatically reduced. Grease should be applied weekly (or as required) for rake guides to ensure smooth and quiet operation.

All bar screens require inspection for visible and audible indications of possible malfunctions, as recommended by the preventive maintenance procedures in the O&M manuals. As a routine practice, the operator should observe all moving mechanisms to

determine if the components are free of obstructions, properly aligned, moving at constant speeds, and producing no unusual vibrations. The operator should also listen to all moving mechanisms and recognize their normal operational sounds. Screeches could indicate lack of lubrication; thumps indicate broken or loose components.

Preventive maintenance requires proper lubrication of all moving parts at recommended intervals. The operator should always follow the manufacturer's recommendations on type of lubricant to use because the lubricant's qualities were selected for the anticipated operating conditions and for compatibility with the materials used in the equipment.

Process Control. Typically, electric motors drive the raking mechanisms of the mechanically cleaned bar screens. Manual controls with an on–off switch activate drive motors. Clock-operated timing switches, level-sensing devices, or programmable logic controllers (PLCs) may control the motors automatically. Of the four control methods, the clock-operated timing switches are the most frequently used; however, more facilities are installing PLCs. Once experience indicates the number of raking operations needed during the average day at a particular installation, the clock-operated timers are set to operate the raking mechanism the required number of times each day. Timers work well but cannot adjust to accommodate sudden large accumulations of debris that can occur during high flow periods. Therefore, level-sensing devices such as bubbler or ultrasonic level systems are usually installed in parallel with the timers and are designed to override the timer control. The level-sensing system detects the increased head loss through the bar screen when debris clogs the bars, with the resultant pressure differential inducing an electrical switch to activate the raking mechanism. The circuit wiring gives the bubbler system precedence over the timer so that the bubbler system will activate the raking mechanism whenever an unusually large amount of debris collects on the screen. Controls are generally configured such that differential level-induced rake actuation resets the timer at $t = 0$ for the next timer-controlled actuation. At the next preset time interval after the bubbler activates the raking mechanism, the timer-operated switch will start the raking unless a large debris accumulation recurs. Controls may be configured with level-induced actuation as primary control with timer-induced override capability, or vice versa, with little difference in the system's function. In either case, timer actuation protects against debris accumulating for long periods resulting in breakthrough and adhesion challenges, and level actuation addresses sudden large debris accumulation on the bars.

Some screening facilities contain a backup float switch on the inlet side of the screen. This float will alarm and activate a cleaning cycle if a high liquid level is sensed on the upstream side of the screen. Screening devices include a limit switch to ensure

that the rake mechanism stops or parks outside the water after a cleaning cycle. This does not apply to continuously cleaned screens. Limit switches are provided to shut down the motor if the shear pin breaks because of a rake jam or failure.

Some facilities have screens designed for manual cleaning. In this case, debris is removed with a hand rake, typically on a daily basis. In general, bar rack installations use automated motor-operated rakes for cleaning, as manual screens are usually unattended for long periods of time. Compared to manual cleaning, the use of a mechanical cleaning device with a bar screen tends to reduce labor costs, provide better flow conditions, and produce less nuisance conditions. Such devices are almost always used in plants larger than 44 L/s (1 mgd) and are used occasionally in smaller plants.

Comminutors, Barminutors, and Other Grinding Devices. Comminutors and barminutors grind or chop solids that could interfere with downstream wastewater treatment processes. Other types of grinding devices are being used in pipes and channels that use twin shafts with cutting teeth. These devices, usually preceded by a bar screen, do not remove the chopped solids from the wastewater flow and rely on their removal by subsequent treatment units. At some small plants, grinding devices are used in place of bar screens. However, shredded rags can adversely affect the operation and maintenance of primary clarifiers, thickening units, and dewatering units. Because of the potential adverse downstream impacts and the many other difficulties associated with the operation and maintenance of comminutors, barminutors, and other grinding devices, their use is limited.

All grinding equipment requires inspection for visible and audible indications of possible malfunctions, as recommended by the preventive maintenance procedures in the O&M manuals. As a routine practice, the operator should observe all moving mechanisms to determine if the components are free of obstructions, properly aligned, moving at constant speeds, and producing no unusual vibrations. The operator should listen to all moving mechanisms and recognize their normal operational sounds. Abnormal screeches indicate lack of lubrication; thumps indicate broken or loose components.

Preventive maintenance requires the proper lubrication of all moving parts at the recommended intervals. The operator should always follow the manufacturer's recommendations on the type of lubricant to use because the lubricant's qualities were selected for the anticipated operating conditions and for compatibility with the materials used in the equipment.

Fine Screens. More and more new and retrofitted treatment facilities are installing fine screens, such as static or drum screens. Fine screens typically consist of wedge-wire, perforated plate, or closely spaced bars with openings of 2–6 mm (0.06–0.25 in.). These

screens are freestanding units typically installed downstream from coarse screens. Wastewater is applied to the top of the screen and the solids are captured on the face of the screen (Figure 18.3). Wastewater passes through the screen and flows to the next process. The solids fall into a trough or conveyor where they are collected and sent to final disposal.

Rotary drum fine screens consist of a rotating horizontal drum that may be internally or externally fed (Figure 18.3). In either case, the solids are captured on the wedge-wire and the wastewater passes through the small openings. The drum slowly rotates to remove the solids and pass the screen through a spray wash system for cleaning purposes. Openings between the wedge-wire are the same as in static screens.

Screenings from fine screens usually contain higher concentrations of organic matter. Some screening designs bag these screenings while other fine-screening devices discharge directly to storage containers. Because of the higher organic content of these

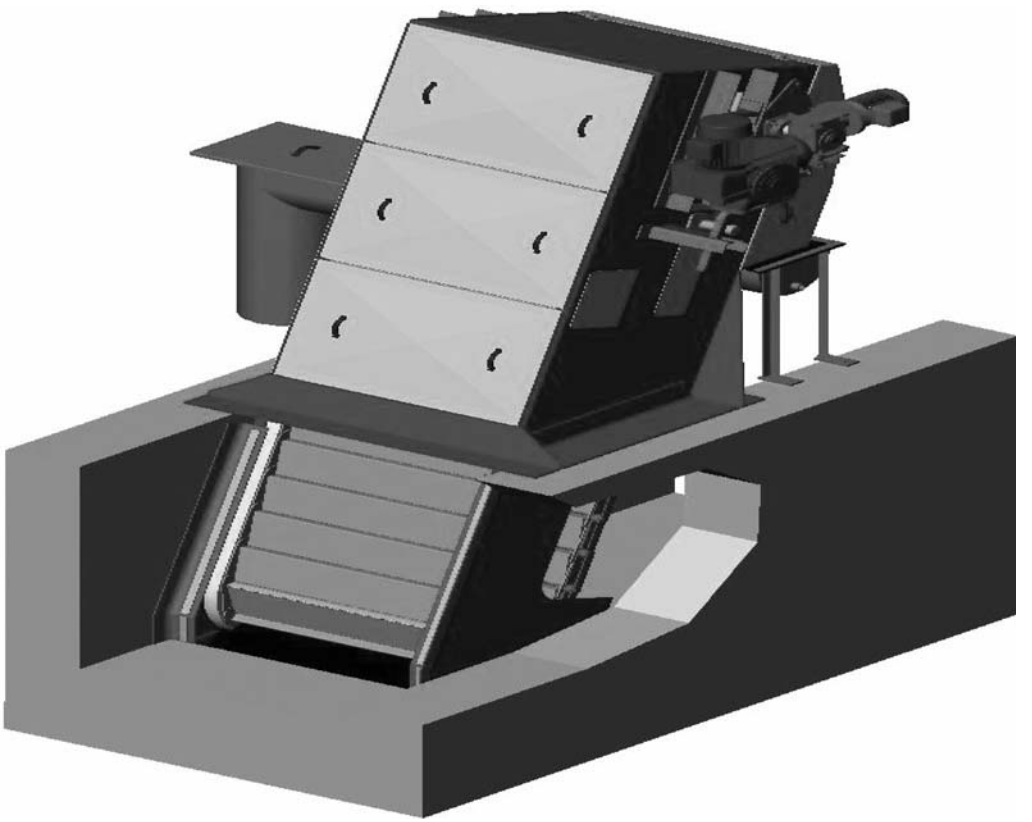


FIGURE 18.3 Environmental fine screen (Courtesy of JWC Environmental).

screenings, operators should transfer them more frequently to final disposal before excessive odors are produced.

Fine screens require inspection for visible and audible indications of possible malfunctions, as recommended by the preventive maintenance procedures in the O&M manuals. As a routine practice, the operator should observe all moving mechanisms to determine if the components are free of obstructions, properly aligned, moving at constant speeds, and producing no unusual vibrations. The operator should listen to all moving mechanisms and recognize their normal operational sounds. Abnormal screeches indicate lack of lubrication; thumps indicate broken or loose components.

Preventive maintenance requires the proper lubrication of all moving parts at the recommended intervals. The operator should always follow the manufacturer's recommendations on the type of lubricant to use because the lubricant's qualities were selected for the anticipated operating conditions and for compatibility with the materials used in the equipment.

Screenings Presses. Screenings presses not only allow for debris to be accepted by landfills by removing excess water, but also reduce the volume of debris for more efficient disposal. Screenings presses (Figure 18.4) consist of a ram, a hopper section, and a wedge section. Presses operate at a range of 4500 to 6000 kPa (1500 to 2000 psig). Similarly, double-walled containers with vacuum hoses attached have demonstrated adequate screening dewatering. These containers comprise a porous inner liner with an outer impermeable shell. Enough water must be removed from the screenings so

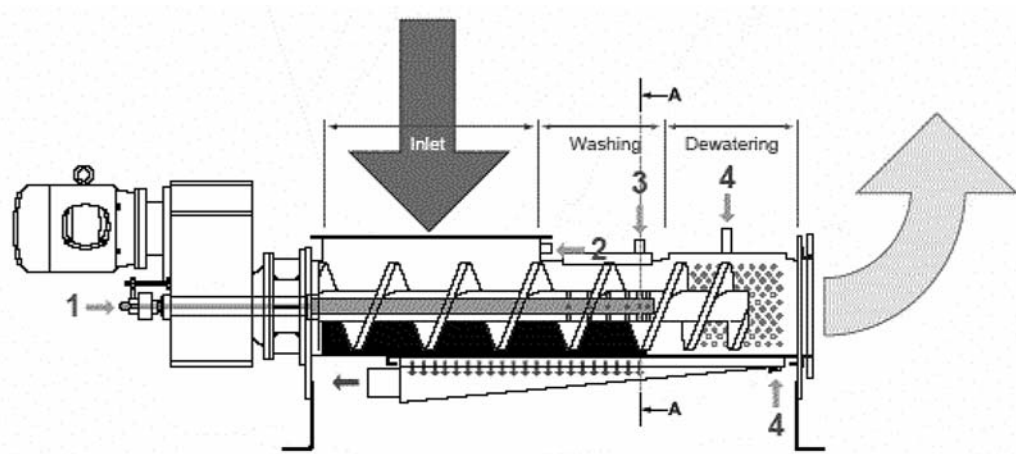


FIGURE 18.4 Screening press (Courtesy of Vulcan Industries, Inc.).

that they pass the paint-filter liquids test at the landfill. This test measures the amount of free water that leaches from the screenings by measuring the quantity of liquid from a representative screening sample that passes through a filter of Mesh No. 60. After the 5-minute test period, if any liquid passes through the filter, the material is deemed to contain free liquid.

MANAGEMENT PRACTICES. The operator needs to avoid any overflows in the screening storage areas. Organic materials that are not transported off-site decay and result in offensive odors. Screenings are a major source of odors. Most importantly, workers must follow good hygiene practices because wastewater-soaked debris harbors pathogenic organisms.

Good management practice dictates daily or even more frequent disposal of screenings by either incineration or landfill. The frequency for disposal of stored screenings will depend on the screenings production related to the size of the available storage container. Once the operator empirically determines the required frequency for screenings disposal, a regular disposal schedule can be set.

Screenings presses require inspection for visible and audible indications of possible malfunctions, as recommended by the preventive maintenance procedures in the O&M manuals. As a routine practice, the operator should observe all moving mechanisms to determine if the components are free of obstructions, properly aligned, moving at constant speeds, and producing no unusual vibrations. The operator should also listen to all moving mechanisms and recognize their normal operational sounds. Abnormal screeches could indicate lack of lubrication; thumps could indicate broken or loose components.

Preventive maintenance requires the proper lubrication of all moving parts at the recommended intervals. The operator should always follow the manufacturer's recommendations on the type of lubricant to use because the lubricant's qualities were selected for the anticipated operating conditions and for compatibility with the materials used in the equipment.

CONVEYING SYSTEMS. Belt conveyors are used in the screenings removal processes to transport debris from the point of removal to the point of collection and eventually disposal. Belt conveyor systems may be operated continuously or intermittently depending on loading conditions.

Belt conveyor systems require inspection for visible and audible indications of possible malfunctions, as recommended by the preventive maintenance procedures in the O&M manuals. As a routine practice, the operator should observe all moving mechanisms to determine if the components are free of obstructions, properly aligned,

moving at constant speeds, and producing no unusual vibrations. The operator should also listen to all moving mechanisms and recognize their normal operational sounds. Abnormal screeches could indicate lack of lubrication; thumps could indicate broken or loose components.

Preventive maintenance requires the proper lubrication of all moving parts at the recommended intervals. The operator should always follow the manufacturer's recommendations on the type of lubricant to use because the lubricants qualities were selected for the anticipated operating conditions and for compatibility with the materials used in the equipment.

TROUBLESHOOTING. The most common problems in the screening process are related to the following three categories:

1. Unusual operational conditions, such as sudden loads of debris that clog or jam the screening equipment;
2. Equipment breakdown and component failure; and
3. Control failure.

Mechanically cleaned screens sometimes receive sudden large loads of debris that jam their raking mechanisms.

To understand the screening facility, the equipment used, and the limitations of the equipment, the operator should refer to the O&M manuals for the specific equipment used at the plant. After these manuals have been read and understood, efficient resolution of problems can become routine. Please refer to the Troubleshooting Reference Chart at the end of this chapter for a listing of common screening equipment problems, their causes, and their remediation.

GRIT REMOVAL

Wastewater grit material generally consists of fine, discrete, non-biodegradable particles that have a settling velocity greater than that of organic solids. Such materials include sand, cinders, rocks, coffee grounds, cigarette filter tips, and other relatively nonputrescible organic and inorganic substances.

Grit removal, an essential element of preliminary treatment, protects equipment by reducing clogging in pipes and protecting moving mechanical equipment and pumps from abrasion and accompanying wear. This process helps by preventing accumulation of materials in downstream processes such as aeration tanks, digesters, or other solids-handling processes that result in loss of usable volume.

Grit chambers are used to settle grit from the wastewater. The settled grit is then consolidated and separated from the wastewater using bucket elevators, screw conveyors, pumps, and cyclones. Grit is finally rinsed by classifiers to remove unwanted organics.

EQUIPMENT. ***Grit Chambers.*** Grit removal begins with the grit settling in square, rectangular, or circular chambers or by centrifugal force. There are three types of grit settling chambers: hand-cleaned, mechanically cleaned, and aerated vortex, which are the most typical degritting units.

Hand-cleaned grit chambers are used in the smallest plants with flows generally less than 3.8 ML/d (1 mgd). This type of grit chamber consists of at least two elongated gravity channels with control devices at their outlets to regulate the wastewater velocity at approximately 0.3 m/s (1 ft/sec). Maintaining 0.3 m/s can sometimes be difficult with this type of grit tank. If the flow velocity is more than 0.3 m/s the grit inorganics could be flushed out of the tank. Inversely, if the flow velocity is less than 0.3 m/s, then organics settle in the tank. Some have hopper-shaped bottoms for grit storage. Floor drains are provided to empty the tanks for manual grit removal by shoveling.

Mechanically cleaned grit chambers are gravity-type units that are rectangular, circular, or square tanks. Most of the rectangular grit tanks have velocity control devices and a mechanical cleaning mechanism, such as a chain-and-flight system. Grit is scraped to a sump hopper and removed by bucket elevators, screw conveyors, grit pumps, or airlift pumps. Square or circular tanks contain deflector baffles at the inlets and a weir at the effluent end to equally distribute the flow. These units include a circular collector mechanism that scrapes the grit to a central collection hopper (sump) where it is removed by grit bucket elevators, reciprocating rakes, grit pumps, airlift pumps, or a screw conveyor system. The screened wastewater enters along one side of the tank or along its perimeter.

After the grit is removed from the sump, it is dropped into a classifier or washer that removes most of the water and organic matter collected with the grit. Pumps may also be used to remove grit from the sump. In larger plants with wider channels, chain-and-flight or screw collectors move the grit to a central sump for removal.

When the grit tank is initially filled, the influent gate must open slowly to avoid damaging the collectors. When the flights are submerged, the operator may then turn on the longitudinal collectors, the screw collector, bucket elevator, or pump, and, if present, the cross-collector and washer. This approach avoids start-up under load conditions after the grit builds up. All components of the system can be interconnected electrically so that all will stop and an alarm will sound when any component fails to function. This feature helps prevent equipment damage and loss of the tank in use.

Longitudinal collectors operate at a low speed and the bucket elevator moves fast enough to accommodate the grit as it collects. Otherwise, the collectors pack the grit and can either break a shear pin or damage the equipment. The period of collector operation depends on the rate of grit accumulation. Although automatic operation reduces equipment wear, manual control may nonetheless be necessary during periods with unexpectedly high grit loads.

The following items need to be checked regularly: gates, bolts on flights and elevator buckets, chains and sprockets, flight shoes and rails, collector screws, and shear pins. The underwater equipment and chain idlers must be lubricated with the manufacturer's lubricant and at the recommended lubrication frequency.

Aerated grit chambers provide a period of wastewater detention to trap grit through air-induced rotation of the wastewater at approximately 0.3 m/s (1 ft/sec). Compressed air, typically from the plant's process air supply, enters the grit chamber through diffusers at a controlled rate to induce the proper velocity of the spiral roll for the settling of grit. Typically, 4.6 to 12.4 L/s·m of tank length (3 to 8 cu ft/min/ft) is required for proper aerated grit operation.

When an aerated grit chamber is initially filled, or after the tank is being returned to service, the operator should turn on the air when the wastewater reaches the diffusers to avoid fouling the diffusers. Grit should not be allowed to accumulate above the diffusers. Large grit accumulations complicate diffuser inspection, result in diffuser damage, and reduce the efficiency of the grit collection.

If diffusers must be lifted to allow grit removal with a crane-operated bucket, the operator should maintain a reduced flow of air through the raised diffusers to prevent clogging. Crane-operated buckets remove grit only in large plants (typically in plants larger than 400 ML/d [100 mgd]). If the diffusers do not have to be raised during grit removal, an air volume reduction will usually be necessary to allow control of the bucket while it descends into the basin hopper. The wastewater flow can be maintained without restriction during the bucket removal of grit.

If short-circuiting of the aerated grit chamber occurs, it sometimes may be reduced by installing submerged transverse baffles or longitudinal baffles adjacent to the diffusers or along the wall opposite the diffusers. Table 18.1 presents typical performance and loading data for aerated grit chambers.

Adequate ventilation is essential if the chamber is enclosed; otherwise, the corrosive atmosphere will inevitably affect all exposed elements including electric wiring and controls. Aeration risers and headers should be inspected at least annually for corrosion or rupture. Bent or damaged tubes should be straightened or replaced as required. Sparger (the device releasing the air into the wastewater) openings should be cleared regularly. If surface turbulence diminishes, the diffusers may need cleaning to

TABLE 18.1 Aerated degritting removals.

Parameter	Typical operating ranges
Transverse velocity at surface	0.6–0.8 m/s (2–2.5 ft/sec)
Depth-to-width ratio	1.5:1 to 2:1
Air supply	4.6–7.7 L/m·s of length (3–5 cu ft/min/ft)
	0.3–0.4 m^3/m^3 (0.04–0.06 cu ft/gal)
Detention time	3–5 min (peak)
Quality of grit	7.5–75 mL/m^3 (1–10 cu ft/mil. gal)
Quality of scum (skimmings)	7.5–45 mL/m^3 (1–6 cu ft/mil. gal)

remove rags or grit. Rags are removed whenever the headers are raised. If the headers cannot be lifted, the tank must be drained.

Vortex grit chambers are gravity-type grit chambers that swirl the raw wastewater in the chamber. Inorganics are removed in the tank hopper section and the organics remain in suspension where they are carried out by the tank effluent. Some vortex tank designs rely on natural hydraulics to achieve the proper rotational rate, while other designs use natural hydraulics and a slow, rotating-paddle-type mixer to achieve the proper separation. The grit that settles in these tanks can be removed by an airlift pump or a nonclogging, recessed-impeller-type grit pump. Grit removed from these tanks can be transferred to a grit dewatering channel, cyclone, grit classifier, or other grit handling equipment to remove additional water.

Operators must ensure that the tank is maintaining the proper swirl velocity. If the velocity is too low, organic material will settle out with the inorganic material. This occurs because the velocity is not sufficient to maintain the organic material in suspension, while the inorganic material, because of its heavier density, settles to the bottom of the unit. If the velocity is too high, a greater amount of inorganics will pass through the system and exit before they have the opportunity to settle out to be removed. Operators must inspect the pumping system during every shift to ensure that the equipment is not plugged.

Conveying Systems. Bucket elevators are simply buckets attached to chains that scoop grit from the grit chamber sump and remove it from the wastewater.

During operation, buckets should be inspected frequently to check the volume of grit collected. If the buckets are filled, the elevator speed should be increased or an additional grit channel should be placed into service. If the grit volume is decreasing, the opposite actions may be appropriate.

Cast nylon or other strong, lightweight buckets reduce wear on the elevator chain. A spray of water on the chain as it emerges from the wastewater helps prevent grit from becoming lodged in the chain joints. Polyurethane floats attached to the flights will reduce their effective weight, thus reducing the wear of the shoes and rails. As a precaution, however, grit must be kept below the height of the floats. Drain holes on the bottom of the buckets should be cleared occasionally so water can drain freely.

Shaftless or shafted screws can be used in the grit collection trough. They need to be on a set of wear bars. They pull the grit into a sump from which a dry pit pump draws the slurry and delivers it to the cyclone and classifier.

Grit Pumps. Grit pumps are dry pit or submersible type, usually with a vortex impeller (recessed type) that does not contact the debris it is conveying. This feature helps to reduce wear of the impeller. Pumps used to convey grit are also made from hardened materials in order to resist wear in such an abrasive environment.

The removal of grit by pumps offers the advantage of eliminating the need for a bucket elevator and their submersed sprockets. However, blockage might occur in the pump suction line or in the intake area of the sump. If this occurs, removal of the blockage may require reversing the pumping direction or blowing air into the sump. Some plants contain flushing connections on the suction and discharge side of the pumps to remove blockages.

Cyclones. Cyclones (Figure 18.5) use centrifugal force in a cone-shaped unit to separate grit and organics from the wastewater. A pump discharges a slurry of grit and organics into the cyclone at a controlled rate. The slurry enters the cyclone tangentially near its upper perimeter. This feed velocity creates a vortex that produces a grit slurry at the lower, narrower opening and a larger volume of slurry containing mostly volatile material at the upper port. The grit stream falls into a grit washer, and the degritted flow leaves the cyclone through the opening near the top of the unit and is returned to the treatment process. In some systems, a mechanical mixer induces the centrifugal effect.

The cyclone degritting process includes a pump as an integral part of the process because the cyclone has no moving parts and depends on a steady supply of liquid. The volume of pumped slurry and the resultant pressure at the cyclone are critical requirements specified by the cyclone manufacturer. Temperature, solids concentration, and other characteristics of the slurry may require changes in the sizes of the upper and lower orifices after installation and some initial operating experience. In some designs, these orifices are manually adjustable.

To start the system, both ports of the cyclone are inspected to ensure that they are clear. The operator opens the inlet valve and starts the grit or sludge collector, pump,

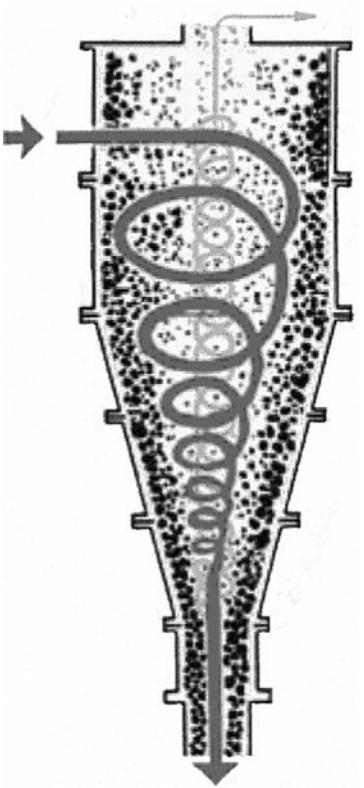


FIGURE 18.5 Cyclone (Courtesy of Weir Specialty Pumps).

and washer. Pressures at the cyclone and the pump inlet need to be checked regularly. Operation should be routine, provided the proper volume of slurry is delivered to the cyclone at the proper pressure. Thus, the equipment needs regular observation. Excessive vibration of the cyclone may be caused by an obstruction in the lower port, and excessive flow at the lower end may result from a damaged liner or an obstruction of the upper port. Items needing regular inspection include bearings, pumps, valves, pipe work, and cyclone lining (wear).

Classifiers. Grit classifiers (Figure 18.6) effectively remove organics from the grit. Screw and rake grit classifiers have proved to be reliable and usually produce a product low in organics. To ensure a low volatile content, however, ample dilution water is required. Pumps normally provide sufficient dilution water, but bucket elevators may not, especially during periods of peak grit capture. Consequently, they may require supplementary liquid.

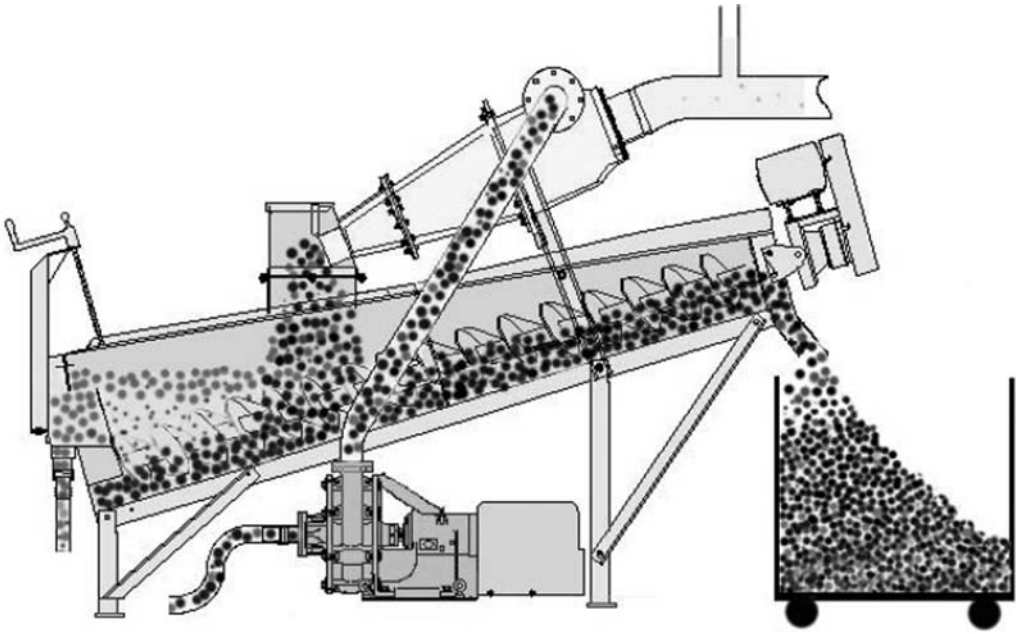


FIGURE 18.6 Grit classifier (Courtesy of Weir Specialty Pumps).

Grit washing occurs at the low end of the classifier in a well that has an adjustable weir to govern the depth of liquid above the settled grit. Most washers are equipped with spray nozzles to remove stray putrescibles. For optimum washing, some cyclones use an adjustable lower orifice to change the volume of liquid discharged with the grit.

The classifier may be either a reciprocating rake device or a screw collector. Either type may include water sprays for grit washing. Both the reciprocating rake and the screw collector are inclined upward at an optimum angle for draining water and organic matter. The grit then falls into a wheelbarrow, container, truck, or storage hopper. At some plants where the hoppers are distant from the washers, pneumatic ejectors blow the grit to the storage bin. A belt conveyor system may be used for transport of the washed grit. Washers need regular lubrication and must be checked for wear.

GRIT TRANSPORTATION WITHIN THE PLANT. Grit-removal equipment is typically located adjacent to the storage hoppers or containers. If this equipment is located elsewhere, pneumatic ejectors or belt conveyors may be used to transfer the grit to the loading area. Ejectors, operated by compressed air, are cone-shaped steel hoppers equipped with slide gates at their top and bottom.

A practice used by some operators involves emptying all of the ejector hoppers at the end of each shift and then using a blow of water to ensure clearing of the lines. Occasional maintenance to flush the lines is recommended. If slide gates are used, they should be operated at the beginning and end of each shift. Permanent flushing-water lines at the gates are helpful. The discharge line needs regular inspection to avoid pipe leaks or ruptures.

PROCESS CONTROL. Grit, if not removed early in the treatment process, will inevitably cause problems later. Therefore, a high level of early grit removal is a sound objective. However, the operator must consider grit-removal equipment wear versus increased removal efficiency and resultant downstream equipment longevity. Aerated chambers and cyclone systems are easy on equipment. Hand-cleaned channels avoid equipment wear. Increased wear for chain-and-flight collectors and the bucket elevator will result from a high level of grit removal.

The removal of grit from the system depends on a number of factors. If too much grit is being removed, then excessive organic material will be removed with the grit. Also, operating the grit-removal equipment excessively will increase maintenance problems due to equipment wear. Operators must determine the proper grit-removal practice for their facility.

Increased removal of grit may cause more organic material to be removed, which could cause undesirable results such as increased plant odors or the landfill not accepting the grit because of odor or water content. Proper operation of grit washers reduces this potential problem. A plant without grit washers may encounter adverse public reactions, particularly if the unwashed, odorous grit has to be trucked through populated areas. When unwashed grit must be transported, the operator may have to choose between a less efficient collection system and odor control during transportation. Furthermore, as landfill regulations become stricter, grit with a high organics content may be prohibited at the landfill site. Grit must pass the paint-filter liquids test before it is allowed in a landfill.

MANAGEMENT PRACTICES. Because grit-removal equipment has many moving parts, many possible types of malfunctions and breakdowns can adversely affect the operation and efficiency of the device. The operator needs to learn the equipment and how to assess problems that will occur. The operator should always follow the manufacturer's O&M manuals for its equipment.

TROUBLESHOOTING. Please refer to the Troubleshooting Reference Chart at the end of this chapter for a listing of common grit equipment problems, their causes, and their remediation.

ADDITIONAL PRETREATMENT CONSIDERATIONS

FLOW EQUALIZATION. Reducing flow fluctuations (diurnal and storm) in the collection system benefits the operation and performance of the treatment plant. Temporary storage of flows in existing sewers, or the use of separate flow-equalization facilities or retention basins, merits consideration because limiting flow fluctuation is beneficial to the equipment operations. Plant flows through parallel units, such as screens and grit chambers, need to balance to aid optimum performance of each unit. For further information concerning flow equalization, the operator should refer to *Preliminary Treatment for Wastewater Facilities* (WEF, 1994).

ODORS AND ODOR CONTROL. Odors often emanate from the headworks of a plant because of the long duration of wastewater transit through the collection system. This may produce hydrogen sulfide and other anaerobic byproducts of decomposition that cause dangerous confined-space situations and complaints. Whenever possible, septic influent flows should be eliminated in the collection system using appropriate techniques (see Chapter 13). Otherwise, odor control with prechlorination, iron salts, potassium permanganate, hydrogen peroxide, or preaeration may be necessary.

Installations operate special odor control units that use sodium hydroxide, sodium hypochlorite, activated carbon, or potassium permanganate to control releases of odor. These units usually require covering the influent structures, collecting the gases, and then treating them. Each of the odor control techniques requires adherence to the safety precautions and equipment considerations discussed in the plant's O&M manual and Chapters 5 and 13 of this manual.

SEPTAGE MANAGEMENT. The need for the regulation and close control of septage wastes from septic tanks, grease traps, and other sources has been well documented. Many of these wastes have extremely high concentrations of biochemical oxygen demand; chemical oxygen demand; total suspended solids; and fats, oil, and grease. Adequate pretreatment using aeration, grit removal, and screening should precede treatment of septage wastes at the treatment plant. Many municipalities have enacted a waste hauler's ordinance that licenses and controls access for septage dischargers, including sampling of waste loads.

The elimination of toxic and hazardous wastes must conform to the Resource Conservation and Recovery Act guidance, as well as to the capabilities of the biological treatment units. Extreme caution must be used to stop those who would be midnight

dumpers to the treatment system. At a time when hazardous waste management has become the concern of every facility owner, this topic deserves the operator's special attention. The plant operator needs the municipality's strict enforcement of an industrial sewer-use ordinance to prevent toxic shock loads to the system.

RECYCLE FLOWS. Numerous sidestreams (recycle flows) are generated in a wastewater facility. Digester supernatant, dewatering equipment filtrate and centrate, vacuum- and gravity-drying bed filtrate, sand or mixed-media backwash water, and other sidestreams are too often returned to the plant headworks in a fashion that may be detrimental to the downstream processes. Careful monitoring and control of the sidestreams help to prevent shock loads and other adverse effects on the treatment processes. If possible, recycled flows should enter the treatment system during low hydraulic and organic loading periods or when there will be a minimal effect on the process performance.

SAFETY CONSIDERATIONS

Because screening and grit equipment is located at the plant influent, the accumulation of potentially explosive or toxic gases is always a concern. Operating personnel must exercise extreme caution in these confined areas and explicitly follow all safety procedures for confined-space entry. Good safety practice demands continuous monitoring of hydrogen sulfide and methane levels in these confined areas and smoking must be prohibited in them.

Operators must follow good housekeeping procedures in the preliminary treatment area. All screenings, grit, grease, and other such items should be regularly cleaned up to prevent slip and fall injuries. The operator should ensure that all safety guards are in place and that all safety devices are in good working order. The rotating equipment used in preliminary treatment is not commonly supplied with safety devices such as light curtains or power interruption trip cords (except some belt conveyors), so personnel must be trained to shut off and lock out equipment before attempting to free troublesome debris.

Proper barriers must be maintained around all equipment and tanks. For example, aerated grit tanks are turbulent and less buoyant than non-aerated water, which makes it more difficult for a worker that has fallen into the tank to extricate himself/herself. Screenings and grit contain pathogenic organisms and sharp objects that can result in injuries. Plant personnel should wear gloves when working near these materials. Chapter 5 presents more safety information.

DATA COLLECTION, SAMPLING, AND ANALYSIS PLAN

SCREENING PROCESS. Development of cleaning and disposal schedules for the screening process requires determining the amount of screenings that accumulate. The easiest way to make this determination is to place screenings accumulated during a 24-hour period in a container of known volume and divide the volume by the flow. For example, if 3 m^3 (4 cu yd) of screenings collect during 24 hours, and flow for that period averages approximately 440 L/s (10 mgd), then screenings accumulate at a rate of 0.08 m^3/ML (0.4 cu yd/mil. gal). Accurate volumetric measurements are especially needed for disposal by landfilling. Conducting a paint-filter test on the screenings is important and commonly required before the screenings can be disposed of at the landfill.

DEGRITTING PROCESS. Although the daily volumes of grit removed will vary considerably, monthly and yearly quantities generally do not vary unless there is an increase in infiltration or inflow problems. Proper records are needed to alert the operator to any unusual changes. For hand-cleaned chambers, the volumes of grit removed should be recorded whenever a channel is cleaned, and immediately thereafter, the volumes of grit per day and per flow unit should be calculated. For mechanically cleaned grit tanks, aerated chambers, and vortex grit systems, the daily volumes removed are calculated and recorded based on the number and weights of containers or trucks. Records should include volumes per day and per unit of wastewater flow, which can be determined in the same way as the amount of screenings.

The volatiles concentration in the grit should be determined periodically for a representative sample of the grit removed. To determine the volatile content of the grit, a large sample, composited over at least 8 hours, is necessary for valid laboratory results. Single grab samples of grit are not representative and, therefore, are less useful. If visual inspections of grit are made daily, composite samples and tests are needed only on a monthly or quarterly basis. Visual inspections can ensure that the process is operating normally. Any changes in visual characteristics signal the need for laboratory analysis.

RECORDS AND REPORTS

Records should be kept for all screening and degritting equipment. They should contain information on preventive maintenance procedures, including lubrication schedules (with type used) and spare parts needed, used, and available. Records of all stoppages and malfunctions for each piece of equipment are necessary to determine the

TABLE 18.2 A summary of troubleshooting for systems.

Equipment	Indicators/observation	Probable cause	Solutions
Trash/bar racks	Clogged with debris.	Increased concentrations of debris; insufficient cleaning rate.	Increase frequency of cleaning screen.
Mechanical bar screens	Excessive screen clogging.	Increased concentrations of debris; insufficient cleaning rate. Check industrial wastes (foods, other). Inadequate cleaning frequency.	Check upstream conditions and cleaning frequency. Increase frequency of removal and disposal to an approved disposal facility. Use a coarser screen or identify source of water causing the problem so its discharge to the system can be stopped.
	Obnoxious odors, flies, and other insects.	Accumulation of rags and debris.	Check method of debris removal. Increase frequency of removal and disposal to an approved disposal facility.
	Excessive grit in bar screen chamber.	Flow velocity too low.	Check depth of grit in chamber, and irregular bottom. Check flow velocity. Remove bottom irregularity or reslope the bottom. Increase flow velocity in a chamber or flush regularly with a hose.
	Mechanical rake inoperable, circuit breaker will not reset.	Jammed mechanism.	Check screen panel. Remove obstruction. Adjust spring tension if appropriate.
	Rake inoperative, but motor runs.	Broken shear pin, cable, or limit switch.	Inspect shear pin, cable, or switch. Identify cause of break; replace shear pin, cable, or limit switch.
	Rake inoperative, no visible problem.	Defective remote control circuit.	Check switching circuits, then replace circuit and motor.

TABLE 18.2 A summary of troubleshooting for systems (*continued*).

Equipment	Indicators/observation	Probable cause	Solutions
Mechanical bar screens (***continued***)	Marks or metal against metal on screen binding.	Screen needs adjustment.	Screen through one cycle and listen for or observe metal-to-metal contact. Manufacturer's adjustments recommended in O&M manual.
	Rough operation of chain mechanism (if applicable).	Heavily worn or stretched chain.	Lubricate chain; remove links as necessary for smooth operation; replace chain.
Comminutors and barminutors	Screeching sound during operation.	Worn components.	Lubricate machine as indicated; replace component.
	Thumping sound during operation.	Broken or loose components.	Replace or tighten component.
Screenings presses	Obnoxious odors; flies.	Insufficient screening disposal rate.	Increase frequency of screening disposal.
Belt conveyors	Slow operation; screeching sounds.	Worn components.	Lubricate machine as indicated; replace worn component.
	Belt tracking	Belt stretched; self-aligning idlers seized; tail pulley misaligned.	Adjust take-up; clean and lubricate self-aligning idlers; adjust tail pulley alignment.
Bucket elevators	Slow operation; screeching sounds.	Worn components.	Lubricate machine as indicated; replace worn component.
Grit systems	Grit packed on collectors.	Collector operating at excessive speeds. Bucket elevator or removal equipment operating at low speeds.	Check speed and removal system speed. Reduce collector speed and increase speed of grit removal from collector.
	Too much vibration of cyclone degritter.	Obstruction in the lower port. Obstruction in the upper port.	Check flow from lower port and remove obstruction. Reduce flow.

TABLE 18.2 A summary of troubleshooting for systems (*continued*).

Equipment	Indicators/observation	Probable cause	Solutions
Grit systems (*continued*)	Rotten-egg odor in grit chamber.	Hydrogen sulfide formation.	Sample for sludge deposits and total and dissolved sulfides. Wash chamber and dose with hypochlorite.
	Accumulated grit in chamber.	Submerged debris. Flow velocity too low or broken chain or flight.	Inspect chamber for debris and wash chamber daily. Remove debris. Check equipment and repair equipment.
	Corrosion of metal and concrete.	Inadequate ventilation.	Check ventilation and sample for sludge deposits and total dissolved sulfides. Increase ventilation and perform annual repair and repainting.
	Removed grit is gray in color, smells, and feels greasy.	Improper pressure on cyclone degritter. Inadequate airflow rate. Grit removal system velocity too low.	Check discharge pressure on cyclone degritter. Keep pressure at cyclone between 28 and 41 kPa (4 and 6 psi) by governing pump speed. Oil as O&M manual specifies. Check air flow rate. Use dye or floating objects to check velocity. Increase velocity in grit chamber (0.3 m/s [1 ft/s] is typically optimum unless operating strategy calls for lower velocity with washing).
	Surface turbulence in aerated grit chamber is reduced.	Diffusers covered by rags or grit.	Check diffusers. Clean diffusers and correct screens or other pre-treatment steps to prevent.
	Low recovery rate of grit.	Bottom scour at excessive speeds. Too much aeration.	Check velocity. Maintain velocity near 0.3 m/s (1 ft/sec). Check aeration.

TABLE 18.2 A summary of troubleshooting for systems (*continued*).

Equipment	Indicators/observation	Probable cause	Solutions
Grit systems (*continued*)			Reduce aeration. Increase retention time by using more units or reducing flow to unit.
	Overflowing grit chamber.	Pump surge problem.	Check pumps. Adjust pump controls or control infiltration and inflow.
	Septic waste with grease and gas bubbles rising in grit chamber.	Sludge on bottom of chamber.	Check grit chamber bottom. Wash chamber daily. Remove debris. Repair chain. Repair shear pin on conveyor.
Grit pumps	Decreased pump efficiency.	Worn seals, shaft components, or impeller.	Replace seals; lubricate pump as specified; inspect and replace impeller as needed.
Cyclones	Decreased grit removal efficiency.	Inlet pressure is too low.	Increase inlet pressure by adjusting the grit pump discharge.
	Loud operation.	Torn or collapsed liner.	Replace liner.
	Heavy underflow volume.	Clog in cyclone.	Clear clog.

source of problems and which parts wear out most frequently. Preventive maintenance schedules must be kept up to date and followed carefully. As each maintenance task is performed, the operator should record the date.

At plants where screenings are collected for separate disposal, records must be kept of the quantities collected. Such records provide the basis for screening disposal scheduling and budgeting. They also provide screening production trends to give advance warning of increasing screenings accumulations, which could require expansion of disposal operations. The amount of grit collected should be recorded to determine the quantity to be landfilled and, if off-site disposal is used, to help establish a budget for disposal.

TROUBLESHOOTING REFERENCE CHART

Table 18.2 contains a summary of troubleshooting as presented, in discussion, throughout this chapter.

REFERENCES

U.S. Environmental Protection Agency (1978) Field Manual for Performance Evaluation and Troubleshooting at Municipal Wastewater Treatment Facilities; EPA-68/10-4418; U.S. Environmental Protection Agency: Washington, D.C.

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Primary Treatment

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INTRODUCTION

Primary treatment separates the readily settleable and floatable solids from wastewater by providing a tank where the velocity of the wastewater is reduced to a fraction of a centimeter per second (foot per second). Other benefits of primary settling include equalization of sidestream flows and removal of the biochemical oxygen demand (BOD) associated with settleable solids.

To improve settling performance, preaeration or chemical addition sometimes precedes the sedimentation basins. Some treatment facilities install chemical-feed equipment strictly for the addition of chemicals to the wastewater influent flow to enhance floc formation to enhance settling. Other treatment plants use chemicals for

odor control or phosphorus removal and, in the process, receive the additional benefit of increased settling in the primary sedimentation tanks. However, most primary sedimentation tank facilities do not use any chemicals to enhance settling.

Many treatment plants use primary sedimentation tanks for thickening primary sludge in addition to separating solids from wastewater. In these cases, the primary tanks are sized to accommodate sedimentation and thickening. Some treatment plants use primary sedimentation tanks to cosettle primary sludge and waste activated sludge. In this instance, the primary sedimentation tank is also used as a thickening unit.

In recent years, wastewater specialists have investigated the use of fine screens for primary treatment in place of primary sedimentation tanks. In addition, recent research has also included using primary sedimentation tanks as fermenters to increase the production of volatile fatty acids (VFAs) to enhance and improve biological nutrient removal in the secondary treatment process. This chapter will discuss standard primary treatment systems, dissolved air flotation primary treatment systems, combined grit removal/primary treatment systems, primary sludge fermentation, and fine screen treatment systems.

DESCRIPTION OF PROCESS

SETTLEABLE SOLIDS REMOVAL. Suspended particles may be classified as granular or flocculent. Granular particles (sand and silt) settle at a constant velocity, with no change in size, shape, or weight. Ideally, most granular particles are removed upstream in the grit chambers. Flocculent particles (organic matter, flocs formed by coagulants, or biological growths) tend to flocculate during settling, with changes in size, shape, and relative density. The clusters ordinarily settle more rapidly than individual particles. Settleable solids, including portions of the granular and flocculent material, settle under quiescent (calm) conditions within a reasonable time. Nonsettleable solids, finely divided and colloidal materials, are too fine to settle within usual settling times.

Chemicals, used to remove more finely divided suspended and colloidal material than is possible with sedimentation alone, react with constituents of the wastewater or in combination with other added chemicals to form a heavy, flocculent precipitate. The settling precipitate traps the suspended and colloidal particles and adsorbs them on the floc surface.

REMOVAL OF FLOATABLES. Removal of floatables, including grease and scum, helps protect downstream plant unit processes, reduces the pollutants discharged, and

improves the aesthetics of the plant effluent. Under quiescent conditions, part of the grease and scum settles with the sludge, whereas the remainder floats to the surface for removal by a suitable skimming device.

VARIABLES AFFECTING SETTLEABLE SOLIDS REMOVAL. The efficiency of a settling basin depends largely on hydraulic loading parameters, namely surface overflow rate and hydraulic retention time, tank configuration, wastewater characteristics, particle characteristics, temperature, and industrial wastewater contributions. Each of these variables is discussed below and the operational considerations affecting settling efficiency are presented in the subsequent section on process control.

Hydraulic Loading Parameters and Tank Configuration. Settling tank performance depends on tank surface area (length and width or diameter), tank volume (area and depth), and the positioning of the inlet and outlet structures (Figure 19.1). For any influent flow, tank area governs the surface overflow rate and tank volume determines the hydraulic retention time. Although the rate of removal of granular particles settling at uniform velocities depends almost entirely on the tank surface area, the rate of removal of flocculent particles settling at variable velocities depends on the tank volume, including depth and surface area.

The surface overflow rate (SOR) is expressed as

In metric units

$$\text{Surface overflow rate } (m^3/m^2 \cdot d) = \frac{\text{Flow } (m^3/d)}{\text{Tank surface area } (m^2)} \quad (1)$$

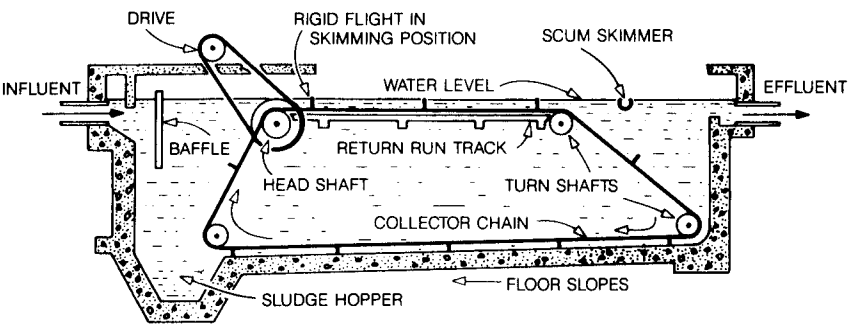


FIGURE 19.1 Section of a single rectangular tank for primary sedimentation.

In U.S. customary units

$$\text{Surface overflow rate (gpd/sq ft)} = \frac{\text{Flow (gpd)}}{\text{Tank surface area (sq ft)}}$$

The hydraulic retention time represents the time required for a unit volume of the wastewater to pass entirely through the tank at a given rate of flow. The formula for detention is

In metric units

$$\text{Hydraulic retention time (h)} = \frac{\text{Tank volume } (m^3 \times 24\ h/d)}{\text{Flow } (m^3/d)} \qquad (2)$$

In U.S. customary units

$$\text{Hydraulic retention time (h)} = \frac{\text{Tank volume, cu ft } (7.48\ \text{gal/cu ft} \times 24\ h/d)}{\text{Flow (gpd)}}$$

The retention period should be sufficient to allow nearly complete removal of settleable solids. A longer hydraulic period would not improve removal and might actually impair removal efficiencies by allowing the wastewater to become septic.

Because the dimensions of settling tanks are fixed, the overflow rate and detention time will vary with flow, resulting in variable removal efficiencies. Consequently, the number of units required for sedimentation may vary if the flow changes significantly.

Inlet and outlet structures, including appropriate baffles, play an important role in sedimentation. Inlets reduce entrance velocity and distribute flow uniformly through the basin. Excessive inlet velocities could cause the settled solids to be scoured or washed out from the settling tank. Rectangular tanks use suitable openings, baffles, or other means across the inlet, whereas circular tanks use a circular, baffled influent well. Proper inlet design also allows for an even distribution of flow between multiple tanks. Outlets for the overflow of clarified wastewater (primary effluent) are generally single or multiple weirs. Baffles are normally ahead of the outlet weirs to prevent the loss of floating solids. Proper outlet conditions will allow uniform flow overflow and avoid localized high-velocity areas.

Wastewater Characteristics. Sedimentation is affected by the freshness of the wastewater, particle characteristics, temperature, and the amount and types of industrial wastes. A discussion of each of these variables follows.

Freshness. Solids in stale (septic) wastewater settle less readily than those in fresh wastewater because biological degradation of the stale wastewater reduces the particle sizes and the gel generated by the biological reaction tends to float the particles. The collection system affects the freshness of the wastewater. The time elapsed while wastewater flows through the sewer system depends on the physical characteristics of the system, such as sewer slope and length, number of pumping stations, and the method of operating the collection system. In regard to the latter, many raw wastewater pumping stations store flows in the sewer, thus extending flow time through the entire sewer system. This extended storage time diminishes the freshness of the wastewater. Large contributions of oxygen-consuming industrial wastewater may also affect the freshness of wastewater. Another factor that affects freshness of wastewater is temperature. Typically, the warmer the wastewater temperature the more likely it is to become septic.

Particle Characteristics. A dense particle settles more quickly than a light one; a particle with a large surface area to weight ratio settles slowly; and a particle with an irregular shape settles slowly because of its high frictional drag. The size, shape, and density of a particle depend on the sewer network and the types of upstream unit processes. The age or freshness of the wastewater, related to the wastewater collection system, influences particle characteristics. Some preliminary treatment devices, such as comminuting and pumping, fragment the particles, reducing their ability to settle.

Temperature. Wastewater temperature influences the rate of settling. Warm weather increases the rate of biological activity, thus diminishing the freshness of the wastewater in the collection system and promoting gasification in the settling basins and slow settling. On the other hand, the lower viscosity of warm water, compared with that of cold water, allows particles to settle faster. At a water temperature of 27°C (80°F), the settling rate exceeds that at 10°C (50°F) by nearly 50%.

Primary tank efficiency decreases during the winter months because of high wastewater viscosity at cold temperatures. Another reason for poorer winter performance is the increased density of cold wastewater. As water density increases, settling rates decrease.

Temperature differences, and the associated density differences, between the tank contents and the incoming flow may create density currents within the basin. These currents can interfere with effective particle settling characteristics, thereby impairing settling performance.

Industrial Contribution. The amount and type of industrial wastewater could influence sedimentation. Industries may contribute large, short-term hydraulic or or-

ganic loads that may "shock" the treatment plant unit processes. Industrial shock loads of organics, in either suspended or soluble form, may cause septic conditions with associated settling problems. High industrial peak flows will increase surface overflow rates and decrease hydraulic retention times, thus impairing settling performance.

VARIABLES AFFECTING REMOVAL OF FLOATABLES. Efficiency of grease and scum removal depends on tank configuration, wastewater characteristics, and type and condition of removal mechanism. Each is described below.

Tank Configuration. Primary tank baffling at the outlet must be continuous and deep enough to prevent grease and scum from traveling underneath the baffles. Grease removal efficiencies vary slightly depending on the equipment and the system used.

Wastewater Characteristics. Two wastewater characteristics that influence grease and scum removal efficiency are temperature and pH. At summer wastewater temperatures or at a pH less than 7 (acidic), grease and scum may tend to stay in suspension, and some may enter the settled sludge instead of floating to the surface.

Removal Mechanism and Conditions. Depending on the type of tank scum, removal mechanisms may consist of a scum beach and box, scum troughs, paddle wheel removal mechanism, a telescopic valve, or other such mechanism. If a scum removal mechanism is faulty, poorly operated, or poorly maintained, it could result in the release of scum and floatables escaping over the tank effluent weirs. This equipment and scum baffles must be checked and maintained by plant personnel.

INTERACTION WITH OTHER UNIT OPERATIONS. Process treatment objectives require all process units to be operated in an interrelated manner, and primary sedimentation units are no exception. A properly operated primary settling tank helps with the operation of downstream units. Conversely, proper operation of the primary settling tank depends, to a large degree, on the sound operation of several unit operations, upstream and downstream.

Upstream Units. The upstream units affecting sedimentation are described below, including comminuting (grinding), bar screens, grit removal, and influent pumping.

Comminuting and grinding operations reduce floating and entrained solids concentrations, changing their settling properties. Improper comminution leads to the carryover of rags and debris that clog and tangle the sludge collecting and pumping mechanisms of primary tanks.

Bar screens remove debris larger than the screen openings. This debris would otherwise interfere with other plant processes. Inefficient removal of such debris re-

sults in carry-over of rags and debris that will clog sludge pumps and tangle in primary tank collectors. Fine bar screens can fragment organic solids, altering their settling properties.

The grit chamber removes discrete inorganic particles. If grit enters the primary tanks, pumping and other problems will ensue. The abrasive grit causes excessive wear of collector mechanisms, pump impellers, and sludge lines. In addition, a buildup of grit in the primary tank will reduce its effective volume for sludge storage and reduce the tank's detention time.

At influent pumping stations, safe operation depends partly on careful operation of the primary tanks. When primary tanks are drained, large quantities of septic sludge may enter the wet well of the pumping station. This situation could result in dangerous accumulations of hydrogen sulfide or combustible gases.

Downstream Units. The downstream units interacting with sedimentation include secondary processes, solids handling systems, and recycle flows from liquid and solids processes. These units are described below.

Secondary Processes. Improper primary tank operation may overload the secondary process with solids. Primary settling removes settleable solids and suspended solids efficiently if the process is properly designed and operated. If settleable solids are allowed to pass through to the secondary system, the resultant increase of secondary sludge may adversely affect the operation of the secondary clarifiers. Also, grease carry-over from primary tanks may interfere with the activated sludge or fixed-film (trickling filter or rotating biological contactor) biological system operations, possibly impairing final effluent quality. If a primary tank is being operated as a fermenter or there is a separate thickener/fermenter, care must be taken to ensure proper recycle rates and solids retention times. If these are not properly controlled, it could hinder the biological phosphorus removal process.

Solids Handling Systems. Operation of primary tanks may affect solids-handling systems in several ways. Without prethickening of the removed primary sludge, pumping of thin sludge may reduce plant digester capacity (either aerobic or anaerobic), cause hydraulic overloading of concentration tanks and thickening processes, and increase sludge heating costs. The continuous pumping of dilute sludge could result in the failure of the digestion process. If sludge becomes septic, downstream solids-handling processes, including thickening and dewatering, may be adversely affected, with resultant odor problems or poor operating efficiencies.

Pumping of toxic primary sludges to aerobic or anaerobic digesters may result in digester failure. The operator typically can prevent process failure caused by toxicity only by

- Watching for obvious physical changes in the wastewater such as color, odor, or consistency;
- Altering unit process operations as appropriate if changes are detected;
- Notifying municipal officials if industrial contributors are suspected; and
- Watching for abrupt changes in the chemistry of the anaerobic digestion process, such as pH, alkalinity, gas production, methane content, and volatile acid level.

Recycle Flows. Recycle flow sources include thickening, conditioning, dewatering, digestion, secondary and tertiary processes, and cooling waters. These are described below.

Thickeners or dewatering units, if properly operated, produce a good quality return flow (low in BOD and suspended solids) that will not impair primary sedimentation. Use of polymers to enhance thickening or dewatering improves return-flow quality and generally will not affect primary tank performance.

Supernatant liquors from digesters, if sent to primary settling basins, may shock load them with heavy doses of septic sludge. This could impair pumping and cause septicity, odors, and solids carry-over. If the addition of supernatant liquor to primary tanks cannot be avoided, the supernatant loading should be equalized to reduce its effects.

Waste activated sludge from secondary processes is sometimes pumped to the primary settling tanks for thickening with the primary sludge. This practice can cause pumping problems, septicity, and solids carry-over if the extra solids are not accounted for during removal from the primary tank. If waste sludge must return to the primary tank, an even pumping rate, preferably limited to low- or average-flow periods, is necessary. Also, sending waste activated sludge to the primary settling tanks will reduce the solids concentration of the primary sludge, resulting in longer pumping times to the solids-handling facilities. It is important that operations personnel take into account the quantity of waste activated sludge and primary sludge that accumulates in a primary sedimentation tank because this combined sludge must be removed from the tank. If the total cosettled quantity of sludge is not taken into account in the sludge withdrawal process, the primary tanks will become overloaded with sludge and be carried over to the secondary treatment process, thus hindering that process. Some facilities have reported advantages to the cosettling of waste activated and primary sludge. These advantages have included improved suspended solids removal, reduced odors, and improved anaerobic digester operation.

Tertiary processes, such as sand filters, return backwash flows to the primary tanks, which increases the hydraulic loading on the tank and could reduce the settling efficiencies. Return of cooling waters primarily affects hydraulic loading.

DESCRIPTION OF EQUIPMENT

FINE SCREENS. Although most plants use sedimentation for primary treatment, a few plants use fine screens. These screens include rotary, vibrating, band, disc, or stationary types, with openings ranging from 1 to 6 mm (0.04 to 0.25 in.). Most wastewater installations use screens with openings of 1.5 mm (0.06 in.) to process raw wastewater. Fine screens used for primary treatment could reduce the need for preliminary treatment units such as fine bar screens, grit removal, or grinders. Materials of construction include woven wire, perforated plate, or closely spaced bars. Figure 19.2 shows two types of rotary fine screens. These units typically contain a high-pressure spray header system to keep the screen clean. Because of the small openings, these units should be removed from service occasionally and cleaned with a high-pressure spray to remove grease and solids blocking the openings. This practice is especially important on stationary screens that do not have cleaning systems. It is recommended that a hot water source be located next to the fine screens to help cleanse the units of grease.

Records from operational treatment facilities have shown that fine screens used for primary treatment typically have removal efficiencies that are less than conventional type primary treatment processes. Reports have shown that fine screens typically remove 15 to 30% of the suspended solids and 15 to 25% of the biological oxygen demand.

SEDIMENTATION TANKS. Sedimentation tanks can be rectangular, circular, or square. In the rectangular type, wastewater flows from one end of the tank to the other

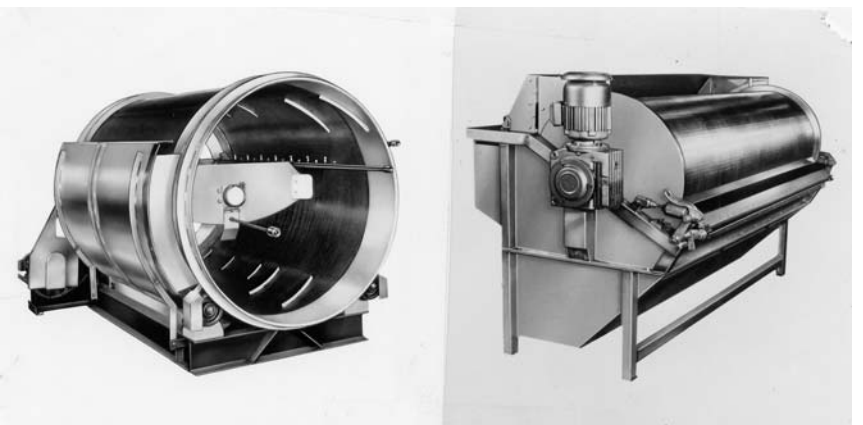


FIGURE 19.2 Typical fine screens: internally fed rotary wedge wire screen (left) and externally fed rotary wedge wire screen (right).

and scrapers move the settled sludge to the inlet end. In the circular and square types, the wastewater typically enters at the center and flows towards the outside edge (Figure 19.3), with the settled solids scraped or otherwise transported to the center. In some circular tank designs (called peripheral feed clarifiers), wastewater enters at the outer edge and flows inward. Imhoff tanks perform the dual function of settling and anaerobic digestion; however, these tanks are old technology and are no longer allowed in most states.

The collection process entails moving settled solids to a point in the settling tank where it is drawn off. Primary sedimentation tanks, except for those in a few small plants relying on manual removal, use mechanical collection. One of the following types of equipment may be used:

- Flight and chain (rectangular basins),
- Traveling bridge with screens (rectangular basins), or
- Rotating scrapers (circular and square basins).

Typically pumping, but sometimes gravity flow, removes sludge from the settling tanks. Positive-displacement-type pumps such as piston, progressive cavity, or diaphragm pumps are typically used. However, a number of plants also use torque-flow, centrifugal-type pumps, or hose (peristaltic) pumps. Chapter 8, Pumping of Wastewater and Sludge, describes the different types of pumps used for this application. For gravity removal, sludge flows from the collection point to a separate vault with a lower liquid surface level than the primary tank.

Rectangular Tanks. A rectangular tank, either a single unit or one of several adjacent units, typically has a length several times its width. Either wood or nonmetallic flights are mounted on parallel strands of steel or nonmetallic conveyor chain (Figure 19.4),

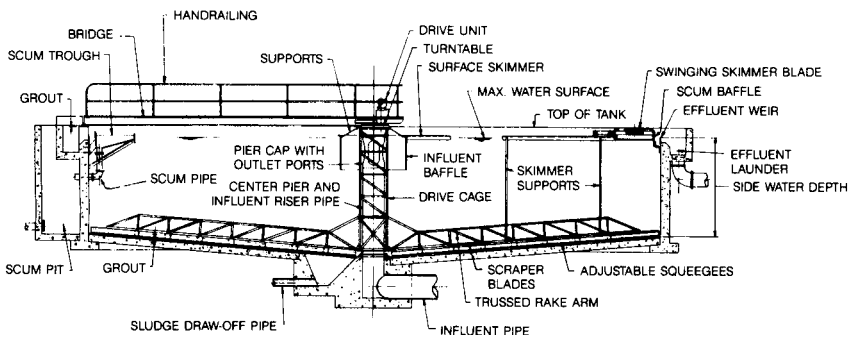


FIGURE 19.3 Section of a circular sedimentation tank.

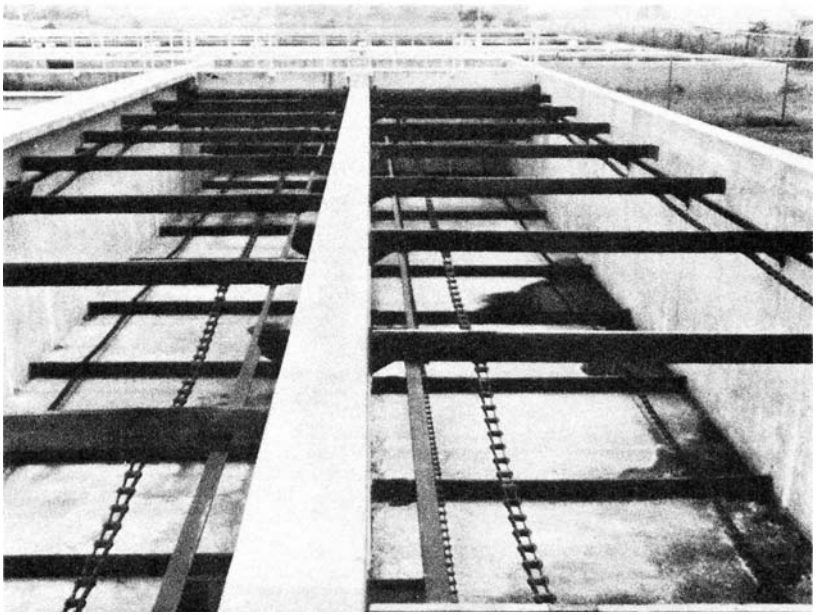


FIGURE 19.4 Rectangular primary sedimentation tank with wood or nonmetallic flights mounted on parallel chains.

or a single bottom scraper mounted on a bridge moving on rails fastened to the tank walls (Figure 19.5) moves settled sludge to a hopper at one end of the tank, typically the inlet end.

Chains and flights, guided by submerged sprockets, shafts, and bearings, are driven by a motor through a speed reducer. The flights are typically arranged to push floating surface material to the effluent end of the tank and push settled solids to the influent end of the tank on their return travel. Nonmetallic chain, flights, and sprockets are currently used more often in new installations and in retrofits of existing tanks. The nonmetallic equipment is lighter, making it easier to maintain, and requires less power to operate. Also, the nonmetallic equipment is less susceptible to corrosion. Other plants prefer metallic-type chains for their collector mechanisms because they are less likely to decay in sunlight and are less affected by temperature or stretching. In some tanks, flat water sprays, angled toward the liquid surface, move the scum and grease to the skimming device.

A traveling bridge, towed by a cable or powered by a traction drive, skims grease and scum with its surface scraper and moves sludge to the sump with its lower scraper blade. Typically, as the bridge travels with the flow, the scraper is up while the grease

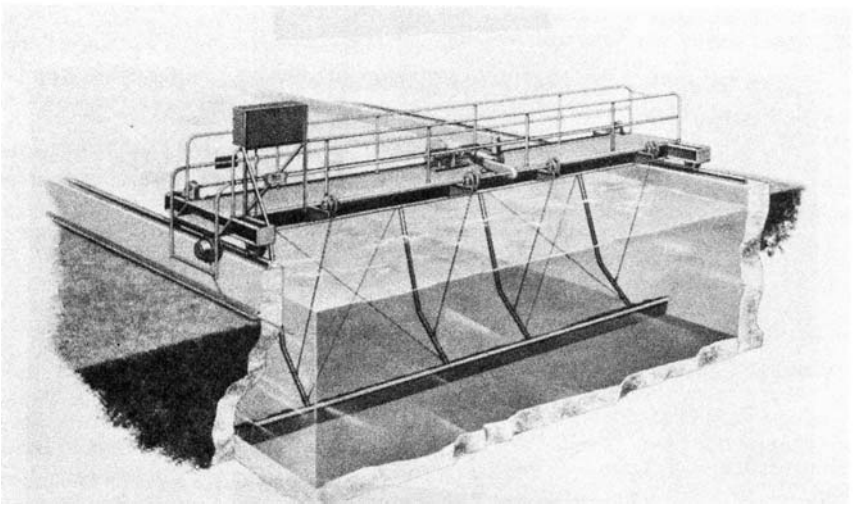


FIGURE 19.5 Rectangular primary sedimentation tank with traveling bridge sludge collector.

skimmer is down. When the bridge is moving opposite to the flow, the scraper is down to move the sludge to the hopper while the skimmer blade is raised.

The settled solids may collect in a single hopper, multiple hoppers, or a transverse trench with a hopper at one end. The transverse trench may be equipped with a flight-and-chain collector referred to as a *cross collector* or a screw conveyor that moves the sludge to the hopper.

A slotted pipe or rotating helical wiper skimmer is used in rectangular primary tanks, whereas slotted pipes or scum boxes are used in square and circular tanks to remove floating material. The material is then pumped or conveyed to another process, such as a digester, concentrator, or holding basin. Methods used to convey scum, grease, and other floating material include pneumatic ejectors, positive-displacement pumps, or recessed impeller centrifugal pumps as described in Chapter 8.

Circular Tanks. In the most common type of circular tank, a center feed well introduces the flow in a manner that dissipates inlet velocities and distributes the flow evenly around the tank (Figure 19.3). The wastewater moves radically from the feed well to the weir and overflow trough at the perimeter of the tank. Settled solids are raked to a hopper near the tank center by arms attached to a drive unit at the center of the tank (Figures 19.6 and 19.7) or by a traction unit operating on the tank wall. A surface blade attached to the collector (Figure 19.8) moves floating material to a scum hopper.

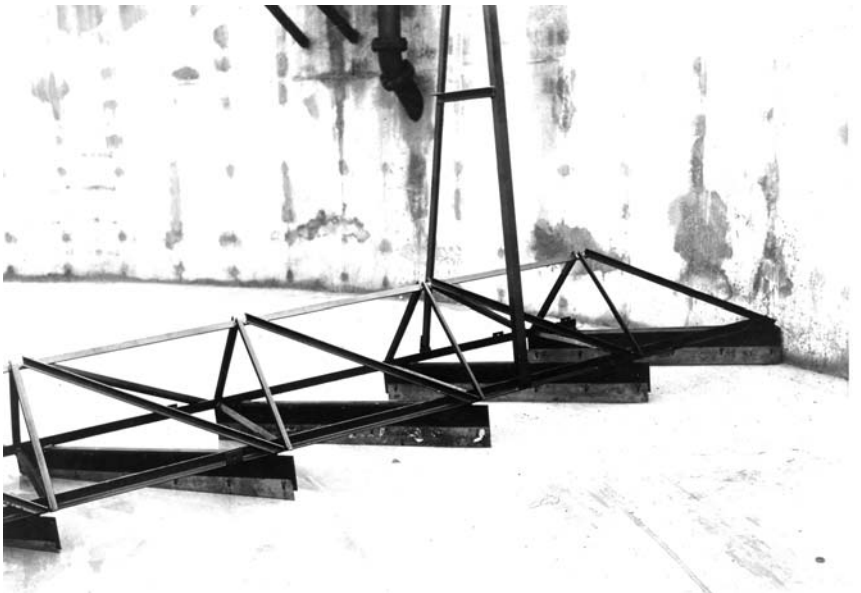


FIGURE 19.6 Circular sedimentation tank with sludge-scraping mechanism.

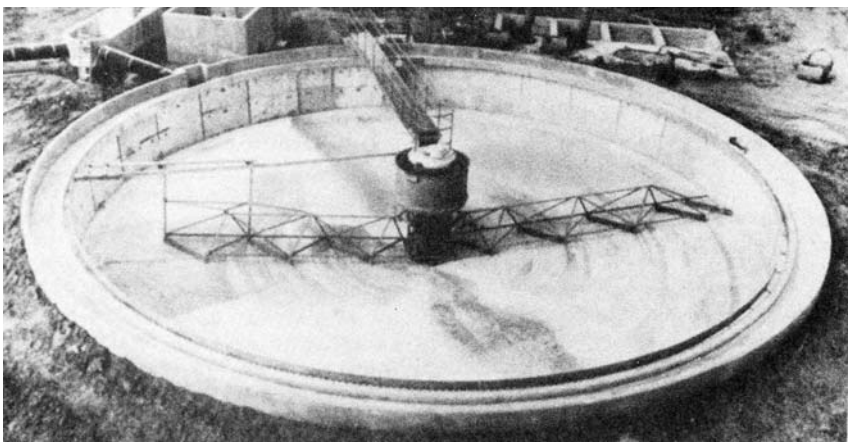


FIGURE 19.7 Scraper arms move the settled solids to the center of the tank.



FIGURE 19.8 Circular sedimentation tank showing grease skimmer and effluent weirs.

Square Tanks. These tanks remove settleable solids and floatables in a manner similar to that of circular tanks. Corner sweeps are added to the scum and sludge collector arms to remove floatables and settleables from the corners. Sometimes these corner sweeps can result in mechanical and operational problems. Some designs use sloped concrete fillets in place of corner sweeps.

PUMPING APPURTENANCES. Appurtenances include cleanouts in grease lines, sludge lines, pumps, flushing systems, and line-cleaning devices. Flushing of lines, pumps, and sumps use high-pressure water or air. Sludge lines may also be cleaned with steam or hot water. Line cleaning equipment includes hydraulically propelled tools (pigs) of metal or plastic and special fittings to insert and catch the cleaning device.

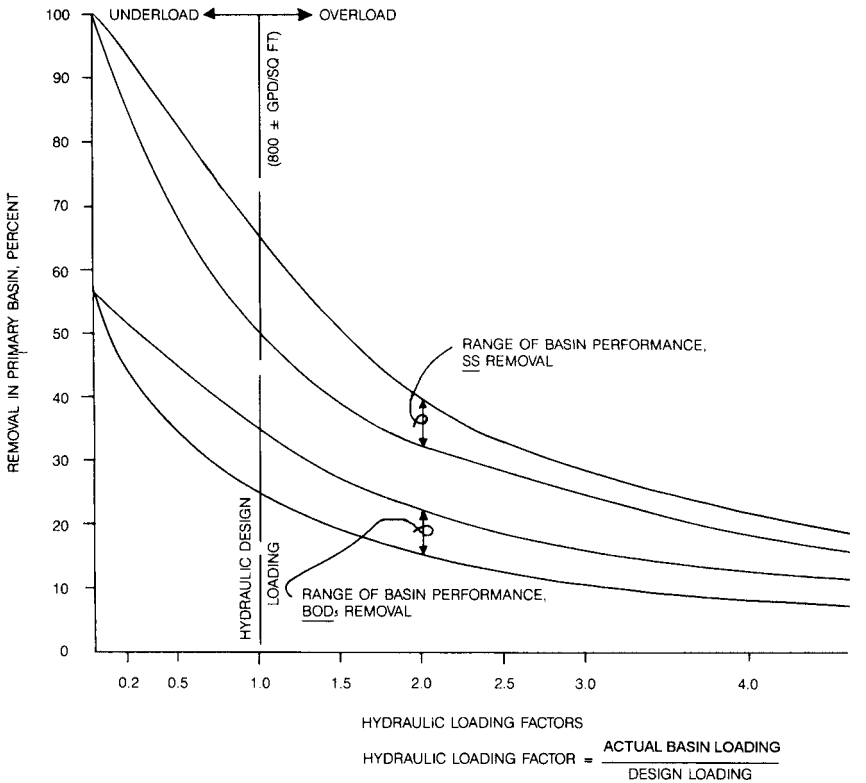


FIGURE 19.9 Estimated removals of suspended solids and five-day BOD (BOD_5) in primary basins at various hydraulic loadings (without chemicals) (SS = suspended solids; gpd/sq ft × 0.040 74 = $m^3/m^2 \cdot d$).

CHEMICAL ADDITION. Chemical addition may enhance settling performance and/or remove nutrients such as phosphorus. Commonly used chemicals include ferric chloride, polymers, alum, and lime. Equipment required to store, mix, dilute, and feed chemicals to the influent includes a variety of metering pumps, storage tanks, and piping. Chapter 9, Chemical Storage, Handling, and Feeding, and Chapter 24, Physical–Chemical Treatment, offer details regarding chemical addition.

EXPECTED PERFORMANCE

The BOD and suspended solids removal efficiencies of a primary sedimentation tank depend on many previously described variables, typically dominated by the surface overflow rate. Figure 19.9 shows BOD and suspended solids removal efficiencies re-

lated to the hydraulic loading factor—SOR; that is, the ratio of actual SOR to design SOR. With a loading factor of 1.0, the figure shows suspended solids removals ranging from 50 to 65% and BOD removals of 25 to 35%. Use of chemicals can increase suspended solids removals to the 75 to 85% levels, with proportionate increases in BOD removals (Heinke et al., 1980).

Performance for grease and scum removal cannot be accurately measured. However, lack of scum or floatables in the primary effluent or secondary influent channels generally indicates good performance.

PROCESS CONTROL

Good process control involves the seven operational aspects: solids handling, skimming of floatables, hydraulic considerations, recycle flow management, odor control, housekeeping, and chemical addition, if applicable.

SLUDGE HANDLING. Two variables, sludge thickness (or solids concentration) and quantity, affect handling operations. The quantity depends on thickness and the suspended solids loading and removal efficiency of the primary tanks. These two variables and their interaction with the two sludge-handling activities—collection and pumping—are discussed below.

Sludge Thickness (Solids Concentration). The necessary thickness of the sludge removed from primary sedimentation tanks depends on the type of solids-handling facilities downstream. If the sludge is pumped to thickeners, a "thin" concentration (0.5 to 1.0%) may be permissible. If the sludge is pumped to digesters or a dewatering process, a thicker concentration is necessary.

Thin primary sludge may needlessly burden downstream solids-handling processes. With reasonable control of solids removal, the operator may obtain a sludge thickness of 4 to 6%. The process control goal is to find a blanket or level that provides a thick sludge without adversely affecting tank removal efficiency, overloading collector equipment, or allowing decomposition in the bottom of the clarifier. If waste activated sludge is pumped to the primary tank, the sludge concentration removed from these units will be in the range of 2 to 4% solids.

Sludge Quantity. The operator may estimate the volume of sludge to be removed from the primary tank by measuring the influent and effluent suspended solids, percentage of dry solids in the pumped sludge, and wastewater flow. The method of calculating the wet sludge volume to be removed is given below.

In metric units

$$\text{Dry solids removed (kg/d)} = \frac{\text{mg/L removed} \times \text{Flow (m}^3\text{/d)} \times 1000}{10^6} \text{ or} \quad (3)$$

$$\text{mg/L removed} \times \text{Flow (m}^3\text{/d)} \times 10^{-3} \text{ or}$$

$$\text{mg/L removed} \times \text{Flow (ML/d)}$$

In U.S. customary units

$$\text{Dry solids removed (lb/d)} = \text{Suspended solids removed (mg/L)} \times \text{Flow (mgd)} \times 8.34 \text{ (lb/gal)}$$

In metric units

$$\text{Wet sludge removed (kg/d)} = \text{Dry solids removed} \times \frac{100}{\text{Dry solids, \%}} \quad (4)$$

In U.S. customary units

$$\text{Wet sludge removed (lb/d)} = \frac{\text{Dry solids removal (lb/d)} \times 100}{\text{Dry solids in sludge, \%}}$$

In metric units

$$\text{Wet sludge removed (m}^3\text{/d)} = \frac{\text{Wet sludge removed}}{\text{Specific gravity of the sludge} \times 1000} \quad (5)$$

In U.S. customary units

$$\text{Wet sludge removed (gpd)} = \frac{\text{Wet sludge removed (lb/d)}}{8.34 \text{ lb/gal}}$$

From the above equations, the operator may derive the approximate duration of pumping for a known pump capacity. Lack of daily analytical information may prevent daily use of the above equations; nonetheless, use of estimated values will provide an appraisal of wet sludge volumes valuable to the operator as a general guideline. The operator may then adjust the guideline based on daily observations of the sludge blanket levels and the guideline number determined weekly using eqs 3 through 5. Of course, chemical addition would generate more material for removal

than that indicated by these equations. Chapter 24 presents an example of the calculation of the solids volumes generated with chemical addition.

Operators should calculate the amount of solids into and out of the primary tank to ensure that the system is operating efficiently. Calculating the balances in and out of the tank provides a useful tool for operators to monitor the system to ensure that it is within operating parameters.

Collection. The collectors may run on varying schedules (continuous or intermittent) depending on the type of plant, equipment, and characteristics of the wastewater. If the plant is designed to pump a thin sludge to thickeners or to a degritting unit, the collectors must run continuously. If the primary tanks are square or circular, running the collectors continuously is generally necessary because sludge movement to the hoppers requires more time than that for rectangular tanks. Continuous operation avoids the possibility of overloading the mechanism with accumulated solids. Regardless of tank type or plant design, continuous collector operation allows easy operation of an automatic withdrawal system. Because of its many advantages, continuous sludge collector operation is preferred for most plants.

Intermittent operation of the collectors may be necessary if the primary tanks are used to thicken the waste sludge from the secondary process or if primary sludge is pumped directly to digestion or dewatering units. As a good practice for intermittent operation of rectangular tanks, the operator may start the collector mechanisms approximately 1 hour before sludge is drawn and then turn off the collector when pumping stops. This procedure helps avoid overloading the collector mechanisms or packing the sump.

Sludge Pumping. Positive-displacement pumps such as piston, progressive cavity, or diaphragm pumps are typically used to remove sludge from the primary sedimentation tanks. Many plants use centrifugal torque flow pumps or hose pumps for primary sludge. Pumping may be either continuous or intermittent. With several pumps, each pump may withdraw sludge from a single hopper simultaneously. A single pump should withdraw from only one hopper at a time because differing head losses among the suction lines may cause unequal sludge withdrawals from the individual tanks. Pumping for short durations at frequent intervals is a good practice, and pumping for long periods at infrequent intervals is to be avoided because excessive sludge to an anaerobic digester can upset the process. Ideally, pumping approaches continuous operation to evenly feed downstream processes. Some plants vary the amount of sludge pumped with diurnal flow or historical solids loading patterns.

The proper solids concentration of sludge pumped (see Chapter 8) from settling tanks varies from plant to plant. The operator monitors solids concentrations from

sample ports in the discharge lines and measures sludge levels before and after pumping to ensure that the proper pumping frequency and duration have been selected. Some techniques used to measure sludge blankets include using a pole to "feel" the height of the blanket, sample aspiration at various depths, core sampling, and electronic light-penetration measurement. Routine monitoring of the torque indicator, when available, will give the operator an indication of the sludge inventory. By observing and recording daily torque readings, the operator can determine whether the rate of primary sludge pumping needs to be adjusted. Using this observation in conjunction with other operational parameters such as sludge blanket depth, volume of sludge pumped, and visual/olfactory observations (black or septic color, increased odor, and rising/floating/clumping sludge) will prompt the operator to adjust the sludge pumping rate.

Many plants use automatic sludge pumping controlled with either a timer, a programmable logic controller (PLC), or a timer with a density meter. With the first and second options, preset times operate the pumps for each tank at the selected frequency and duration. With the third option, the timer turns the pump on and the density meter shuts the pump off. In this option, sludge thickness governs the pumping time. With any type of automatic system, routine level measurements are necessary to ensure the operator that sludge buildups are not occurring. Wastewater treatment plants typically designed today do not include density meters because of their expense and maintenance needs. In addition, wastewater treatment plants designed today use centralized computer systems to control sludge pumping and/or grease removal.

Pumping Appurtenances. Cleanouts, typically provided in sludge lines and pumps, need to be checked if pumping trouble occurs. All lines should be equipped for cleaning with hydraulically propelled tools or balls because regular sludge line cleaning reduces jamming at valves or fittings. The frequency of line cleaning depends on velocities in the pipe, the grease content of the sludge, grit in the pipe, chemical constituents in the line, and temperature. As the weather becomes colder, grease coatings become thicker and tougher, which means that line cleaning may be necessary as often as twice monthly.

Flushing systems are used to clean sludge pumps, suction lines, and discharge piping. If a flushing system is provided, a few minutes of weekly flushing helps to keep lines clean. Whenever sludge becomes difficult to pump, the system should be flushed. Plant water connections are usually provided at the end of the suction line to clear the sludge pump. At some plants, compressed air is also used for cleaning a packed sump or suction line.

FLOATABLE SOLIDS SKIMMING. Grease, fats, oils, plastics, and other floatables must be consistently removed. Skimmings and floatables that are removed from primary tanks are pumped to various disposal facilities in wastewater treatment plants. Some plants transfer their skimmings to concentrators or dissolved air flotation thickeners. The concentrated skimmings are then transferred to an incinerator or trucked off site for disposal. Other plants transfer skimmings to dewatering facilities such as belt presses, whereas others pump their skimmings to anaerobic digesters; this practice of pumping is gradually being phased out because of problems within the digesters because of excessive scum buildup. The removal frequency depends on the amount of floatables in the incoming wastewater, flow variations throughout the day, and wastewater temperature. Circular tanks, because of their design, are skimmed continuously; most rectangular tanks remove skimmings periodically. Rectangular tanks need skimming at least once a day and more frequently whenever grease or floatables appear in the primary effluent, secondary influent channels, or the final clarifiers. Rectangular tanks typically use scum troughs that are manually operated or they can be automatically operated by a timer or PLC. Control of odors may also require more frequent skimming. The skimming process must capture enough wastewater to allow scum conveyance through eductors, screw conveyors, and pipelines.

HYDRAULIC CONSIDERATIONS. Surface overflow rates and hydraulic retention times for proper settling generally vary within the following ranges: average SOR without waste activated sludge should be in the range 32 to 49 $m^3/m^2 \cdot d$ (800 to 1200 gpd/sq ft), and the peak SOR should not exceed 122 $m^3/m^2 \cdot d$ (3000 gpd/sq ft). If waste activated sludge is cosettled in the primary tank, the average SOR should be in the range of 24 to 32 $m^3/m^2 \cdot d$ (600 to 800 gpd/sq ft), and peak SORs should be in the range 49 to 61 $m^3/m^2 \cdot d$ (1200 to 1500 gpd/sq ft). The detention time is 1 to 2 hours.

The two hydraulic control variables for the primary influent are the flowrate and the number of tanks in service. Because most plants must accept flow as it enters the plant, flow control is limited. Nonetheless, variations in flow sometimes can be reduced by changing the pumping rates at the pumping stations in the collection system or at the plant headworks. This practice takes advantage of the temporary storage capacity available in the sewer system. Also, storm-related variations in flow can be reduced by an aggressive infiltration–inflow correction program and, in combined sewer systems, by proper maintenance of diversion chambers. Some plants have equalization basins to smooth diurnal flow variations. Plant recycle flows should be timed to smooth rather than aggravate variable hydraulic loading of the primary treatment units.

With multiple primary tanks having long detention times, tanks may be taken out of service when plant flows are considerably less than design flow. The following operational considerations apply to removing primary tanks from service:

- Remove a tank from service less frequently than monthly,
- Rotate the removal of tanks from service,
- Keep idle tanks filled with plant effluent water, and
- Exercise mechanisms of idle tanks daily.

If the primary tank detention times are short because of a shortage of tanks, then the operator's flexibility for tank maintenance is limited because the tank downtime must be kept to a minimum. Some procedural options include the following:

- Use all available tanks for primary influent settling so that one primary tank at a time can be temporarily removed from service.
- Reduce downtime of tanks by a comprehensive preventive maintenance program.
- Minimize the effect of recycle flows by altering their timing or time of day, redirecting them to another portion of the plant, and eliminating nonessential flows.
- Modify influent flow by adjusting pumping stations and reducing infiltration and inflow.
- Add chemicals to increase removal of settleable solids while one tank is removed from service.
- Request additional tankage.

Ensuring equal flows among multiple tanks and uniform flow distribution across the width of each rectangular tank (or around the perimeter of circular tanks) are important hydraulic objectives. Good flow distribution will minimize variations in sludge blankets and aid overall performance. Level weirs and properly adjusted influent gates help equalize flows to each tank. Because flows vary throughout the day, the gates may require several adjustments during the day to maintain good flow distribution. Influent flow distribution boxes with an upflow pipe and influent weirs for each tank have been installed in New York City and Nassau County, New York. The use of influent weirs allows the gate to be left wide open and accounts for flow variations throughout the day.

RECYCLE FLOW MANAGEMENT. Recycle flow management can improve settling tank performance by minimizing hydraulic and solids loadings while reduc-

ing the potential for septicity. Good recycle flow management includes the following actions:

- Identify each recycle flow and its duration and quality;
- Assess the effect of each recycle on sedimentation performance; and
- Eliminate, reduce, redirect, or smooth the recycle flows as indicated by the evaluation.

ODOR CONTROL. Chapter 13, Odor Control, covers odor control in detail. Following is a short checklist of operational considerations for controlling odors of primary treatment facilities:

- Remove scum routinely, with increased frequency during warm weather.
- Remove sludge before it can bubble or float.
- Wash weirs and other points where floatables and slime collect. Some facilities use submerged pipes with holes rather than effluent troughs. The submerged pipes do not splash the primary effluent, thereby reducing the release of hydrogen sulfide.
- Wash down all spills and grease coatings.
- When draining a tank, immediately flush it completely. If sludge does not drain quickly, spray lime, calcium hypochlorite, or potassium permanganate on the sludge surface to reduce odors. Because even a clean tank can produce odors, flushing the tank with a chlorine solution or keeping the tank floor covered with a low concentration of chlorine solution will reduce odors.
- If the wastewater is septic, add chemicals in the collection system or at the plant, as appropriate, to reduce sulfides.
- If tanks are covered for odor control, keep plates and access hatches in place.
- Routinely check any odor scrubbers or deodorizers for plugging, adequate supply of chemicals, proper pressures for misting, and/or effectiveness of carbon.
- The splashing of primary effluent into weir troughs and effluent channels can result in the release of hydrogen sulfide. If possible, try to minimize the splashing of primary effluent into the channel or weirs. If it cannot be accomplished operationally, then installing submerged effluent pipes may be necessary. This will require a tank modification to verify the plant hydraulics and provide a proper control to avoid fluctuations in the tank levels.
- Minimize the stripping of hydrogen sulfide from the wastewater when using channel air diffuser systems.

HOUSEKEEPING. Adoption of the following regular practices will not only increase removal efficiency, but will provide better working conditions for the operator:

- Regularly remove accumulations from the inlet baffles and effluent weirs with a hose or a broom with stiff bristles. Only experience will determine the necessary frequency.
- Clean scum removal equipment regularly; otherwise obnoxious odors and an unsightly appearance will result.
- Keep cover plates in place except when operations or maintenance require their removal.
- Immediately flush and remove all wastewater and sludge spills. Avoid hosing down motors and enclosed control devices.
- Establish a housekeeping schedule for the primary treatment area, including galleries, stairwells, control rooms, and related buildings, and assign responsibility for each item to a specific employee.
- Repaint surfaces as necessary for surface protection and appearance.

CHEMICAL ADDITION. Chemical addition principally improves solids removal in the primary tanks, but it may also help control odors and remove nutrients such as phosphorus. Different chemicals are added ahead of the primary tanks to serve different functions.

- Polymers are used to improve settling.
- Chlorine or potassium permanganate is added for odor control, and it may also improve settling by oxidizing the hydrogen sulfide.
- Iron compounds such as ferric chloride, ferric sulfate, ferrous sulfate, or aluminum compounds such as aluminum sulfate (alum) or sodium aluminate are added for phosphorus removal and they can also improve settling.

Good process control of chemical addition emphasizes application of the proper amounts of chemicals for settling enhancement and ensures that chemicals are well mixed. The following process control considerations apply:

- Determine the proper dosage and mixture of chemicals by jar testing. Because wastewater characteristics can change because of growth, industry, or season, repeat jar tests frequently to prevent underdosing or overdosing.
- Verify, by field measurement or calibration at least weekly, that metering systems are delivering the required quantities of chemicals.

- Verify through weekly or more frequent process control testing that the desired effluent quality is being attained.
- Check, as described below, for adequate mixing of chemicals, particularly when tank performance deteriorates:

– Does the chemical injection point allow sufficient time for good mixing?
– Are the mixers clogged with rags or other debris?
– If used, are air diffusers plugged?

- Ensure adequate inventory of chemicals for continuation of proper dosing through a long weekend or other extended periods without deliveries.
- Following chemical addition, allow for more sludge volume with different pumping characteristics and for more frequent line cleaning.

PROCESS CONTROL DATA. The testing required for primary treatment influent, effluent, and sludge varies among plants. In deciding which tests are essential, the operator must consider permit requirements, downstream treatment units, and anticipated industrial wastes. Typical tests for evaluating the primary sedimentation unit process include settleable solids, suspended solids, total solids, volatile solids, five-day BOD (BOD_5), pH, and oil and grease concentrations. Chapter 17, Characterization and Sampling of Wastewater, and Chapter 28, Characterization and Sampling of Sludges and Residuals, describe each of these tests; their typical applications to primary sedimentation are outlined briefly below.

Suspended and Settleable Solids. Suspended solids are typically analyzed on composited samples, whereas settleable solids can be determined from composite or grab samples. These tests are typically performed daily at large plants (flows higher than 19 ML/d [5 mgd]) and at least twice weekly at smaller plants. Samples of the influent and effluent of the tank are taken at points where the wastewater is well mixed. Test results indicate the removal efficiency of the primary units, the solids loading entering downstream treatment units, and the quantity of sludge to be pumped.

Total and Volatile Solids in Wastewater. The results of these tests, when coupled with suspended solids values, provide useful information on the type, concentration, and quantity of solids. This information provides detection and, in some cases, quantity estimation of wastes from industries. Infiltration of surface and groundwater may also be detected.

Total and Volatile Solids in Sludge. These tests typically are performed daily on manually composited samples removed from the tanks. The results provide information on

the solids loading on digesters and dewatering units. Exact knowledge of the percentage of moisture in the sludge enables the operator to check visual observations on the degree of compaction, the need for changing sludge removal rates and quantities, and the amount of excess water entering the digestion and dewatering units.

Biochemical Oxygen Demand. Tests for BOD_5 on composite samples of influent and effluent are typically performed daily and no less than twice a week, even in small plants. Tests on the tank effluent provide an excellent measure of the organic loading on downstream biological processes. Soluble BOD tests on the influent and effluent can serve as indicators of septic conditions in the tank.

pH. The pH of untreated wastewater is measured periodically to establish the normal range and is also measured whenever an unusual waste contribution is suspected. Consistently low pH values of grab samples indicate either partial decomposition of wastewater in the collection system or regular discharges of partially decomposed or acid waste to the collection system. If continuous measurements are available, they provide an early warning of unusual wastes.

Fats, Oils, and Grease. Tests for fats, oils, and grease (FOG) are performed periodically on untreated wastewater to determine the strength of commercial or industrial contributions. Tests for sludge FOG differ from those for wastewater. Some industrial oils or greases cannot be detected. Chapter 17 and *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 1995) provide more details on FOG tests.

TROUBLESHOOTING

To remedy difficulties experienced with the primary treatment units, the operator must know the characteristics of the collected primary sludge, design shortcomings of the primary tanks and equipment, and indicators of operational problems. Brief descriptions and tabulations are given below concerning each of these three aspects of troubleshooting.

CHARACTERISTICS OF COLLECTED SLUDGE. The quality of sludge removed from sedimentation tanks varies widely among plants. Variations depend principally on

- Composition, freshness, strength, constituents, and settleability of the wastewater entering the tank;
- Characteristics and adequacy of the settling tank; and
- Management of the settling tank, including the methods of sludge removal.

Table 19.1 summarizes the typical characteristics of sludge settled from wastewater of largely domestic origin.

DESIGN SHORTCOMINGS. The operator needs to recognize design shortcomings that affect settling performance and possible remedies. Some of the remedies

TABLE 19.1 Characteristics of raw sludge from plain sedimentation tanks (Manual, 1973; Manual, 1988; TWUA; U.S. EPA, 1973, 2001).

Parameter	Description	Remarks
Physical texture	Nonuniform, lumpy.	—
Color	Brown.	Dyes from industrial wastes may color the sludge or it may be dark gray or black in color if septic (see septicity below).
Density	Solids content varies.	A good quality for drawing should average 5% solids.
Odor	Typically offensive.	May have little or no odor in the presence of such industrial wastes as metallic salts.
Volatile matter	Average range 70 to 80% of total dry solids.	Occasionally may run as high as 85% or as low as 60%. If appreciably less than 70%, the presence of grit should be suspected.
pH	Usual range 5.5 to 7.5; average value approximately 6.5.	Affected by industrial wastes and septicity of sludge.
Septicity	Typically nonseptic.	Septic raw sludge is common if the raw wastewater is septic, sludge is retained too long in tanks, or a poor-quality supernatant liquor comes from the digestion tanks.
Sludge volume	From 70 to 700 cu ft/mil. gal of wastewater treated; average approximately 250 to 350 cu ft/mil. gal.[a]	High volumes indicate that the sludge withdrawn is too thin or some voluminous industrial waste is present; low volumes indicate weak wastewater, poor tank efficiency, or sludge buildup in tanks.
Digestibility	Typically easily digested.	Nondigesting raw solids indicate harmful industrial wastes such as metallic salts or fibrous matter.
Grease content	Typically 10 to 20 mg/L.	Appreciably higher figures indicate industrial wastes such as waste oils or wool scouring wastes.

[a]cu ft/mil. gal $\times$ 0.074 8 = L/m^3.

may be carried out by plant personnel at low cost. Table 19.2 presents a list of design shortcomings observed for sedimentation basins and associated equipment and the possible remedies of those shortcomings.

OPERATIONAL PROBLEMS AND SOLUTIONS. The nature of an operational problem and its severity are frequently temperature dependent. In colder weather, sludge will be more difficult to pump, sludge lines will collect grease more quickly, and skimming quantities will increase; however, septicity and odor will likely diminish. Table 19.3 presents a troubleshooting guide that will enable the operator to identify problems with primary sedimentation and determine their solutions.

MAINTENANCE

The elements of a sound maintenance program include a good preventive maintenance program, established written procedures for emergency maintenance, and a system to

TABLE 19.2 Common design shortcomings and ways to compensate (U.S. EPA, 1973).

Shortcoming	Solution
Poor flotation of grease.	Preaeration of wastewater to increase grease buoyancy.
Scum overflow.	Move scum collection system away from outlet weir. Lower scum baffle deeper into the tank.
Sludge hard to remove from hopper because of excessive grit.	Install grit chamber or eliminate sources of grit entering the system.
Short-circuiting of flow through tank, causing poor solids removal.	Modify hydraulic design and install appropriate baffles to disperse flow and reduce inlet velocities.
Heavy wear and frequent breakage of scrapers and shear pins because of grit.	Install grit chamber.
Inadequate removal of heavy grease loading.	Install flotation or evacuator equipment
Septic conditions resulting from sidestream overloading.	Divert or provide alternate disposal for other plant process wastes (that is, centrates and supernates) that are typically recirculated to the sedimentation tank.
Excessive corrosion because of septic wastewater.	Coat all surfaces with proper paint or other coating.
Consistent problems with thermal currents in clarifier.	Install flow equalization and mixing basin ahead of the clarifier.
Poor scum removal because of wind.	Install a wind barrier to protect tank from wind effects. Modify scum collection system to compensate for wind.
Septic wastewater.	Improve hydraulics of collector system to reduce accumulation of solids.

TABLE 19.3 Troubleshooting guide for primary sedimentation problems (Manual, 1973; Manual, 1978; TWUA; U.S. EPA, 1973, 2001).

Indicators/observations	Probable cause	Check or monitor	Solutions
Floating sludge.	Excessive sludge accumulating in the tank.		Remove sludge more frequently or at a higher rate.
	Scrapers worn or damaged.	Inspect scraper.	Repair or replace as necessary.
	Return of well-nitrified waste activated sludge.	Effluent nitrates.	Vary age or returned sludge or move point of waste sludge recycle.
	Sludge withdrawal line plugged.	Sludge pump output.	Flush or clean line.
	Damaged or missing inlet baffles.	Damaged baffles.	Repair or replace.
Black and odorous septic wastewater or sludge.	Sludge collectors worn or damaged.	Inspect sludge collectors.	Repair or replace as necessary.
	Improper sludge removal pumping cycles.	Sludge density.	Increase frequency and duration of pumping cycles until sludge density decreases.
	Inadequate pretreatment of organic industrial wastes.	Pretreatment practices.	Preaerate waste. Have pretreated by industry.
	Wastewater decomposing in collection system.	Retention time and velocity in collection lines.	Add chemicals or aerate in collector system.
	Recycle of excessively strong digester supernatant	Digester supernatant quality and quantity.	Improve sludge digestion to obtain better quality supernatant. Reduce or delay withdrawal until quality improves. Select better quality supernatant from another digester zone. Discharge supernatant to lagoon, aeration tank, or sludge drying bed.
	Sludge withdrawal line plugged.	Sludge pump output.	Clean line.
	Septic dumpers.	Random sampling of trucks.	Regulate or curtail dumping.
	Insufficient run time for sludge collectors.	Review operator logs.	Increase run time or run continuously.
Scum overflow.	Frequency of removal inadequate.	Scum removal rate.	Remove scum more frequently.

TABLE 19.3 Troubleshooting guide for primary sedimentation problems (Manual, 1973; Manual, 1978; TWUA; U.S. EPA, 1973, 2001) (*continued*).

Indicators/observations	Probable cause	Check or monitor	Solutions
Scum overflow (*continued*).	Heavy industrial waste contributions.	Influent waste.	Limit industrial waste contributions.
	Worn or damaged scum wiper blades.	Wiper blades.	Clean or replace wiper blades.
	Improper alignment of skimmer.	Alignment.	Adjust alignment.
	Inadequate depth of scum baffle.	Scum bypassing baffle.	Increase baffle depth.
Sludge hard to remove from hopper.	Excessive grit, clay, and other easily compacted material.	Operation of grit removal system.	Improve operation of grit removal unit.
	Low velocity in withdrawal lines.	Sludge removal velocity.	Increase velocity in sludge withdrawal lines. Check pump capacity.
	Pipe or pump clogged.		Backflush clogged pipe lines and pump sludge more frequently.
	Hydraulic overload.	Influent flowrate.	Provide more even flow distribution in all tanks, if multiple tanks.
Undesirably low solids contents in sludge.	Short-circuiting of flow through tanks.	Dye or other flow tracers.	(See Short-circuiting of flow through tanks.)
	Overpumping of sludge.	Frequency and duration of sludge pumping; suspended solids concentration.	Reduce frequency and duration of pumping cycles.
Short-circuiting of flow through tanks.	Uneven weir settings.	Weir settings.	Change weir settings.
	Damaged or missing inlet line baffles.	Damaged baffles.	Repair or replace baffles.
Surging flow.	Poor influent pump programming.	Pump cycling.	Modify pumping cycle.
Excessive sedimentation in inlet channel.	Velocity too low.	Velocity.	Increase velocity or agitate with air or water to prevent decomposition.

Poor suspended solids removal.	Hydraulic overloading.	Flow.	Use available tankage, shave peak flow, chemical addition.
	Septic influent.	pH, dissolved oxygen, hydrogen sulfide.	Intensify and resolve upstream causes. Pretreat with chlorine or other oxidizing chemical until problem is resolved.
	Short-circuiting.		(See Short-circuiting of flow through tanks.)
	Poor sludge removal practices.	Monitor pumping duration and sludge levels.	Frequent and consistent pumping.
	Recycle flows.	Inventory flows—quality and quantity.	(See Rectangular Tanks section.)
	Industrial waste.	Influent sampling.	Eliminate industrial wastes that hinder settling.
	Density currents wind or temperature related.	Monitor wastewater temperature and wind.	Eliminate storm flows from sewer system. Install wind barrier.
Excessive growth on surfaces and weirs.	Accumulations of wastewater solids and resultant growth.	Inspect surfaces.	Frequent and thorough cleaning of surfaces.

ensure an adequate supply of essential spare parts. Table 19.4 presents a troubleshooting guide identifying some of the more frequent maintenance problems and their possible solutions.

PLANNED PREVENTIVE MAINTENANCE PROGRAM. Primary settling tanks represent a tremendous investment in machinery, including equipment that typically operates underwater. Protection of this investment requires at least an annual inspection of the tanks and appurtenant equipment. A thorough inspection includes the following procedures:

- Inspect all mechanical equipment for wear and corrosion. Replace as necessary and apply a protective coating to chains, sprockets, guide rails, shaft bearings, bearing brackets, and other equipment parts.
- Lubricate all metal parts.
- Check flights for chipping or breaking, missing or loose wear shoes, or missing bolts. Replace these items as necessary.
- Check baffle boards for warping or breakage and replace them as required.
- Adjust the tension of chains, both longitudinal and cross-collector. Note that nonmetallic chain has tension and slack requirements different from those of steel chain, and nonmetallic chain stretches much more during its initial break-in period, thus requiring frequent checks.
- Check all suction lines and sumps for debris collection and clogging. Clean all lines before filling tanks.
- Check all mechanical parts of the skimming unit for wear or corrosion. Counterbalance the chain for buckets and trolley or carriage (adjustment may be required).
- Inspect all concrete above and below the waterline, particularly blind areas such as sumps and anchorage areas for mechanical equipment. Patch concrete and caulk and seal joints as necessary.

The most likely circular sedimentation tank equipment problems include

- Failure of the overload protection, resulting in equipment damage;
- Oil seal leak or failure; and
- Failure of the needle bearings (roller bearing) or worm and pinion gear, possibly resulting from excessive wear or lack of lubrication.

The equipment of circular tanks needs periodic lubrication (turntable, worm drive, and lower gear drive), oil changes, and inspection (gear wear and gears and bearings for

TABLE 19.4 Troubleshooting guide for maintenance of primary sedimentation process.

Indicators/observations	Probable cause	Check or monitor	Solutions
Erratic operation of sludge collection mechanism.	Broken shear pins, damaged collector.	Shear pins and sludge collector.	Repair or replace damaged parts.
	Rags and debris entangled around collector mechanism.	Sludge collector.	Remove debris.
	Excessive sludge accumulation.	Sound bottom of tank.	Increase frequency of pumping sludge from tank.
	Inadequate preventive maintenance program.		Annual draining and inspection of tank.
Broken scraper chains and frequent shear pin failure.	Improper shear pin sizing and flight alignment.	Pin sizing and flight alignment.	Realign flights and change shear pin size (after checking with manufacturer).
	Ice formation on walls and surfaces.	Inspect walls and surfaces.	Remove or break up ice formation.
	Excessive loading on mechanical sludge scraper.	Sludge loading.	Operate collector for longer period and/or remove sludge more often.
	Inadequate preventive maintenance program.		Annual draining and inspection of tank.
Excessive corrosion on unit.	Septic wastewater.	Color and odor of wastewater.	Paint surfaces with corrosion-resistant paint or coating.
Noisy chain drive.	Moving parts rub stationary parts.	Alignment.	Tighten and align casing and chain. Remove dirt or other interfering matter.
	Chain does not fit sprockets.		Replace with correct parts.
	Loose chain.		Adjust chain to manufacturer's recommended tension.
	Faulty lubrication.	Lubrication.	Lubricate properly.
	Misalignment or improper assembly.	Alignment and assembly.	Correct alignment and assembly of drive.
	Worn parts.		Replace worn chain or bearings. Reverse worn sprockets before replacing.
Rapid wear of chain drive.	Faulty lubrication.	Lubrication.	Lubricate properly.
	Loose or misaligned parts.	Alignment.	Align and tighten entire drive.

TABLE 19.4 Troubleshooting guide for maintenance of primary sedimentation process (*continued*).

Indicators/observations	Probable cause	Check or monitor	Solutions
Chain climbs sprockets.	Chain does not fit sprockets.		Replace chain or sprockets.
	Worn-out chain or worn sprockets.		Replace chain. Reverse or replace sprockets.
	Loose chain.		Tighten.
	Alignment.		Align sprocket and chain.
Stiff chain.	Faulty lubrication.	Lubrication.	Lubricate properly.
	Rust or corrosion.		Clean and lubricate.
	Misalignment or improper assembly.	Alignment and assembly.	Correct alignment and assembly of drive.
	Worn-out chain or worn sprockets.		Replace chain. Reverse or replace sprockets.
Broken chain or sprockets in chain-drive system.	Shock or overload.	Influent flowrate.	Avoid shock and overload or isolate through couplings.
	Wrong size chain or chain that does not fit sprockets.		Replace chain. Reverse or replace sprockets.
	Rust or corrosion.		Replace chain. Correct corrosive conditions.
	Misalignment.	Alignment.	Correct alignment.
	Interferences.		Make sure no solids interfere between chain and sprocket teeth. Loosen chain if necessary for proper clearance over sprocket teeth.
Oil seal leak.	Oil seal failure.	Oil seal.	Replace seal.
Bearing or universal joint failure.	Excessive wear.		Replace joint or bearing.
	Lack of lubrication.	Lubrication.	Lubricate joint and/or bearing.
Binding of sludge pump shaft.	Improper adjustment of packing.		Adjust packing.

alignment). Necessary maintenance activities include brushing and cleaning gear housings, removing and cleaning oil pump strainers, and replacing skimmer blades as necessary.

One of the most important elements in a preventive maintenance program is a schedule for protective coating and painting. Ferrous metal above the waterline needs regular repainting every 3 years; ferrous metal below the waterline needs repainting every 5 to 10 years. Paint manufacturers' recommendations will be helpful in establishing a painting program.

For further information regarding the maintenance of rectangular, square, or circular settling tank mechanisms, operators can review their plant equipment maintenance instructions, *Basic Maintenance of Rectangular Secondary Clarifiers* (WEF, 1993), and *Basic Maintenance of Circular Secondary Clarifiers* (WEF, 1992).

EMERGENCY MAINTENANCE. Some emergency maintenance considerations are presented below. When a problem occurs, stop the flow and drain the tank. The time required for tank drainage must be known. Notify all concerned staff, including those who might occupy the influent pumping station wet well, of the tank draining schedule and of the possible presence of dangerous gases in the wet well if the tank drainage is being returned to the influent wet well. While draining, run all operable flights to facilitate tank cleaning.

To clear sludge from a rectangular tank, support flights above the floor on blocks in inoperable collector bays so that sludge can be washed to the sump. Flushing valves in the effluent walls will expedite cleaning by allowing primary effluent to flush the inoperable bays. After work is completed, check the floor and sump areas for debris such as broken flights, tools, and broken pins. Check for proper operation of all mechanical equipment before returning the tank to service.

To avoid disastrous results, never use a shear pin larger than the correct size.

SPARE PARTS. The spare parts inventory must include a stock of the parts necessary to maintain primary tank operation. The stock of major spare parts typically includes flights and drive chains for rectangular tanks and wiper blades, skimmer assembly, turntable gears, and a motor for circular tanks. Rectangular tanks also use wearing shoes on the collector flights. It is recommended that a stock of wearing shoes be kept for spare parts. There should be enough wearing shoes to equip one tank and have an excess of 10% for miscellaneous replacements. A suggested stock of spare parts is listed below.

- Motors;
- Gear reducers;

- Sprockets, chains, and flights (enough to equip one tank);
- Wall brackets (enough to equip one tank);
- Chain pins, six per strand of chain; and
- Shear pins, ten per tank.

When determining the stocking of spare parts, operators must also take into account the fail occurrence of a piece of equipment and the delivery time of a piece of equipment. For example, if a piece of equipment fails frequently, then additional spare parts for that equipment must be in stock at the treatment facility. In addition, if there is a long delivery lead time for a piece of equipment, that should also be taken into consideration when ordering and stocking spare parts. Equipment suppliers should be consulted for complete spare parts recommendations.

SAFETY

Chapter 5, Occupational Safety and Health, discusses safety for the overall wastewater treatment plant. Some safety considerations, especially for primary sedimentation, are listed below.

- Apply confined space entry procedures relating to pump pits, ejector pits, and enclosed or partially enclosed primary tanks;
- Use extreme caution to avoid falls during entry to and exit from drained tanks;
- Require hard hats and provide good footing to avoid slips and falls while working on tank floors;
- Provide constant ventilation of covered tanks and prohibit smoking in their vicinity;
- Practice meticulous personal hygiene when work requires contact with sludges, wastewater, and scum;
- Exercise caution to prevent burns or eye injuries from chemical feed pumps and tanks;
- Keep access plates and hatches in place;
- Keep tank area well lighted;
- Lockout/tagout inlet gates or valves before entering an empty tank; and
- Lockout/tagout electrical equipment during maintenance or when inspecting an empty tank.

RECORDS AND REPORTS

Maintaining good performance of the primary units requires records of operation, sampling and analysis, and maintenance. Good operating records should include the following items:

- Number of tanks in operation;
- Sludge levels;
- Pumping time;
- Skimming time;
- Equipment run times;
- Operator and shift;
- Housekeeping checklist;
- Chemicals used (if applicable);
- Suspended solids concentrations of the influent, effluent, and primary sludge (and waste activated sludge if cosettling is used at the plant);
- Flowrates of the influent, effluent, and sludge;
- pH; and
- Volatile solids.

Table 19.5 is a summary of test results to be recorded to properly monitor the primary treatment process. Chapter 6, Management Information Systems (Records and Reports), includes typical laboratory sheets.

Maintenance records typically include summaries of preventive, predictive, and corrective maintenance performed. In addition, these records must give the time, date, equipment, and employee for each task. Sample records appear in Chapter 6.

COMPUTER SYSTEMS

Numerous primary treatment processes have been controlled at local control panels through the use of timers or PLCs. Larger plants could typically control their primary treatment systems by centralized plant control systems such as distributed control systems, supervisory control and data acquisition systems, PLCs, and other such systems.

TABLE 19.5 Test results to be recorded for primary sedimentation.

Liquid		
Primary influent	**Primary effluent**	**Sludge**
Biochemical oxygen demand	Biochemical oxygen demand	Solids
Suspended solids	Suspended solids	Volatile solids
Volatile suspended solids	Volatile suspended solids	pH
Settleable solids	Settleable solids	
pH	pH	
Temperature	Fat, oils, and grease	
Fat, oils, and grease		

Advances to computer-type control systems have allowed treatment plants to closely control and monitor their primary sedimentation processes. Computer systems can control sludge withdrawal times and pumping rates, allow operators to start and stop collector mechanisms and/or monitor their status (running, failed, or stopped), and control the scum withdrawal times. In addition, computers assist operators with the opening and closing of influent valves to place a tank into or out of service. This is especially helpful during a rainstorm when operators must perform other duties at the same time. Computers help reduce the number of employees needed by eliminating labor-intensive activities, such as skimmings removal or sludge withdrawal.

Because computers are more powerful and more affordable, small- to medium-sized wastewater treatment plants can have them installed to aid the plant operators in process control. Computers can also alert the operators of alarm conditions and inform the operator when mechanical maintenance needs are required at the primary treatment area.

PRIMARY SLUDGE FERMENTATION

Effluent standards for wastewater treatment plants are becoming increasingly stricter. More and more plants are being required to reduce the nitrogen and phosphorus loadings to their receiving waters. Plants that are being required to remove phosphorus are accomplishing this task either by chemical addition or by biological methods in the secondary treatment process. In both cases, primary sedimentation tanks are playing a more active role. When chemicals are used before the primary sedimentation tanks for phosphorus removal, the soluble phosphorus is converted to an insoluble form where it settles in the primary tanks.

In the 1980s, researchers found that the primary sedimentation process could play an important role in the success of the biological phosphorus removal process. The researchers determined that VFAs were a critical substrate in the success of biological phosphorus removal processes. The various studies have found that by increasing the VFAs to the biological phosphorus removal systems, these systems could successfully achieve the effluent phosphorus limits stipulated by the regulatory agencies. Therefore, to increase the VFAs to the biological phosphorus removal system, researchers focused on the primary sedimentation process.

To increase the VFAs, the primary sludge has to be fermented. Studies determined that maintaining a solids retention time of 3 to 5 days was optimal for VFA production. Longer solids retention times resulted in the production of methane that resulted in reduced VFAs.

Typically, two primary sludge fermentation systems are used in the primary treatment area to increase VFAs. The first fermentation method used at wastewater treat-

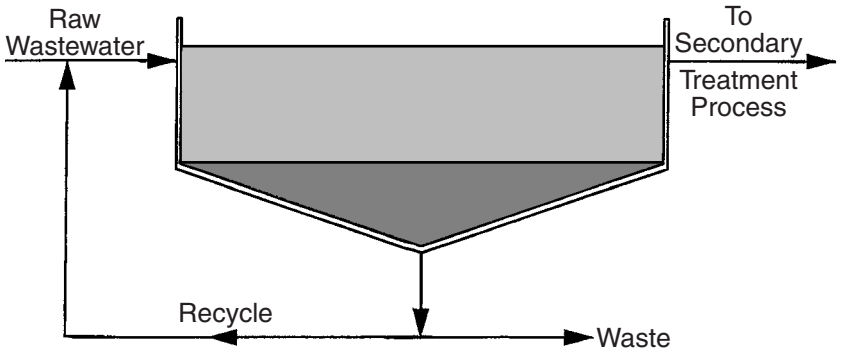


FIGURE 19.10 An example of deep primary tanks (activated primary tanks).

ment plants is deep primary tanks (activated primary tanks), as shown in Figure 19.10. In deep primary tanks, the sludge can be stored and/or returned to the primary influent to meet the required solids retention time. The second fermentation design is a separate thickener/fermenter tank. For this design, the primary sludge is pumped to a separate sludge thickener/fermenter that is specifically designed to meet the required solids retention time. The thickener overflow (supernatant) and a portion of the fermented sludge are recycled back to the primary sedimentation tank. Another portion of the settled solids are pumped to the solids-handling facilities or stabilization processes, such as an anaerobic digestion process. It should be pointed out that the fermenter can be designed as a static fermenter or a complete-mix fermenter, as shown in Figure 19.11. The static fermenter has no mixing devices and the complete-mix fermenter has submerged-type mixers that continuously stir the tank contents. A separate fermentation-type system can also include both a complete-mix fermenter followed by a static-type sludge thickener, as shown in Figure 19.12.

Primary sludge fermentation processes can increase the risk of concrete and equipment deterioration in primary tanks and associated systems because of the generation of acids produced with the fermentation system. Primary sludge fermentation systems can produce odors; therefore, odor control systems should be considered with this process.

The role of primary sedimentation may be changing in the future from a simple settling basin to an important process to enhance biological phosphorus removal systems.

ALTERNATIVE PRIMARY TREATMENT METHODS

Most wastewater treatment plants use conventional-type primary sedimentation processes; however, some treatment facilities use other processes for their primary

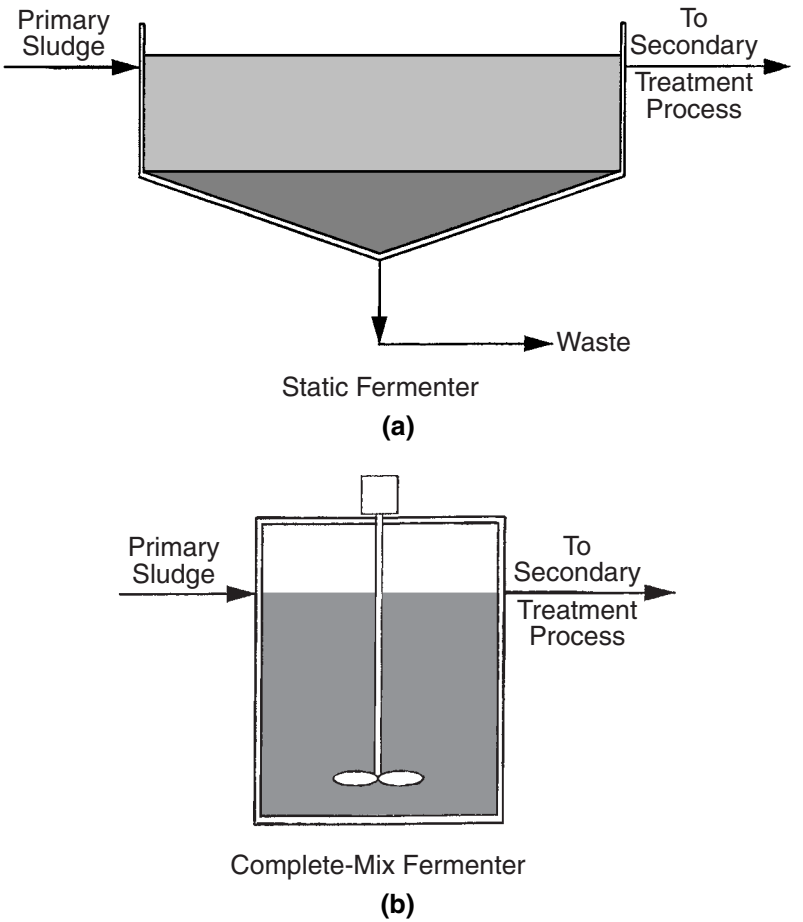


FIGURE 19.11 An example of a fermenter that can be designed as (a) a static fermenter or (b) a complete-mix fermenter.

treatment process. These alternate primary treatment methods include enhanced primary treatment, or combined preliminary/primary treatment alternatives, and/or dissolved air flotation, or fine screens for primary treatment. The following is a brief description of each of these processes.

ENHANCED PRIMARY TREATMENT. Typically, enhanced primary treatment consists of the use of chemicals to increase the removal efficiencies of suspended solids and BOD. Chemicals such as iron compounds (ferric chloride and ferric sulfate), alu-

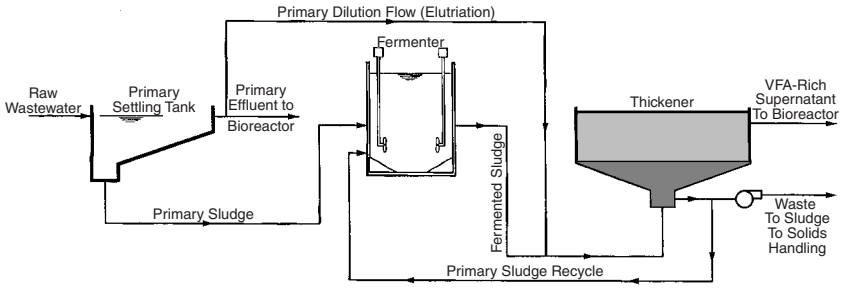


FIGURE 19.12 An example of a separate fermentation type system that can also include both a complete-mix fermenter followed by a static-type sludge thickener.

minum salts such as aluminum sulfate (alum), or lime can be used to increase the removal efficiencies in a conventional primary sedimentation tank. These chemicals can also be used to assist in the removal of phosphorus. It has been reported that with the use of chemicals, the removal efficiencies for the suspended solids have been in the range of 60 to 90% and BOD removal efficiencies have been in the range of 40 to 70%. As previously stated, these chemicals can also be used to assist with the reduction of phosphorus but also have the benefit of improving primary tank efficiencies. Earlier in this chapter, discussions were presented describing the addition of chemicals to a primary tank. It is important to note that the addition of chemicals will increase the quantity of solids to the solids stabilization and disposal facilities. In addition, operators should be aware that the quantity and quality of the solids produced by the addition of chemicals could affect the solids stabilization process. For example, the chemical sludge may affect the anaerobic digestion process by changing the pH, adding additional inert solids, or other such conditions.

FINE SCREENS. Fine screens were discussed earlier in this chapter. As previously discussed, there are different styles of fine screens such as static, drum, or cylindrical disc screens that have been used for reducing solids and BOD. The openings on the fine screens are in the range of 1 to 6 mm (0.04 to 0.25 in.), with the average openings being 1.5 mm (0.06 in.). The removal efficiency of a fine screen is typically less than that of a conventional primary sedimentation process. The solids that collect on the screens are usually removed by spray water at a pressure of approximately 275 to 345 kPa (40 to 50 psig). The operation of a fine screen can be affected by the quantity of grease in the wastewater. Grease can block the small openings of the screen, making the screen ineffective; therefore, plants considering fine screens for their treatment process should

consider installing a hot water system with a high-pressure spray system to clean the screens.

DISSOLVED AIR FLOTATION PRIMARY SYSTEMS. Dissolved air flotation systems at wastewater treatment plants for primary treatment processes were first used more than 30 years ago. A primary air flotation system can follow grit removal or combine grit removal and primary treatment. The tanks were typically circular with a similar scraper-type collector mechanism to a circular primary tank. Air would be compressed to approximately 275 to 415 kPa (40 to 60 psig) and mixed with water in a pressure tank. After the water passes through that tank, it travels through a pressure-control valve. Once it passes through the control valve, the pressurized air is released to atmospheric conditions, producing millions of miniature bubbles. These bubbles would attach to the solids and float them to the surface of the tank. The heavier solids would settle to the bottom of the tank. The upper and lower solids would be collected by the scraper mechanism and removed from the tank, where they were pumped to the solids-handling facilities. A polymer would be used to assist with the flotation process.

The solids concentration of the floated solids is between 3 and 5%. Solids concentrations higher than 6% are hard to move in pipes and pumps. These units had high operation and maintenance costs, required extensive maintenance, and were known to starve the activated sludge system of food for the microorganisms.

COMBINED GRIT REMOVAL/PRIMARY TREATMENT PROCESSES. The combined grit removal/primary treatment process is a process where the grit is cosettled with the primary sludge. This process eliminates the need to construct grit removal tanks. The City of New York has been successfully operating this type of process for more than 40 years. Although this system is not widely used, it has application when the grit loading is low and when land use is at a premium to build treatment facilities.

In this operation, primary sludge is pumped from the primary tanks to cyclone separators that remove the heavier grit particles from the primary sludge stream. For this system to work properly, the primary sludge must be pumped in a dilute slurry, between 0.25 and 1.0% solids. After grit separation, the primary sludge stream is then forwarded to a thickening device for concentration. Most primary systems remove grit before the primary tanks because of concern for collector and pumping equipment wear that can occur. As a result, care must be taken to provide collector and pumping equipment that is extremely durable to support this operation. This includes stainless steel collector equipment, specially hardened pump casings to resist wear, and specially lined primary sludge lines.

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Section 1

Introduction

The activated-sludge process is still the most widely used biological treatment process for reducing the concentration of organic pollutants in wastewater. Well-established design standards based on empirical data have evolved over the years. Our understanding of the process has advanced from a system originally designed simply for biochemical oxygen demand (BOD) reduction, to one that now is designed to remove nutrients such as nitrogen and phosphorus. Despite these advances, poor process performance can still present problems for many plants.

The objective of this manual is to help operators and other wastewater treatment professionals acquire a greater understanding of the process, solve performance problems, and improve operations. The manual is intended as both a training and reference tool. The format will make the book useful to newcomers and experienced professionals alike.

This manual describes the process variations and focuses on operation, addressing pertinent process theory, alternative process control strategies, energy conservation, and troubleshooting the activated-sludge process. Since the last printing of this manual in 1987, there have been advancements and improvements in process configurations and control strategies to achieve higher degrees of treatment efficiency.

Section 2 provides an overview of the activated-sludge process starting with the fundamental concepts of microbiology and biochemistry. It describes how the propagation and control of living organisms are key to achieving the basic process goals of removing BOD, nitrogen, and phosphorus. Conventional process configurations are discussed along with current modifications including sequencing batch reactors, coupled systems, and combined systems. A description of facilities and equipment is provided.

Control of activated-sludge systems is based on maintaining proper aeration and mixing in the biological reactor and controlling the biomass inventory of the system.

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The secondary clarifier is integral to the activated-sludge process because it maintains control of the biomass in the system. Section 3, "Process Control", describes the different strategies for controlling the biomass inventory in the system to achieve and maintain optimum process performance.

Section 4 describes energy use in wastewater treatment plants and discusses energy-saving opportunities through process and equipment considerations. It also discusses how automatic sensors and controls can be key tools in conserving power.

Section 5 presents the procedures used for solving common operational problems. Included are easy-to-use troubleshooting tables that correlate observations to possible causes and remedies and items to check in the process of narrowing down the causes. This section has been updated to include troubleshooting for nitrogen- and phosphorus-removal systems.

A new section on "Aerobic Digestion" has been included as Section 6. Although the goal of aerobic digestion is to stabilize sludge, rather than reduce organic pollutants and nutrients, the principles of mixing and aerating the organisms and controlling the process are similar to those of the activated-sludge process. Thus, a brief overview of the aerobic digestion process is given here.

Appendices contain material that expands on the concepts presented in the sections. Practical examples supported with sample calculations on subjects ranging from how to determine nutrient supplement requirements to chemical addition for pH control or settling enhancement are included. Appendices covering preventive maintenance and safety are also provided.

Section 2

Process and Equipment Description

INTRODUCTION

The activated-sludge process is a suspended-growth process, predominantly aerobic, that maintains a high microorganism population (biomass) by means of solids recycling from the secondary clarifier. The biomass converts biodegradable organic matter and certain inorganic compounds into new cell biomass and products of metabolism. Biomass is separated from the treated wastewater in the clarifier for recycling or wasting to solids-handling processes. Preliminary treatment processes precede the activated-sludge system and primary treatment is typically used in all but some of the smaller treatment facilities.

DESCRIPTION OF UNIT PROCESSES

BASIC SYSTEM COMPONENTS. Figure 20.1 presents a general schematic of a conventional flow-through activated-sludge process. In the conventional flowsheet (see section on "Process Variations" for other system configurations) influent wastewater and recycled biomass are first combined, mixed, and aerated in a biological reactor. The contents of the biological reactor is referred to as mixed liquor and consists of microorganisms; and biodegradable and nonbiodegradable suspended, colloidal, and soluble organic and inorganic matter. Particulate matter is referred to as mixed liquor suspended solids (MLSS) and the organic fraction is called mixed liquor volatile suspended solids (MLVSS).

Microorganisms consist primarily of organic matter (70 to 80%) and are often measured as MLVSS, although it must be emphasized that a fraction of the MLVSS is inert

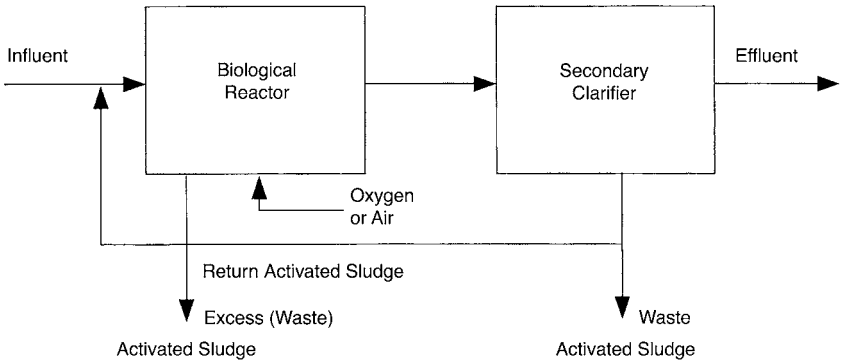


FIGURE 20.1 Schematic diagram of a typical activated-sludge process.

organic matter including organisms that are no longer viable (living and actively metabolizing). The system is referred to as an *open culture* system in which the organisms are in a dynamic state of change depending on external environmental conditions (see "Microbiology and Biochemistry" below).

Wastewater components are biodegraded, sorbed, or remain untreated (recalcitrant or nondegradable) in the biological reactor. After sufficient time for appropriate biochemical reactions, mixed liquor is transferred to a settling reactor (clarifier) to allow gravity separation of the MLSS from the treated wastewater. Settled solids are then returned (return activated sludge [RAS]) to the biological reactor to maintain a concentrated biomass for wastewater treatment. Because microorganisms are continuously synthesized in the process, some of the MLSS must be wasted from the system. Wasting is accomplished by diverting a portion of the RAS or biological reactor solids (waste activated sludge [WAS]) to solids-handling processes. Sludge wasting strategies are used to increase, decrease, or maintain a selected biomass concentration in the system. This is a principal mechanism used for process control.

The basic activated-sludge system consists of a number of interrelated components

- A single biological reactor or multiple reactors designed for completely mixed flow, plug flow, or intermediate patterns of flow designed to achieve carbonaceous organic matter removal. If required, these may also provide ammonia oxidation, nitrogen removal, and phosphorus removal depending on target effluent requirements. The primary biological reactors may be preceded by an aerated, anoxic, or anaerobic selector reactor designed to control bulking, denitrify, or select polyphosphate uptake microorganisms to promote enhanced phosphorus removal.

- An oxygen source and equipment to disperse atmospheric, pressurized, or oxygen-enriched air into the biological reactors at a rate sufficient to maintain a positive mixed liquor dissolved oxygen (DO) concentration.
- A means to appropriately mix the biological reactor contents to ensure suspension of the MLSS without shearing the floc.
- A clarifier to separate, and possibly thicken, the MLSS from the treated wastewater.
- A method of collecting settled MLSS within the clarifier and returning it to the biological reactors.
- A means of wasting MLSS from the system.

Activated-sludge system designs are based on the hydraulic retention time (HRT) in the biological reactor, the amount of time biomass is retained within the system (mean cell residence time [MCRT]), the organic loading, and the organic load (food) to biomass (microorganism) ratio (F:M).

MICROBIOLOGY AND BIOCHEMISTRY. The activated-sludge process consists of a mixture of flocculated bacteria, fungi, protozoa, and rotifers maintained in suspension by aeration and mechanical mixing. The primary branches of biology that are relevant to designers and operators of activated-sludge processes are the naming and classification of organisms (taxonomy), their metabolic activities (physiology), and their interrelationships with the surrounding environment (ecology). Taxonomy to the nonbiologist is the most difficult of these branches. Organisms are often classified on the basis of their physical characteristics and metabolic activities. Identification of organisms is important in diagnosing problems in the process, but this is often left to biologists. The operator can, however, become acquainted with the most commonly occurring organisms in the process and use simple techniques for identifying important groups of organisms that may effect the process. For example, the use of microscopic techniques to identify filamentous organisms in activated sludge has proved useful in diagnosing and controlling bulking problems (U.S. EPA, 1987a, and Jenkins et al., 1993).

The functioning and activity of organisms (physiology) is important in determining the role of the consortium of organisms in the process. Classification is often based on energy source, cell carbon source, and requirement for oxygen. Organisms that use sunlight as their primary source of energy are called phototrophs and all others, using chemicals as a source of energy, are chemotrophs. Organisms that use inorganic carbon (carbon dioxide, CO_2) are referred to as autotrophs and those using organic carbon are heterotrophs. The energy flow within the organism during metabolism is important relative to the amount of energy that is captured and the products of metabolism. Energy flows

by means of enzymatic-mediated electron transport from the electron donor (sources of energy) to the final electron acceptor. When the final electron acceptor is oxygen, the reaction is aerobic. If the final acceptor does not involve an external electron acceptor such as oxygen, the metabolism is referred to as fermentative and the organism carrying out the reaction may be referred to as an anaerobe. Organisms may also use external, inorganic electron acceptors; the most notable being those that use nitrates and sulfates. These reactions are anaerobic, but are often referred to as anoxic. Thus, organisms may be classified as aerobic or anaerobic depending on the final electron acceptor. Many organisms may be active in both the presence and absence of oxygen (facultative).

The qualitative biochemical reaction that occurs in the process may be expressed as

$$\text{Food + Nutrients + Organisms + Electron acceptor} \rightarrow \text{New organism + products} \tag{20.1}$$

More specifically, for a chemoheterotrophic aerobic reaction that would be common in activated sludge systems, the general (unbalanced) expression might be

$$\text{Organic matter + Oxygen } (O_2) + \text{Nutrients + Microbes} \rightarrow \text{New microbes + } CO_2 + \text{Water } (H_2O) \tag{20.2}$$

For a chemoautotrophic aerobic reaction occurring in nitrifying systems, the overall expression, which consists of a two-step process, might be

$$\text{Ammonium } (NH_4^+) + O_2 + CO_2 + \text{Biocarbonate } (HCO_3^-) + \text{Microbes} \rightarrow \text{New microbes + } H_2O + \text{Nitrate } (NO_3^-) \tag{20.3}$$

Finally, a chemoheterotrophic anoxic reaction that might take place in the clarifier or in a dedicated anoxic zone of the biological reactor once nitrate is present might be expressed as

$$NO_3^- + \text{Organic matter + Carbonic acid } (H_2CO_3) + \text{Microbes} \rightarrow \text{New microbes + Nitrogen } (N_2) + H_2O + HCO_3^- \tag{20.4}$$

It should be emphasized that the reactions described above represent the overall reaction taking place as a result of the composite metabolism of the entire consortium of organisms found in the process. The reactions shown are the result of many metabolic steps but consist of two general metabolic processes—synthesis and respiration. Synthesis is an energy-consuming reaction and results in the production of new biomass. Respiration is an energy-yielding reaction that is linked to synthesis by an im-

portant series of energy transfers. The amount of biomass produced and the character of the products of respiration depend on the terminal electron acceptor. Aerobic reactions are the most efficient, resulting in high biomass yields and low-energy products that are highly stabilized. Anaerobic reactions are the opposite, producing low biomass yields and poorly stabilized products. Anoxic reactions fall in between, depending on the acceptor. Synthesized biomass and storage products may serve as an energy source to microbes in the system. This metabolism is often referred to as endogenous respiration (respiration of internal reserves as contrasted with exogenous respiration that involves external sources of food). Endogenous respiration reduces the total biomass yield of the process and becomes more predominant as the solids retention time (SRT) increases (low loaded, low F:M systems). However, such biomass decreases are at the expense of additional energy consumption (higher oxygen requirements).

Knowledge of the organisms present in the process and the nature of the biochemical reactions that are occurring is important, but the interrelationships between organisms and factors controlling growth and activities of the consortia (ecology) is needed to understand system operation. The process is an open system, creating a dynamic environment of microorganisms. The mix of organisms found in the process is selected by the environmental conditions produced in the system and by the interactions among organisms. This selection, or enrichment, results in a rigorous culture that may change rapidly as conditions change because of the rapid rates of growth of microorganisms. Among the important enrichment factors found in the process are the operational conditions such as residence time, settling, and recycling that promote biomass separation; characteristics of the wastewater including carbon/nitrogen/phosphorus ratios and toxicity; environmental conditions including pH, temperature, DO concentration, and mixing intensity; and reactor configurations that may affect nutrient and DO concentrations or compositions.

An important feature of the activated-sludge microbial system is its ability to separate by gravity under quiescent conditions. This property is achieved by selecting the culture that settles, recycling the settled sludge, and operating the process under loading conditions that will select for a flocculent culture. Similarly, if nitrification is desired, process loading, MCRT, and HRT are provided to select for the autotrophic nitrifying organisms. Enhanced biological-phosphate uptake is achieved by selecting appropriate populations by holding the population in an anaerobic selector.

Through design and operation, treatment objectives may be achieved by this fundamental concept of enrichment. However, not all observed enrichment reactions are consciously selected. Bulking, or poor settling, is an example of an undesirable selection of an organism population that continues to challenge operators. Many types of poor separation problems may arise. These include dispersed growth (no flocculation

or deflocculation), pin floc, bulking, rising sludge blanket, and foaming or scum formation (U.S. EPA, 1987a, and Jenkins et al., 1993). Typically, these problems are caused by undesirable selection processes that sometimes may not be easily controlled. The incorporation of a selector provides a means of selecting microorganisms with good settling characteristics, thereby interfering with the overgrowth of undesirable, poorly settling organisms. Operational adjustments are also used to enhance the development of good-settling floc.

BASIC PROCESS GOALS

The activated-sludge process may be designed and operated to remove carbonaceous biochemical oxygen demand (CBOD), to oxidize ammonia to nitrates, to remove nitrogen compounds, or to remove phosphorus. The design of the system must provide for adequate biological reactor size, oxygenation capacity, and separation facilities to achieve the effluent target requirements. The design of these systems is beyond the scope of this manual, but may be found in *Design of Municipal Wastewater Treatment Plants* (WEF, 1998).

The following sections will address some of the process goals for each of the design objectives cited above.

CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND REMOVAL. The CBOD represents all carbon-based organic matter in the wastewater that is biodegradable, measured as BOD. It is important to note that the five-day BOD (BOD_5) represents only a fraction of the biodegradable carbonaceous organic components in the wastewater (typically, 60 to 65%). The BOD consists of both soluble (dissolved) and particulate fractions. The soluble fraction is often consumed rapidly once in contact with the MLSS. The particulate fraction may sorb rapidly to the biomass and degrade at a rate that depends on its composition. The biological reactor sizing depends on both the rate of BOD uptake and the rate of its degradation. High biomass concentrations are desirable and can result in smaller reactor sizes. However, there is an upper limit to biomass concentration that can be achieved in a given plant based on the oxygen-transfer capacity of the system and the size of the clarifiers. Systems are occasionally designed with oxygen-enriched air processes and oversized clarifiers to reduce biological reactor size, but cost considerations often dictate an optimum size of all components of the system.

Oxygen transfer is an important element of the system. Oxygen must be supplied at a rate equal to demand. Oxygen demand is determined from BOD and nitrogen measurements (if nitrification is anticipated) but recall that BOD_5 values are inappro-

priate measures of the total carbonaceous demand. Long-term BOD measurements or estimates of total oxygen demand must be provided for accurate estimates. It should also be noted that nitrogenous oxygen demand (nitrification reactions) is often measured as a portion of BOD in analytical determinations. Addition of nitrification inhibitors may be used to separate carbonaceous and nitrogenous demand measurements, if required. Variability in oxygen demand occurs both with time and distance in the biological reactor (often referred to as temporal and spatial variation). Sufficient oxygenation capacity must be available to meet much of this variation if a high-quality effluent is required and to avoid selection of undesirable microbial populations.

With a typical municipal wastewater, a well-designed and operated activated-sludge system should achieve a CBOD effluent quality of 5 to 15 mg/L. Effluent suspended solids (SS) should also typically be less than 15 mg/L. Note that effluent SS may include a significant fraction of CBOD. To achieve consistent BOD and total suspended solids (TSS) concentrations less than 5 mg/L, some type of tertiary treatment would be required.

NITRIFICATION. The oxidation of ammonia to nitrate is primarily carried out by autotrophic bacteria in a two-step process (Equation 20.3). The ammonia-oxidizing bacteria obtains its energy by oxidizing ammonia to nitrite and the nitrite-oxidizing bacteria by oxidizing nitrite to nitrate. These reactions produce little energy; therefore, populations of nitrifiers in activated sludge are small (recall that energy is required to synthesize biomass, in this case from inorganic carbon). It is for this reason that for nitrification to occur the activated-sludge process must be designed and operated at higher SRTs and longer detention times to ensure that nitrifiers do not wash out of the system. Nitrification processes may be designed as a combined system where both CBOD removal and ammonia oxidation can take place or in two-stage systems where CBOD removal is achieved in the first stage and nitrification is achieved in the second. There are advantages and disadvantages to either, which will be discussed later in this section. See the U.S. Environmental Protection Agency design manual on nitrogen control (1993) for more information on nitrification processes.

The oxygen demand for complete nitrification is high. For typical municipal wastewater facilities, nitrification will increase the required oxygenation facilities by 30 to 40% of that required for CBOD removal. Nitrification will require approximately 4.6 mg oxygen/mg ammonia-nitrogen oxidized. The DO concentrations in mixed liquor affect the rate of nitrification. Nitrification rates decrease with decreases in DO. Typically, the DO concentration should range from 2 to 3 mg/L for good nitrification performance, although a minimum DO of 0.5 mg/L is acceptable under peak loading conditions.

Optimum growth of nitrifiers has been observed in the pH range of 6.5 to 8.0 although effective nitrification has been reported for systems outside this range. During nitrification, mineral acidity is produced (NO_3^-). If insufficient alkalinity is present, the system pH will drop and nitrification will slow. Approximately 7.1 mg of calcium carbonate ($CaCO_3$) alkalinity is consumed per milligram of ammonia-nitrogen oxidized. A residual alkalinity of 50 to 100 mg $CaCO_3$/L is recommended for stable operation. Supplemental alkalinity may be provided through chemical additions of lime, soda ash, or magnesium hydroxide.

While nitrification occurs over a wide range of temperatures, a reduction in temperature will decrease the rate of reaction. As a result, in colder climates, MCRTs are raised to accommodate the lower nitrification rates. In warmer climates, nitrification has been observed at MCRT values of 3 days or less, whereas in colder climates MCRT values greater than 20 days may be required to achieve effective nitrification.

Nitrification systems for municipal wastewater can achieve greater than 90% removal of ammonia, producing ammonia concentrations less than 1 mg N/L. (U.S. EPA, 1993).

NITROGEN REMOVAL—DENITRIFICATION. Denitrification is a one-step biological process that reduces nitrate-nitrogen to nitrogen gases (Equation 20.4). The gases of nitrogen (N_2, and other nitrogen oxides) produced in the process will be released from solution, thereby causing a reduction in system nitrogen. A number of microorganisms can affect this reaction, all readily present in most municipal wastewater. These organisms are heterotrophic, requiring organic matter for growth. They are capable of using oxygen or nitrate as their terminal electron acceptor and thermodynamic considerations favor oxygen. Therefore, the process of denitrification must take place in the absence of DO and in the presence of organic matter. This is typically provided in the activated-sludge process through the design of an anoxic zone in the biological reactor system. Organic carbon, such as methanol, may be added as a supplemental carbon source, or may be provided by influent wastewater CBOD from a side stream. It should be noted that denitrification may take place inadvertently in the anoxic sludge-settling zone of the clarifier (sometimes causing rising sludge) or in the sludge return (RAS) channels. Denitrification of municipal wastewater requires that ammonia first be oxidized to nitrate. Municipal wastewater nitrification–denitrification systems using activated sludge are numerous. They may be single-sludge systems that incorporate CBOD removal, ammonia oxidation, and nitrate reduction in a number of steps using one clarification process; or they may be phased systems (separate stage) with individual sludges for each of the processes. Several process variations will be described below.

See the U.S. EPA design manual on nitrogen control (1993) for more information on nitrogen-removal processes and their performance.

Denitrification processes are temperature sensitive, decreasing with decreased temperature. Adjustment in system MCRT may be required in colder climates to ensure adequate denitrification. The process generates alkalinity, 3.6 mg $CaCO_3$ alkalinity/mg nitrate-nitrogen reduced. Because denitrification may reduce total process oxygen requirements, some credit for this may be taken. Theoretically, 2.86 kg oxygen demand is satisfied per kilogram (2.86 lb/lb) of nitrate-nitrogen reduced to nitrogen gas (U.S. EPA, 1993).

Separate-stage and single-sludge denitrification processes can both achieve high removal of nitrogen, on the order of 85 to 95% for municipal wastewater.

BIOLOGICAL PHOSPHORUS REMOVAL. In the conventional activated-sludge process for municipal wastewater, the biomass will uptake phosphorus for growth and metabolism in a way that approximately 2% of the biological sludge mass on a dry weight basis is phosphorus. Phosphorus cannot be transformed to a volatile gas, therefore its removal is achieved by sludge wasting. Thus, wasting in a conventional plant may result in 10 to 30% removal of phosphorus. The activated-sludge process may be managed, however, to select for a population of microorganisms that will store excessive quantities of phosphorus, in the range of 3 to 6%. Wasting of this phosphorus-enriched sludge can result in effluent phosphorus concentrations less than 1 mg P/L.

The selection process involves an anaerobic step that results in the release of stored phosphate followed by an aerobic step in which the organisms consume large amounts of phosphorus. In the anaerobic phase, soluble CBOD is consumed by the organisms and stored as organic polymers as a future source of energy. The energy required for this storage step is provided by excess phosphorus stored as polyphosphates in the aerobic stage. As energy is released in the anaerobic phase, the phosphates are released to solution. Once entering the aerobic zone, energy is produced by the oxidation of the stored organic carbon products and polyphosphate storage is initiated by the organism (U.S. EPA, 1987b, and WEF, 1998). There are many organisms capable of storing excess amounts of phosphorus in their cells. These polyphosphate-storing organisms are found in wastewater and can be easily selected for with proper system design and operation.

Biological phosphorus removal (BPR) processes for activated-sludge systems will be described below. With proper design and operation, a BPR system should produce effluent phosphorus concentrations less than 2 mg/L and often less than 1 mg/L. Because

phosphorus in the cell mass is high, careful attention must be paid to achieving low concentrations of volatile suspended solids (VSS) in BPR system effluents (U.S. EPA, 1987b).

PROCESS VARIATIONS

The activated-sludge process has been designed in many different modifications. The process modification selected depends on the treatment objectives, site constraints, operational constraints, client preferences, and design engineer preference and experience, among others. The process can be categorized by loading rates, reactor configuration, feeding and aeration patterns, and other criteria including numerous biological nutrient removal (BNR) processes.

LOADING RATES. The activated-sludge process is often classified on the basis of loading rate. The loading rate may be expressed as a volumetric loading rate, MCRT, or F:M. Table 20.1 shows a typical range of loading rates for conventional, high-rate, and low-rate (often called extended aeration) systems. Within these three loading ranges, the reactor configuration, number of reactors, and aeration and feed patterns can be selected to achieve the target treatment level. Hydraulically, they can be designed as either a continuous-flow process or a batch-flow system.

Conventional systems provide BOD_5 removal efficiencies of 85 to 95% and typically carry MLSS concentrations varying from 1000 to 3000 mg/L. At conventional loading, some nitrification may occur, especially in warmer climates. This results in higher than estimated oxygen demands and may cause sludge flotation in the final clarifiers. Nitrification can be limited by decreasing the MCRT (increasing F:M).

Low-rate systems are typically used for low flows and are characterized by high oxygen requirements and low sludge production rates. These systems are claimed to

TABLE 20.1 Typical process loading ranges for the activated-sludge process.

Loading range	MCRT, d	Volumetric loading, kg BOD/m^3 (lb BOD/1000 cu ft)	F:M, kg/kg · d (lb/lb · d)
High rate	1–3	1.60–16.0 (100–1000)	0.5–1.5 (0.5–1.5)
Conventional	5–15	0.32–0.64 (20–40)	0.2–0.5 (0.2–0.5)
Low rate	20–30	0.16–0.40 (10–25)	0.05–0.15 (0.05–01.5)

be more stable and thus require less operational attention. Typically, BOD removal efficiencies range from 75 to 95% and nitrification is complete. However, these systems may suffer from significant excursions of effluent suspended solids because of poor flocculation (pinpoint floc) and clarifier denitrification.

High-rate systems are often used as pretreatment processes in staged biological treatment systems and are also used where only carbonaceous BOD removal is required. They are characterized by low oxygen requirements and somewhat higher than normal sludge generation compared to conventional plants. The process may produce BOD removal efficiencies over a wide range, from less than 50% to as high as 95% depending on loading rate and waste characteristic. Sludge settling can be a problem at high loading when flocculation does not effectively occur.

REACTOR CONFIGURATION. Reactor configuration deals primarily with the hydraulic characteristics of the process. Continuous-flow systems are often categorized as ideal plug-flow or completely mixed systems, although most operate in a nonideal flow regime somewhere between the two. Batch systems behave like ideal plug-flow systems with respect to biological process performance; the reaction time for batch is interchangeable with the space–time for the plug-flow reactor.

Ideal Complete Mix. Ideal, completely mixed flow implies that the composition of the mixed liquor is the same throughout the reactor volume. The influent wastewater immediately and completely mixes with the reactor contents so that the concentration of a given component is the same as the effluent concentration. As a result, the mixed liquor oxygen uptake rate, DO, soluble BOD, VSS, TSS, nitrogen species, phosphorus concentrations, pH, temperature, and other characteristics are identical throughout the reactor. Because the concentrations of BOD are at the target effluent concentrations for the process, the system has the capability of attenuating wide swings in effluent concentration. Completely mixed flow is difficult to achieve, although the use of square or round reactors with intense mixing can approximate the condition. As discussed later, it can also be approximated by providing multiple feed points along the reactor periphery. Aeration is provided uniformly throughout the reactor by mechanical aeration equipment or diffused aeration.

There are several disadvantages to completely mixed reactors. They are often plagued by filamentous bulking problems. This can be overcome, in part, by using selectors, which provide short term conditioning of the RAS and influent wastewater ahead of the biological reactor, (see “Selectors” below). Theoretically, the process also suffers because degradation kinetics are slower than in plug-flow systems, requiring longer reactor retention times to achieve comparable effluent quality. These systems are

often used for low-rate applications or for treating industrial or industrial–municipal wastewater where large variations in load are anticipated.

Ideal Plug-Flow. In an ideal plug-flow system, the fluid particle entering the system will move uniformly along the reactor length without dispersing in the fluid (Figure 20.2). The particle will remain in the reactor for a time equal to the theoretical detention time (Volume $[V]$/Volumetric flow $[Q]$, V/Q). As a result, the concentration of BOD and the oxygen uptake will decrease along the reactor length. The TSS and VSS will increase along the reactor length as biomass is produced. This type of flow is approximated by long, narrow reactors with length-to-width ratios greater than 10. Plug-flow may also be simulated by basins-in-series or by folding rectangular reactors. Like the complete-mix configuration, it is not practical to produce a true plug-flow system.

By definition, this configuration results in high organic load and oxygen uptake rates at the inlet to the reactor. Oxygen-transfer devices must be capable of high mass transfer at the inlet. Distribution of oxygen along the reactor may be tapered to follow oxygen demand. Theoretically, the plug-flow reactor delivers the highest removal rate per unit volume. It is also less susceptible to filamentous bulking provided that sufficient DO is present at the inlet.

Reactors-in-Series. The reactors-in-series configuration is described as two or more completely mixed reactors operating in a series configuration. It can be approximated with baffles or by folding reactors in a sinusoidal fashion. This configuration, with three or more reactors-in-series, attempts to simulate a plug-flow condition that has a kinetic advantage over mixed-flow systems as mentioned above. This configuration also seems to mitigate filamentous bulking.

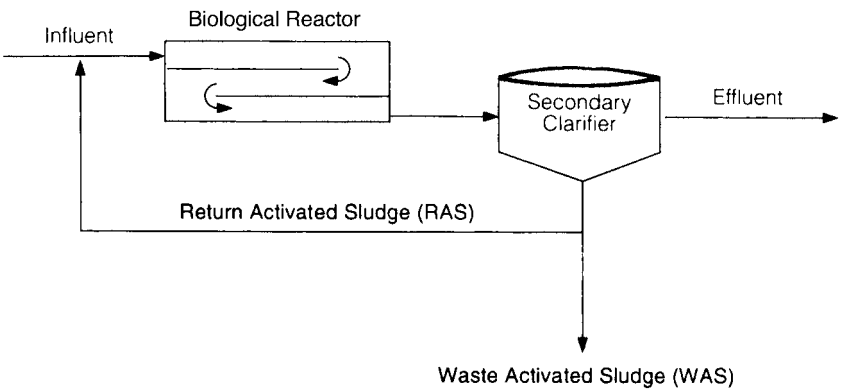


FIGURE 20.2 Plug flow activated-sludge process with folded biological reactor.

Sequencing Batch Reactors. A sequencing batch reactor (SBR) is a fill-and-draw activated-sludge system in which both steps of aeration and clarification take place in the same reactor. Settling occurs when the air and mixers are turned off and a decanter provides for the withdrawal of treated effluent. Discrete cycles are used during prescribed, programmable time intervals, and MLSS remains in the reactor during all cycles. For conventional systems, there are five steps that are carried out: fill, react, settle, decant, and idle (Figure 20.3a). As a result of the batch nature of the process, flow equalization and multiple reactors must be provided to accommodate continuous-flow operation. Mixing and aeration are provided by equipment similar to that found in conventional continuous-flow plants. Specially designed decanters are provided for effluent withdrawal. An intermittent-cycle extended-aeration system allows influent to be fed continuously to the reactor for all cycles (Figure 20.3b), but effluent is withdrawn intermittently.

The SBR is typically designed for small-flow applications, 4000 m^3/d (1 mgd) or less, often as extended-aeration systems. Some larger installations have been built, however, ranging in size from 150 000 to 700 000 m^3/d (40 to 185 mgd). The process is easily adaptable to BNR by programming different sequences of cycles.

Oxidation Ditch. In the typical oxidation ditch, mixed liquor is pumped around an oval or circular pathway by brushes, rotors, or other mechanical aeration devices and pumping equipment located at one or more points along the flow circuit (Figure 20.4). The mixed liquor is moved at a velocity of 0.24 to 0.37 m/s (0.8 to 1.2 ft/sec) in the channel resulting in a circuit time of less than 15 minutes. Most oxidation ditches are designed as low-rate processes with long HRTs (approximately 24 hours), therefore, the cycle time is short and the hydraulic system may be considered to be completely mixed. Ditches may be designed with a single channel or multiple interconnected concentric channels. They are widely used for small- to medium-sized communities.

FEED AND AERATION PATTERNS. Modifications of the activated-sludge process have often been used to enhance process biochemistry or other characteristics to produce a more stable operation at an economical cost. Several of these modifications are described below.

Conventional. In the conventional flowsheet (shown in Figure 20.1) influent wastewater is introduced at the influent end of the system. The RAS may be added to the inlet separately or premixed with the influent wastewater prior to introduction to the reactor. Separate addition allows for more flexibility should a step-feed or contact-stabilization configuration be used in the future. In conventional designs, aeration may be provided uniformly along the reactor length or tapered to meet oxygen demand.

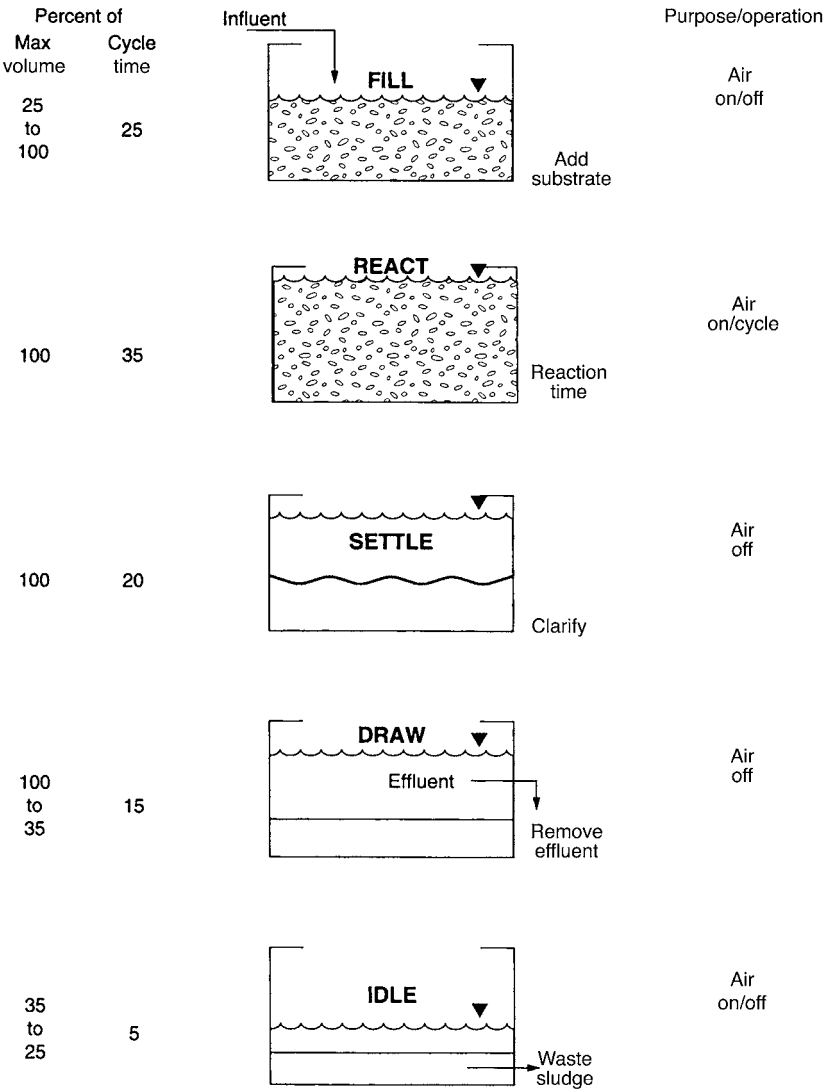


FIGURE 20.3A Typical sequencing batch reactor operation for one cycle.

Contact Stabilization and Sludge Reaeration. Contact stabilization is a modification in which RAS is fed to the head of the biological reactor (reaeration section) and the influent wastewater is added downstream (contact section) of the point of sludge addition (Figure 20.5). In the original configuration, the wastewater received only a short aeration contact time (typically 30 to 60 minutes) after mixing with the reaerated

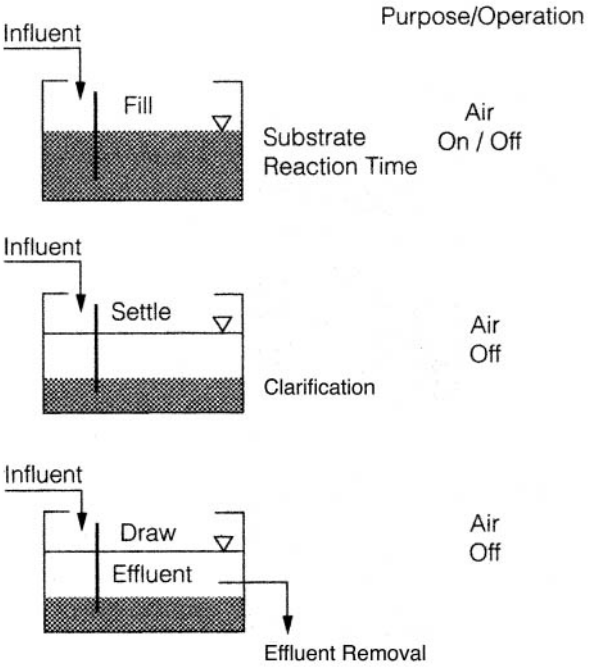


FIGURE 20.3B ICEAS™ system operation.

sludge. Thus, the process relies on rapid uptake (biosorption) of BOD followed by a stabilization step in which the return sludge is aerated to stabilize the sorbed organic matter. These systems are typically designed to operate in the conventional loading rate region (SRTs ranging from approximately 3 to 15 days). Because the RAS flow is only approximately 40 to 70% of the forward flow rate, the total aeration volume is

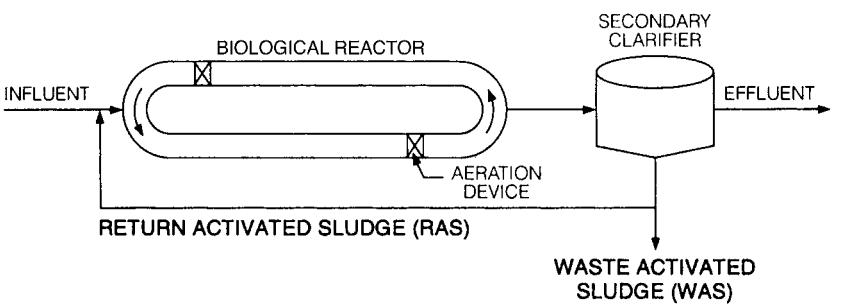


FIGURE 20.4 Oxidation ditch.

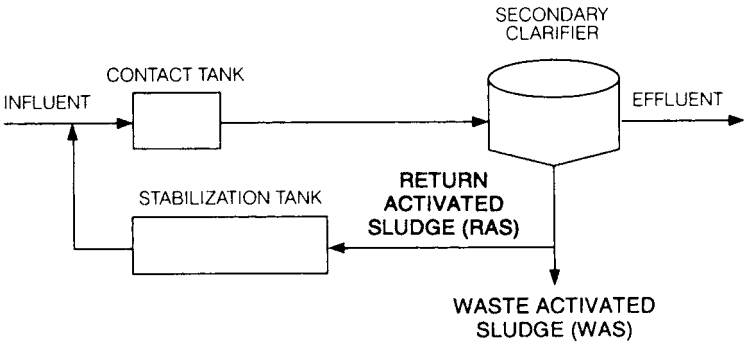


FIGURE 20.5 Contact stabilization activated-sludge process.

smaller than for a conventional biological reactor with equal HRT. As a result of this modification, the capacity of an existing plant can be increased without adding new process volume. The process has also found application in communities with high infiltration and inflow during storms. In conventional plants, high flows may wash out sludge from the system if clarifiers are not oversized. With contact stabilization, the reaerated sludge is isolated from forward flow and therefore remains in the system during high-flow events.

The contact-stabilization modification, in its original form, does not provide significant nitrification and may not be effective for wastewater high in soluble BOD. Some plants have found that the process is effective, however, when the contact time is increased to 4 to 5 hours (often referred to as a sludge-reaeration process).

Step Feed. In the step-feed or step-aeration modification influent wastewater is added at two or more points along the length of the biological reactor (Figure 20.6). This arrangement evens out the organic load and oxygen uptake rate in the reactor, thereby simulating an approximate completely mixed reactor. The RAS is typically added at the influent end of the reactor. The advantage of the system is increased plant capacity without overloaded final clarifiers. For example, for the comparable SRT of a conventional system, the influent MLSS concentration to the clarifier would be lower for the step-feed system. It should be noted that by providing additional piping for step-feed gives the operator the option of operating the plant in a conventional, contact-stabilization, or step-feed modification.

Tapered Aeration. The design of the aeration system in which oxygen supply approximately parallels oxygen demand is referred to as tapered aeration. Such a system would be used in reactors that produce approximate plug-flow systems. Although mostly seen

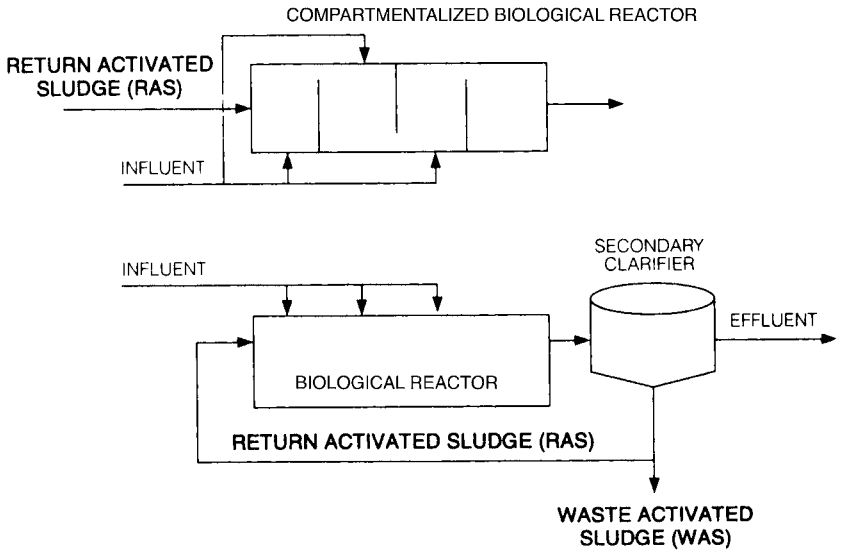


FIGURE 20.6 Step-feed activated-sludge process.

in diffused air systems, the concept can be practiced with mechanical aeration devices. Airflow in diffused air systems to a given reactor sector can be controlled by airline valves with uniform diffuser placement, or preferably by tapering diffuser density. Mixing requirements will typically govern the minimum airflow (or power input) rate near the effluent end of the reactor. This modification makes most efficient use of power, provides greater operational control, and may be used to inhibit nitrification by reducing DO concentrations in downstream sectors of the biological reactor.

Selectors. The use of a selector preceding the biological reactor has effectively controlled filamentous bulking in activated-sludge plants that experience epidemics of poor-settling sludge. The selector may be aerobic, anoxic, or anaerobic and is normally compartmentalized (Figure 20.7). The basic principle of using a selector is to create environmental conditions that promote the growth of bacteria that settle well over those that do not. In brief, mixed liquors that are low in DO, or F:M, tend to favor filamentous microorganisms that interfere with effective settling. Many of these organisms can be put at a disadvantage if mixed liquor is subjected to periods of high F:M. Organisms with the greatest ability to rapidly uptake soluble organic matter and store it for later use during low concentration conditions tend to be ones that flocculate and settle better.

Selectors, because of the high organic load imposed on them, are relatively small with short HRTs (10 to 30 minutes for aerobic selectors and somewhat longer for

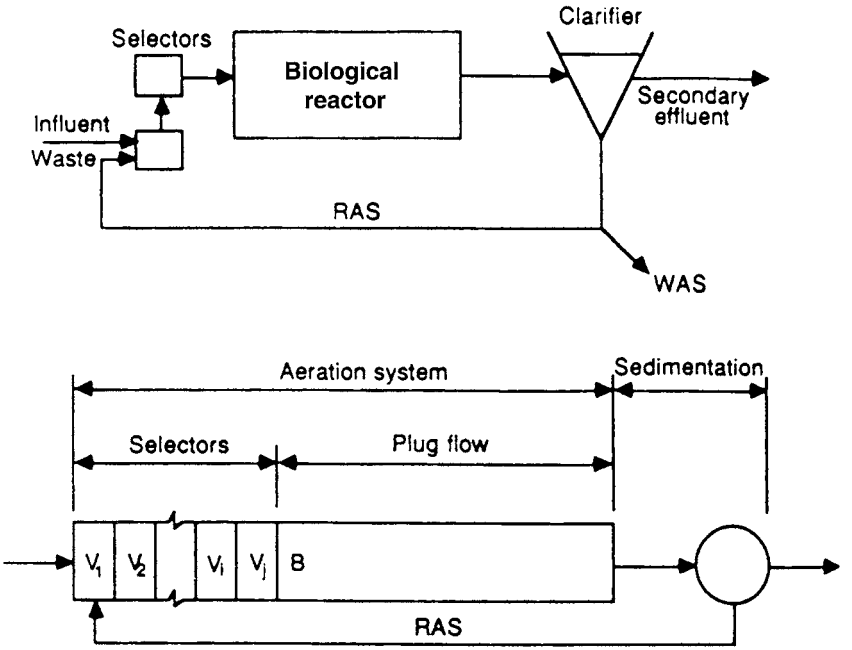


FIGURE 20.7 Typical selector configurations.

anoxic and anaerobic selectors). If these units are too large, low F:M loads may occur, rendering them ineffective. To date, experience has been excellent with selectors. Details on design and operation of selectors may be found in Jenkins et al., (1993) and WEF (1998).

OTHER MODIFICATIONS

HIGH-PURITY OXYGEN. High-purity oxygen may be used in place of air for activated-sludge aeration. Pure oxygen is fed concurrently with wastewater in reactors that are typically covered (Figure 20.8). Oxygen feed is controlled by maintaining constant pressure in the closed reactors. A DO of 4 to 10 mg/L is typically maintained in the mixed liquor. Less than 10% of the inlet oxygen vents from the last stage of the unit. In the past, these systems were operated at high MLSS concentrations and short HRTs thereby requiring less area for the facility. Today, these systems are typically designed with loading comparable to those of conventional activated-sludge processes. One significant advantage for the process is that it essentially eliminates stripping potential volatile organic compounds from the mixed liquor. Because the headspace gases are

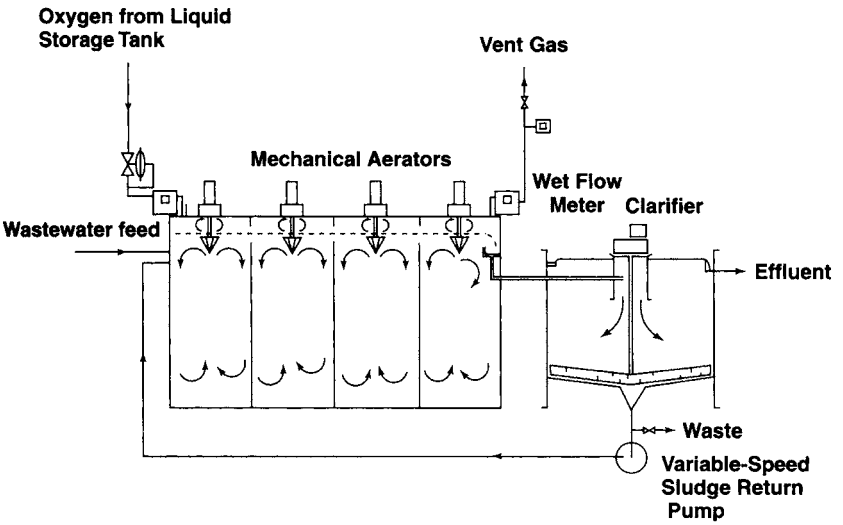


FIGURE 20.8 Closed-tank, high purity oxygen system schematic.

recycled, the CO_2 concentrations in the gas phase are high and, as a result, alkalinity can be consumed in the mixed liquor causing a pH decrease. This can be a problem for systems that are designed for nitrification, often requiring separate stages for CBOD removal and nitrification.

The covered reactors have provisions for warning of potential explosions that could result from presence of combustible gases from the wastewater. Precautions are also taken in the selection of construction materials because of the corrosive and reactive nature of the oxygen–CO_2 gases.

The dissolution of oxygen into the mixed liquor is typically accomplished with mechanical surface aerators or by submerged sparged turbine systems. The three types of oxygen separation devices in use today are the cryogenic air-separation process, pressure swing adsorption (PSA), and vacuum swing adsorption (VSA). The PSA-system has been used in the past and remains in some plants, but the VSA is a more cost-effective system today (WEF, 1998).

COUPLED SYSTEMS. To enhance performance and increase the capacity of biological reactors, the practice of adding inert support media to the biological reactor was developed decades ago. The inert media supports a fixed-growth biomass that augments the mixed liquor microbial population. The early application used panels of asbestos sheeting placed in the biological reactor. More recent application includes the

use of plastic trickling-filter media, polyurethane foam pads, loops of fiber bundles, or small plastic elements. These systems claim improved performance because of the addition of more active biomass to the system and reduce the solids loading to the clarifiers. Experience with these systems is limited in the U.S. presently.

COMBINED SYSTEMS. Most combined systems use a fixed-growth process in series with a suspended-growth system. Typically, the combined system includes a biotower and a biological reactor or aerated channel. Occasionally a rotating biological contactor process may be used as the fixed-growth system. Combined systems are used when designers attempt to compensate for weaknesses of one of the systems by combining the two. For example, fixed-growth processes are known to resist shock loads and provide low maintenance requirements. By combining this with activated sludge, a process known to produce high-quality effluents with the ability to be operated under a variety of different modes, designers have found that the overall system can achieve a high degree of treatment for certain wastewaters and environmental constraints.

A number of processes are currently used in the U.S. and may be categorized into two groups: those that have low to moderate organic loading to the fixed-growth reactor and those with high organic loads (roughing filters). Figure 20.9 illustrates alternative methods for returning RAS or reaeration that are common practices for combined systems. Terms used to distinguish process modes are also presented. The commonly used combined systems include activated biofilter, tricking filter/solids contact, rough-

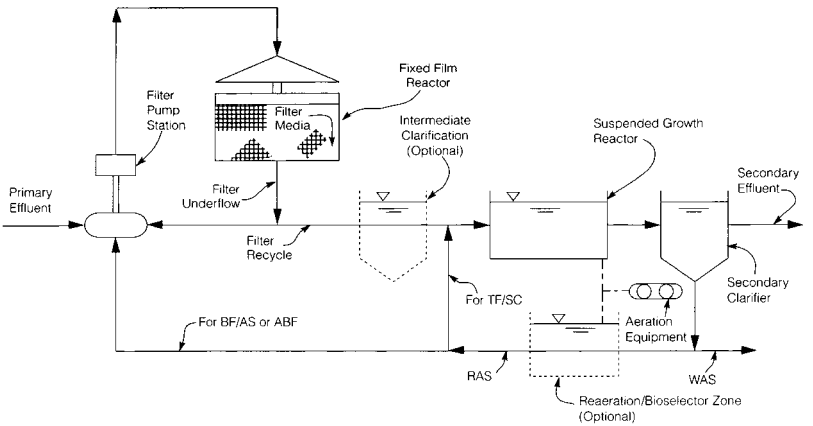


FIGURE 20.9 Schematic flowsheet for combined processes (BF = biofilter, RAS = return activated sludge, and WAS = waste activated sludge).

ing filter/activated sludge, biofilter/activated sludge, and trickling filter/activated sludge. Details about these systems can be found in WEF (1998).

BIOLOGICAL NUTRIENT REMOVAL PROCESSES

There are many processes incorporating activated sludge for the transformation of nitrogen and phosphorus compounds. Biological nutrient removal systems may include one or all of the following: ammonia oxidation, nitrogen removal, and phosphorus removal. Although there are many classifications of these systems, the simplest is as single- and multiple-sludge processes.

SINGLE-SLUDGE PROCESSES. Single-sludge processes are those that use only one biological sludge for the entire process. Such processes may be staged but solids separation occurs only once and the RAS is returned to the entire process. It should be noted that some of these systems are proprietary requiring special fees for their use.

Single-Sludge Ammonia Oxidation. For ammonia oxidation, the single-sludge system employed achieves both CBOD removal and ammonia oxidation (Figure 20.10). Referred to as a single-stage nitrification process, this system is being used more frequently in the U.S. because of its simple design, ease of operation, and lower capital costs. The biological reactor can be designed as a conventional plug-flow, completely mixed, contact-stabilization, step-feed, or oxidation-ditch configuration. To achieve nitrification, higher MCRTs are required to ensure adequate nitrifier populations.

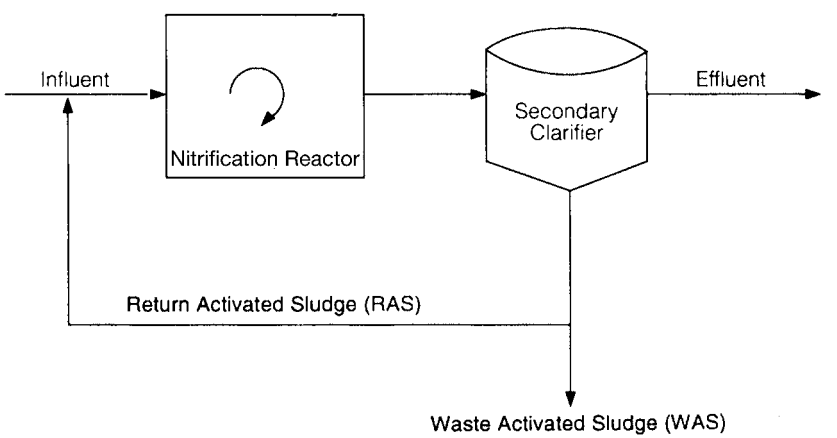


FIGURE 20.10 Carbonaceous/nitrification activated-sludge process.

Single-Sludge Nitrogen Removal. For nitrogen removal, which requires that nitrification precedes denitrification, several single-sludge systems have been used. One of the most simple and widely used processes is the Ludzack–Ettinger process (Figure 20.11) which provides an anoxic zone that precedes an aerobic zone. The RAS is directed to the anoxic zone where it mixes with influent wastewater that serves as the organic carbon source for denitrification. In a modification, mixed liquor is pumped from the aerobic zone back to the anoxic zone. The Wuhrmann, or postdenitrification process (Figure 20.12), provides aerobic treatment followed by an anoxic zone. Organic carbon must be added to the anoxic process (either as an organic supplement, such as methanol, or by bypassing some influent wastewater directly to the anoxic zone), or endogenous carbon must be relied on in the anoxic zone. In the single-stage, conventional system, effective denitrification may be achieved by alternating aeration (on and off) in the biological reactor or oxidation ditch.

Another single-sludge process incorporates four stages in the Bardenpho™ process (Figure 20.13). An anoxic zone precedes an aerobic zone followed by an additional anoxic and aerobic zone. The RAS is cycled to the first anoxic zone and mixed liquor is recycled from the first aerobic zone to the first anoxic zone. The second aerobic zone is used primarily to strip nitrogen gases from the process and to prevent phosphorus release in the clarifier. This process produces a higher removal of nitrogen as compared with the two-stage processes above. To succeed, however, it depends on the oxidizable nitrogen-to-carbon ratio in the influent wastewater (WEF, 1998).

The oxidation ditch configuration has also been used for nitrification–denitrification. To succeed, these systems must be designed and operated to provide sufficient anoxic volume upstream of the aeration device. Simultaneous nitrification–denitrifica-

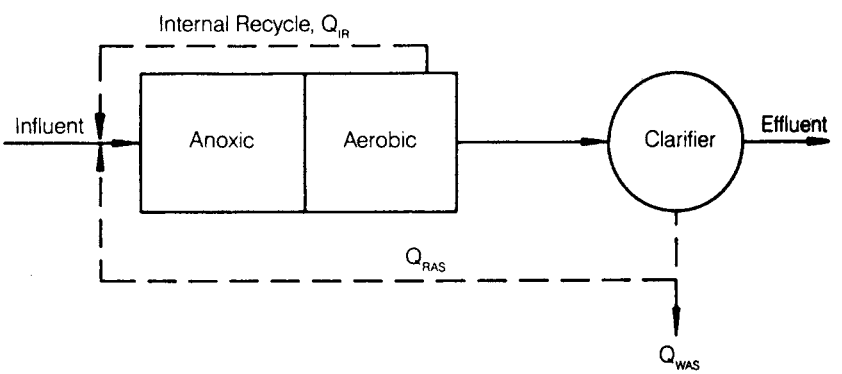


FIGURE 20.11 Modified Ludzack–Ettinger process for nitrogen removal (WAS = waste activated sludge).

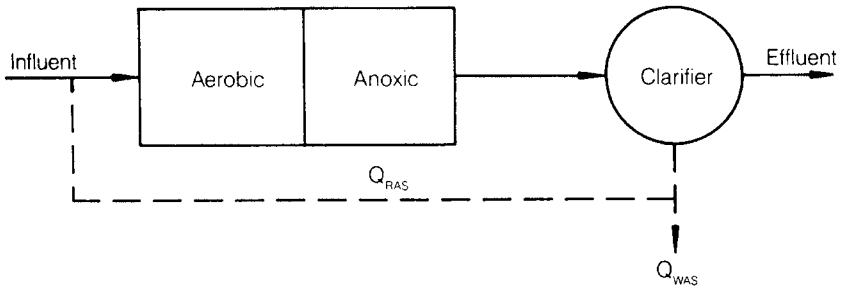


FIGURE 20.12 Wuhrmann process for nitrogen removal (RAS = return activated sludge and WAS = waste activated sludge).

tion also occurs in these systems. Typically, in the oxidation ditch the rates of removal are low because of the relatively long SRTs required for nitrification, the low concentrations of CBOD, and the marginal concentrations of DO for nitrification. A large mass of mixed liquor in the system compensates for this low rate, however. Performance can be highly variable.

Sequencing batch reactors also find application as a single-sludge nitrogen removal alternative. To obtain nitrogen removal, fill-and-react phases are subdivided into static fill, mixed fill, and mixed react. Carbon oxidation and nitrification occur in the aeration phase, while denitrification takes place in the anoxic fill-and-react phases. Organic carbon for denitrification is available at the beginning of each cycle.

Single-Sludge Phosphorus Removal. Phosphorus removal may be achieved with or without nitrogen removal or nitrification in single-sludge systems. Those systems ded-

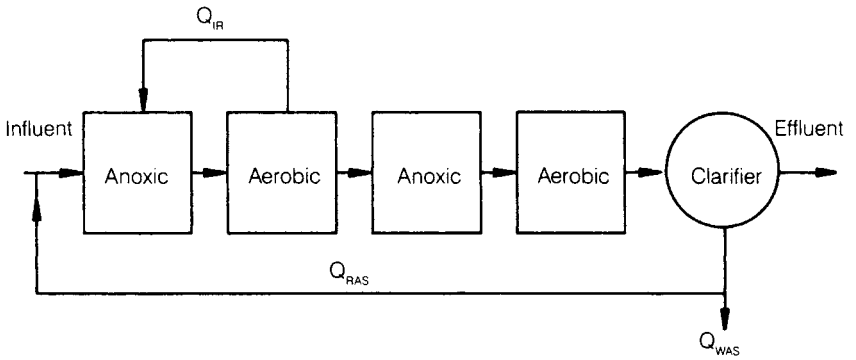


FIGURE 20.13 Four-stage Bardenpho™ process for nitrogen removal (WAS = waste activated sludge).

icated only to CBOD and phosphorus removal include the A/O™ process, PhoStrip™ process, sidestream fermentation processes, and sequencing batch reactors (SBRs). The A/O™ process has two stages—an anaerobic step preceding an aerobic step (Figure 20.14). Typically, each stage is divided into multiple, completely mixed series reactors to simulate a plug-flow system. As described above, the anaerobic step selects the appropriate high polyphosphate-accumulating microorganisms. The process works well as long as nitrification does not occur because nitrate in the return sludge interferes with the selection process in the anaerobic zone (selection requires anaerobic conditions). Thus, A/O™ systems are operated at low MCRTs and short HRTs and are most successful in treating wastewater with high BOD-to-phosphorus ratios (typically greater than 20:1).

The PhoStrip™ process combines biological and chemical removal. It diverts phosphorus-rich biomass in a side stream of RAS to an anaerobic stripper where phosphorus is released in solution. This high phosphorus-rich supernatant is then precipitated with lime while the biomass, stripped of phosphorus, returns to the biological reactor (Figure 20.15). Thus, phosphorus is removed both chemically and by wasting biomass from the system. Similar to other anaerobic–aerobic biological processes, this sequence selects for high polyphosphate-accumulating organisms and results in high phosphorus content in the waste sludge.

An important requirement of the BPR process is the availability of low-molecular weight volatile fatty acids (VFAs) to the biomass in the anaerobic selector. These molecules are consumed by the organisms and are synthesized into large energy storing polymers. If the influent wastewater does not provide an ample supply of these VFAs, they must be supplied from external sources. One way to provide these essential molecules is by adding acetic or propionic acid. Another way is to generate these acids from primary sludge through an anaerobic side stream process. The supernatant from this process is

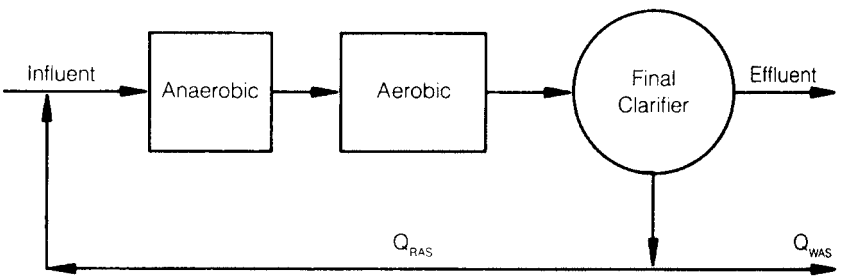


FIGURE 20.14 A/O™ process (RAS = return activated sludge and WAS = waste activated sludge).

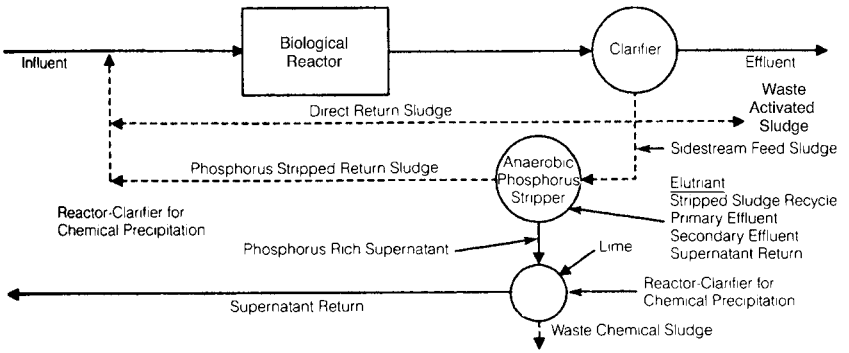


FIGURE 20.15 PhoStrip™ process.

then pumped to the anaerobic reactor in which it mixes with influent wastewater. These side stream fermenters can be incorporated in the primary clarifier, or may be separate unit processes. Occasionally, sufficient acids are produced from primary sludge gravity thickeners.

An SBR may also be used to biologically enhance phosphorus removal. Biological removal will occur when the operating cycle includes an anoxic period to eliminate nitrates and an anaerobic period to induce phosphorus release. Further removal by chemical precipitation may be needed if low effluent phosphorus concentrations are required because of presence of some residual nitrate. Typically, the cycle will be fill, anaerobic stir, aerobic mix, anoxic stir, settle, and decant.

Single-Sludge Nitrogen and Phosphorus Removal. A number of biological processes have been developed for the combined removal of nitrogen and phosphorus. Among the more important configurations are the A^2/O™ process, Modified or Five-Stage Bardenpho™ process, the University of Cape Town process (UCT), the Virginia Initiative Process (VIP), PhosStrip™ II process, the Step-BioP process, and SBRs.

The A^2/O™ process uses three stages—anaerobic, anoxic, and aerobic (Figure 20.16). Each stage is typically divided into multiple completely mixed series compartments. The RAS is recycled to the anaerobic stage and mixed liquor is recycled to the anoxic stage. Because there is no step to remove additional nitrates from the aerobic stage, some nitrate may return with RAS to the anaerobic stage, thereby affecting performance. High BOD-to-phosphorus ratios in the influent wastewater are desirable.

The Modified Bardenpho™ process (often called Phoredox process) uses five stages to achieve nitrogen and phosphorus removal (Figure 20.17). The difference between this and the four-stage process previously mentioned is the anaerobic stage preceding the other four.

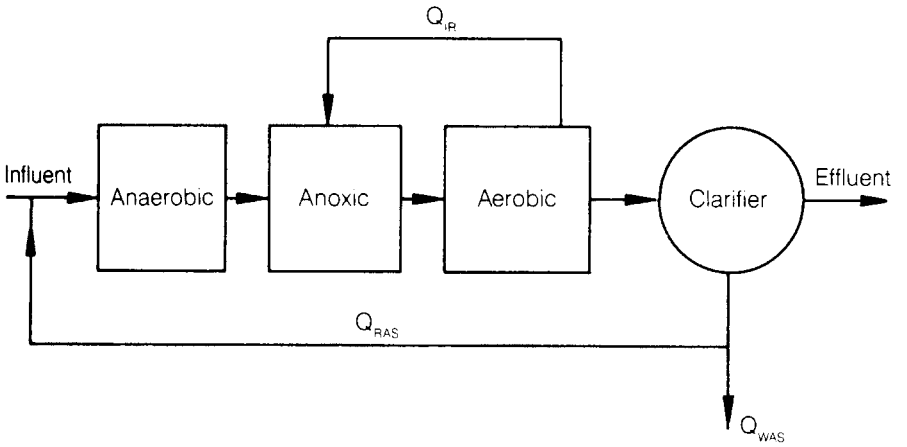


FIGURE 20.16 A^2/O^{TM} process for phosphorus removal (WAS = waste activated sludge).

The UCT process and its modifications were developed to reduce the effect of RAS nitrates on the anaerobic stage. In this three-stage process, RAS is returned to the anoxic stage and mixed liquor is recycled from the aerobic stage to the anoxic stage and from the anoxic stage to the anaerobic stage (Figures 20.18a and b). In a modification of the process, the anoxic stage is subdivided into two compartments so that RAS is cycled to the first and internal recycle of mixed liquor flows to the second. Internal re-

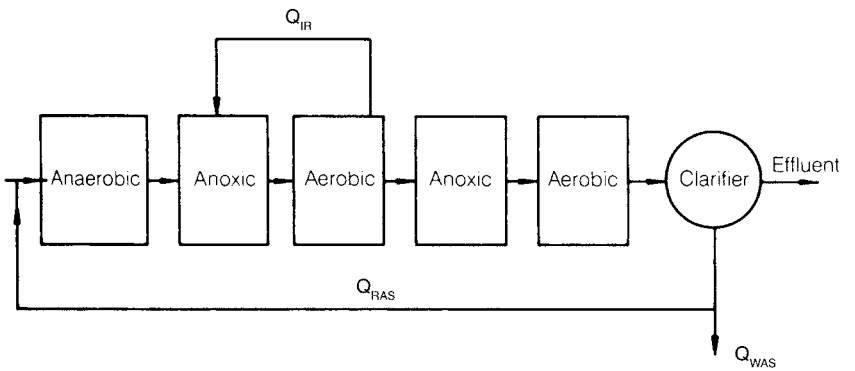


FIGURE 20.17 Modified Bardenpho™ process for phosphorus and nitrogen removal (WAS = waste activated sludge).

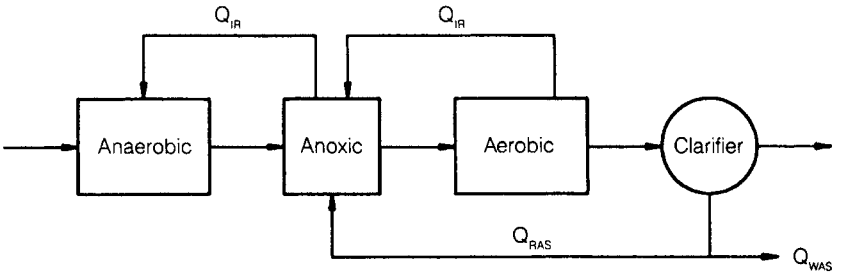


FIGURE 20.18A University of Cape Town and VIP processes for phosphorus and nitrogen removal (WAS = waste activated sludge).

cycling of anoxic mixed liquor comes from the first compartment. This configuration was proposed to reduce the HRT in the anoxic reactor.

The VIP is similar in configuration to the UCT process. The significant differences are that the VIP uses multiple, completely mixed series compartments for the anoxic zone and the process operates at a shorter SRT than the UCT process (5 to 10 days versus 13 to 25 days).

In PhoStrip™ II, denitrification is accomplished by adding an anoxic prestripper ahead of the anaerobic phosphorus stripper for the RAS stream. Sufficient SRT is provided in the aerobic compartment for nitrification.

The SBR process can remove both nitrogen and phosphorus by proper selection of the cycles and cycle times. The seven cycles often used for this purpose are static fill, mixed fill, anaerobic react, aerobic react, anoxic react, settle, and decant. Chemical precipitation of phosphorus may be required if low concentrations of phosphorus are desired because of the presence of residual nitrate in the system.

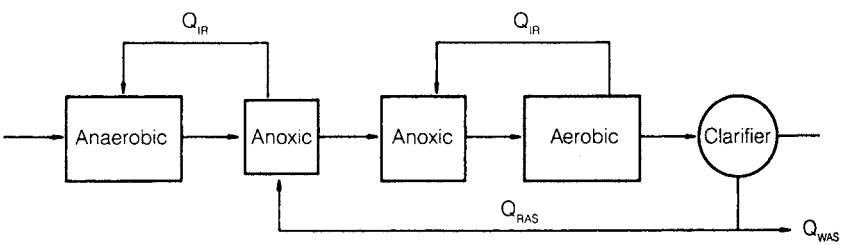


FIGURE 20.18B Modified University of Cape Town process for phosphorus and nitrogen removal (WAS = waste activated sludge).

MULTIPLE-SLUDGE SYSTEMS. Multiple-sludge systems, in contrast to single-sludge systems, isolate sludges for separate treatment tasks. These systems may involve two or three separate sludges. These configurations are used for nitrification and nitrogen-removal objectives. In these systems, fixed-growth processes may be used in one or both stages of the process.

Multiple-Sludge Nitrification. Both carbon oxidation and nitrification are achieved in two separate stages in this system (Figure 20.19). The first stage achieves CBOD removal and uses a separate clarifier and RAS line. Nitrification is performed in the second stage, again with its own clarifier and RAS line. Careful attention must be given to both design and operation of this separate-sludge system. The CBOD leaving the first stage should be approximately 50 mg/L or more to ensure a satisfactory inventory of settleable biomass in the nitrification stage. Note that the biomass yields from nitrification are low, and as a result nitrifier populations can be easily washed from the system. Although the system seems to have greater flexibility than single-sludge systems and operation is independent for each step, experience suggests that the process requires significant attention. Furthermore, construction costs are greater.

Multiple-Sludge Nitrogen Removal. Three dual-sludge treatment systems have been proposed for nitrogen removal. The first uses an aerobic stage for both CBOD oxidation and nitrification. The second stage, with its own clarifier, provides the anoxic step for denitrification. A supplemental carbon source is required for the anoxic stage.

In a second process a portion of the influent wastewater is directed to the second-stage anoxic zone to provide the carbon required for denitrification. Note, however, that some total Kjeldahl nitrogen may not be nitrified and be present in the final effluent.

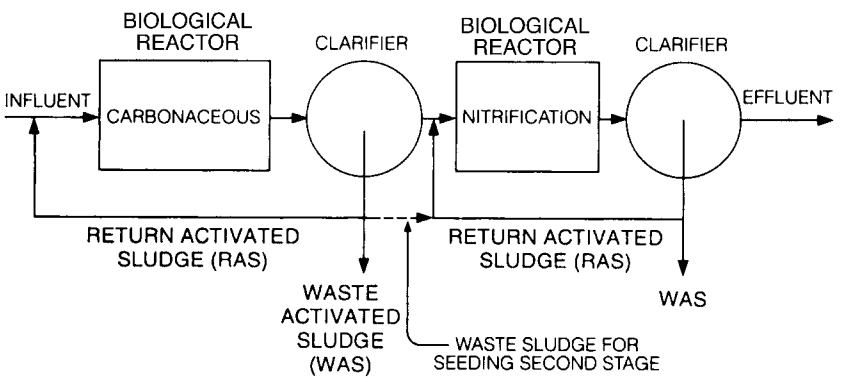


FIGURE 20.19 Two-stage, carbonaceous-nitrification system.

In a third process, the anoxic system precedes the aerobic system, thus providing sufficient BOD for denitrification. An additional recycle stream supplies nitrate to the anoxic system. Some bleed-through of nitrate will occur in this process depending on flow rates of the recycle streams.

A triple-sludge system is designed with separate carbon oxidation, nitrification, and denitrification processes and three separate clarifiers. This system is seldom used and suffers from disadvantages of adding exogenous carbon, high capital cost, and operational complexity.

FACTORS AFFECTING PROCESS EFFICIENCY

The factors affecting process efficiency may be categorized as environmental, design and operational, and maintenance.

Environmental factors that affect performance include wastewater characteristics, system DO, temperature, and pH. Influent wastewater characteristics that affect the process include the nature of the carbonaceous organic matter and nitrogenous compounds, their biodegradability, soluble and particulate fractions, and concentration; the concentration and availability of nutrients; the alkalinity; the flow rate and its temporal variability; and the presence of toxic or inhibitory compounds.

Design factors that affect process efficiency and operational control include reactor volume (affecting HRT), clarifier sizing, pumping capacities of WAS and RAS systems, recycle pumping capacity, hydraulic design, and aeration system size and configuration. The operational factors include MCRT or F:M loading, DO control, RAS pattern and flow, WAS rate, and recycle rates. Good performance also depends on appropriate equipment maintenance, laboratory quality control, proper sampling protocol, and adequate training of wastewater treatment plant staff.

DESCRIPTION OF FACILITIES AND EQUIPMENT USED

BIOLOGICAL REACTORS. The biological reactor is the heart of the process. Air or oxygen is introduced to the aerobic zones both to provide DO for the biomass and to keep the MLSS properly mixed throughout the reactor. The tanks are properly sized to provide sufficient HRT for oxidation of the CBOD (and ammonia if nitrifying is a requirement) in the incoming wastewater, typically 6 to 8 hours for conventional systems, and to ensure proper flocculation of the microorganisms. Depending on the requirements for effluent quality, the reactor may be subdivided or compartmentalized to achieve specific biochemical reactions (anoxic and anaerobic zones).

Biological reactors are often constructed of reinforced concrete, although some package plants (extended air) may use steel. The reactors are typically rectangular to accommodate common-wall construction for multiple reactors, although some installations may choose to use circular or oval tanks (the oxidation ditch is one example). Reactors may be single pass, folded, or placed in a series layout. A minimum of two reactors is desirable, even for small plants, to accommodate shutdown for occasional maintenance. Each reactor must be furnished with inlet and outlet gates or valves so they can be removed from service. Proper drains or sumps should be provided for rapid dewatering (approximately 8 to 20 hours). In addition to aeration equipment, the reactors should be equipped with a froth-control system to control foaming. Inlet design should ensure that flow to the reactor is as uniform as possible to avoid severe short circuiting of influent and to provide for intermixing of RAS with influent wastewater. Where parallel multiple reactors are used, a method for proper flow splitting should be provided to ensure that the flow rate to each reactor is equal. In step-feed systems, a positive means of flow control is especially important.

AERATION SYSTEMS. The supply of oxygen to the biological reactor represents the largest single energy consumer in the activated-sludge facility (50 to 90%). Over the years, oxygen-transfer equipment has evolved to a point where engineers have a wide selection of efficient equipment to meet the needs of all types of facilities. Oxygen-transfer devices are used not only to supply oxygen to the process but also to mix the aerobic compartments of the reactor. Typically, there are two types of aeration devices, diffused-aeration systems and mechanical-aeration systems. Each will be discussed below.

Diffused Aeration. Diffused aeration is defined as the injection of air or oxygen below the liquid surface. The air or oxygen is supplied by low-head blowers with pressures typically up to 210 kPa absolute (30 psia) or 105 kPa gauge (15 psig). Hybrid devices, including jets and u-tube aerators, which combine gas injection with mechanical pumping or mixing, are also included in this category.

Diffusers include both porous and nonporous devices. Details about these devices can be found in WEF (1998). The porous diffusers, often referred to as fine-pore or fine-bubble diffusers, are highly efficient and are currently the most widely used of the diffused-air systems. They are typically produced from ceramic materials, porous plastics, or perforated membranes. Nonporous systems include an array of diffusers that have larger orifices ranging from holes in pipes to specially designed valved orifices. Diffusers are placed near the floor of the biological reactor and may be configured in a grid arrangement, along one or both longitudinal sides. Air is delivered in a piping system from the blowers to downcomers that carry the air down to headers along the bottom

of the reactor. Valves in the air system are used to control airflow to individual reactors or sectors of reactors. Diffusers may be placed in uniform densities or arranged in tapered configurations. The diffuser type, pattern of diffuser layout, reactor geometry, submergence, and airflow rate all influence oxygen-transfer performance. Maintenance of porous diffusers is greater than for the large-orifice diffusers. Clogging and fouling of the fine pores requires occasional cleaning, which can be provided by automatic gas-cleaning systems in situ or by draining the reactors and cleaning with high-pressure hosing or acid spritzing (WEF, 1998).

AIR DELIVERY. The three basic components of the air-delivery system are air filters or conditioners, blowers, and piping. Air filters remove particulates such as dust from the inlet air to the blowers and protect both the blowers and diffusers from mechanical damage or clogging. The degree of air cleaning depends on the inlet air quality, the type of blower, and the diffusers.

Today, many types of dynamic or positive displacement (PD) blowers are used. The dynamic, or centrifugal, blowers which are considered constant-pressure machines, are the most efficient and easiest to operate at variable airflow rates, are quieter than PD blowers, and require less maintenance. Their disadvantages include a limited operating pressure range and reduced delivered air volumes with any increase in back-pressure caused by diffuser clogging. The PD blower is a constant-volume device capable of operating over a wide range of discharge pressures. They have a lower initial cost and require relatively simple control procedures. More details on blowers can be found in WEF (1998), U.S. EPA (1989) and WPCF (1984).

Mechanical Aeration. Mechanical-aeration systems include surface aeration devices and submerged turbine aerators. Surface aerators can be grouped into four general categories

- Radial flow, low-speed aerators,
- Axial flow, high-speed aerators,
- Aspirating devices, and
- Horizontal rotors.

Each is widely used and has distinct applications. Surface aerators are typically float, bridge, or platform mounted and some may be equipped with submerged draft tubes for deep reactor applications. The radial low-speed aerators have gained increased use recently and are considered good mixing devices that are more efficient than high-speed aerators. Axial flow, high-speed aerators are typically used in stabilization lagoons where dispersed growth is found and shearing of biological floc is not an issue. They also may suffer from freezing problems in cold climates. Aspiration devices use a motor-driven

propeller aspirator that draws air down a shaft to orifices at the submerged end. Air velocity and propeller action create turbulence, forming small bubbles. These devices can be positioned at various angles to reach different levels of mixing, aeration, and circulation. The aspiration devices are not often used in activated-sludge applications. Horizontal rotors, designed in several configurations, are used in oxidation ditches. The impeller agitates the liquid surface creating a hydraulic jump that is effective in oxygen transfer. The device provides a horizontal component of velocity that rotates the fluid around the ditch and provides sufficient velocity to maintain MLSS in suspension.

The submerged turbine consists of a motor and gearbox drive mounted over the reactor, one or more submerged impellers, and piped air from a blower to a diffuser ring below the impellers. Impellers may be axial or radial flow. The impellers can move the mixed liquor down, up, or laterally depending on impeller design. These devices provide excellent mixing and are capable of high mass-transfer rates. They are used in a number of activated-sludge applications.

Mixing. In the activated-sludge process mixing is important for maintaining the MLSS in suspension. In most applications, the aerators serve as both oxygen-transfer devices and mixers. Except at the effluent end of plug-flow reactors, oxygen requirements typically control aerator design and operation. However, at the effluent end of plug-flow reactors and in some low-loaded, completely mixed systems, mixing may be the controlling factor, especially during low-flow conditions. In most cases the aeration system is used for mixing in these situations, however, use of low-speed, submerged-propeller, horizontal mixing devices (such as banana blade mixers) to move mixed liquor horizontally along the reactor is another option. A combination of this mechanical mixing with aeration may result in significant power savings when mixing controls the process.

For mixing anoxic and anaerobic compartments of biological reactors, both submerged propeller or turbine mixers have been used. These devices mix without breaking the water surface and are capable of maintaining biological solids in suspension at minimal energy inputs. The number and placement of these units is critical to effective suspension of MLSS.

CLARIFICATION. Separation of MLSS from the liquid stream is vital to the operation and performance of activated-sludge systems. This is typically achieved by gravity separators, although recently some work has been done with membranes. Clarification not only separates the MLSS but in some situations may be designed to thicken the settled sludge before returning it to the aeration process or to wasting (WAS).

Clarifier shapes include rectangular, square, circular, and others, such as hexagonal or octagonal. There seems to be no observable difference in performance at average or peak flow because of shape alone (WEF, 1998). Sludge is typically removed by

chain-and-flight collectors in rectangular clarifiers. Hydraulic suction using floating- or bridge-mounted mechanisms has been used. Circular clarifier mechanisms with hydraulic pickups use mechanical seals to allow continuous solids withdrawal. Mechanical plows are also used on these rotary collectors. Interchannel clarifiers have been used in some small-flow oxidation ditch applications. A clarifier is installed directly in the ditch, thereby eliminating the need for a separate clarifier. Scum and sludge are returned directly to the ditch by hydraulic means.

Clarifier depth continues to be a debated issue relative to its importance in performance. There are many factors that will affect the selection of depth including clarifier diameter, collector characteristics, sludge withdrawal point, and inlet design. Typically, minimum clarifier depths of 3.7 to 4.6 m (12 to 15 ft) are recommended. Deeper clarifiers may be desired for large-diameter clarifiers, but no deeper than 4.6 to 5.0 (15 to 16 ft). Clarifier performance also depends on solids loading rate, surface overflow rate, inlet design, effluent weir arrangement, and settling characteristics of the MLSS. Clarifier performance and characteristics are reviewed in WEF (1998), WEF (2005), and Ekama et al. (1997).

RETURN AND WASTE ACTIVATED SLUDGE SYSTEMS. The RAS system pumps the settled sludge, thickened as much as practical in the clarifier, from the clarifier back to the biological reactors. Most RAS stations use centrifugal pumps for this application. For intermediate-sized plants, the pumps are often connected directly to the sludge withdrawal pipes. In larger plants, a wet well is provided for these pumps to draw suction. Screw pumps are also used in many plants in the U.S. and Europe. The RAS system must also allow for accurate measurement and control of the sludge flow. The RAS pumping systems are typically controlled by a positive variable-flow control device capable of changing flow within the minimum to maximum range for proper process control. The variable-flow control device can be controlled by programmable logic controllers, which can receive and send signals proportional to flow or to preprogrammed patterns. In small plants, throttling of the force main from RAS pumps has been used.

All activated-sludge processes must have a WAS system to remove excess biomass from the system. Waste sludge may be wasted from the clarifier under flow or directly from the biological reactors. The WAS system needs flow metering and pumping equipment independent of other activated-sludge control devices. The most positive and flexible system will include an independent pumping system with flow adjustability and a flow meter that provides feedback to a flow control device.

RECIRCULATION PUMPING. Mixed liquor recycling in several of the BNR processes is typically accomplished by low-head, submersible nonclog pumps, propeller

pumps, or nonclog vertical turbine pumps mounted on the biological reactors. Because water level in the zones is virtually the same, the only pumping head is due to pipe friction and fitting losses. However, offsetting the low-head requirement is the high pumping volume required (recycle ratios may range from 1:1 to as high as 4:1 based on forward flow). Flow is typically conveyed in a pipe rather than a channel to avoid DO entrainment when discharged to an anoxic or anaerobic zone. Also, intakes should be located away from aeration diffusers if possible for the same reason. Constant-speed pumps may be used because it is not essential that recycle flows exactly parallel forward flow. In most cases, multiple pumps can provide sufficient flexibility.

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Section 3

Process Control

INTRODUCTION

Although the activated-sludge process has been used for more than a century to treat biochemical oxygen demand (BOD) in wastewater—its use has been documented in England as early as 1882 (Metcalf and Eddy, 1972)—the process was first patented on October 11, 1913 (Porter, 1917) in the United Kingdom. Today, activated sludge is typically used for treating municipal wastewaters to secondary standards in the United States and elsewhere, and is frequently the selected process for removing ammonia, total inorganic nitrogen, and phosphorus from wastewater.

Understanding of activated-sludge process control has advanced to the extent that controlling the activated-sludge process has now become a science rather than an art. To many operators who have not mastered the principles of activated-sludge process control, however, controlling the activated-sludge process remains a challenge.

This section provides the necessary tools for developing and implementing an activated-sludge process control strategy to fit any activated-sludge process treating municipal wastewater.

It begins with a discussion of the basics of activated-sludge process control in "Primary Components for Controlling Activated-Sludge Systems." These basics will then be applied to the use of activated sludge to treat carbonaceous BOD, nitrify ammonia to nitrite and nitrate, denitrify nitrite and nitrate to nitrogen gas, and then remove phosphorus. The section continues with discussions of process configuration, treating wastewater variables, tracking process performance, and concludes with an introductory discussion of assisted control strategies.

PRIMARY COMPONENTS FOR CONTROLLING ACTIVATED SLUDGE SYSTEMS

INTRODUCTION. Achieving control of the activated-sludge process requires a thorough understanding of key components of the process and how these components are kept in balance. The three most important components of activated-sludge process control are maintaining (1) the correct amount of activated-sludge (microorganism) inventories, (2) adequate activated-sludge dissolved oxygen (DO) concentration, and (3) clarifier control.

CONTROLLING ACTIVATED-SLUDGE INVENTORIES. In the activated-sludge process, organic and inorganic wastes are consumed by microorganisms, resulting in more microorganisms and increased activated-sludge inventories. If activated-sludge inventories are allowed to grow without limit, eventually the overabundance of activated sludge will overload the secondary clarifiers and sludge blankets will rise over the weirs. Activated-sludge inventories would be lost to the effluent; high effluent suspended solids (SS) and BOD would result. This method of wasting inventories is effective and will eventually result in some kind of equilibrium, but not one that is typically desired. Activated-sludge inventories should be low enough so clarifiers are rarely stressed (close to or losing sludge blankets) and aeration requirements are kept to a minimum, but high enough to consistently treat the wastes received to the desired level of treatment. To achieve this, a predetermined amount of activated sludge must be wasted from the process regularly.

Typically, after they are thickened in the secondary clarifier, activated-sludge solids are wasted either directly from the clarifier or from the return activated-sludge (RAS) line. In some cases activated-sludge solids are wasted directly from the biological reactor prior to thickening. This practice is not used as much in larger plants because of the additional pumping and downstream thickening costs that would result from handling the more diluted solids from the reactor. To keep the activated-sludge process operating at peak efficiency, the operator must know how much of the solids inventory to waste and how often.

One of the most important parameters for process control is maintaining the optimal amount of activated-sludge solids in the system to treat the BOD in the influent wastewater. A good way to understand the importance of this is to consider the amount of BOD in the untreated wastewater as "food", and the activated-sludge solids as "microorganisms" that will eat the food in one sitting. If there are not enough microorganisms available to eat all the food in one sitting, there will be leftovers. Leftovers means that effluent BOD is higher than desired. If there are more microorgan-

isms than needed to eat the available food, more of the food will be eaten than expected, and effluent BOD will be lower than expected. The goal, then, would be to achieve an optimal balance between the amount of food, or BOD, in the wastewater to be treated and the amount of microorganisms available in the activated sludge, or the activated-sludge solids inventories, to eat or treat the influent BOD. This balance is typically referred to as the food-to-microorganism ratio, or F:M, and is used widely by operators to control the activated-sludge process.

Food-to-Microorganism Ratio. The F:M is typically used to determine the optimum activated-sludge solids inventory maintained in the process to adequately treat BOD in wastewater influent. The ratio is calculated on a mass basis, which means both wastewater BOD (food) and activated-sludge solids inventory (microorganisms) should be in pounds, using the English system, or kilograms, using the metric system. Because the influent to an activated-sludge process is continuous and varies over time, the BOD is measured in mass per unit time, typically represented as lb BOD/d. Ideally, the solids inventory is constant and does not vary with time, and so it is measured in mass units, or commonly pounds of solids. In an attempt to distinguish the microorganisms in the activated sludge from the inert solids, only volatile solids are used in the F:M calculation. The F:M is calculated as follows:

$$\text{F:M} = Q_{WW} \times \text{BOD} / V_{AB} \times \text{MLVSS} \tag{20.5}$$

Where

Q_{WW} = the wastewater flow to the activated-sludge process, m^3/d (mgd);
BOD = the wastewater BOD concentration, mg/L;
V_{AB} = the total liquid volume of the biological reactors in service, m^3 (mil. gal); and
MLVSS = the mixed liquor volatile suspended solids (MLVSS) concentration in the biological reactor, mg/L.

The resulting F:M will be in units of 1/day (or d^{-1}). Typical F:M values are 0.25 to 0.45 d^{-1} for BOD removal only, and approximately 0.10 d^{-1} and less for nitrification. In some cases, however, actual target F:M values can vary from these typical values and, therefore, a target F:M should be determined individually for each activated-sludge plant.

Mean Cell Residence Time. Mean cell residence time (MCRT) is another commonly used method for determining the optimum activated-sludge solids inventory. Mean cell residence time is theoretically defined as the number of days a microorganism stays in

the activated-sludge system (or solids inventory) before it is wasted out of the system. A longer MCRT leads to more solids being kept in the system and an increase in mixed liquor suspended solids (MLSS) concentration. In contrast, when the MCRT is short, less solids are kept and the MLSS concentration decreases. The basic equation for MCRT is

$$\text{MCRT} = \left(\frac{\text{The activated - sludge solids mass in the system}}{\text{The activated - sludge solids mass leaving the system per day}} \right) \quad (20.6)$$

The MCRT is calculated in days. This basic formula has one controversy; namely, whether to include clarifier solids in the solids inventory. Because of the difficulty in calculating the mass of clarifier solids (i.e., the solids concentration throughout the clarifier sludge blanket is highly variable along with the variability of the blanket volume), and because clarifier solids remove little, if any, BOD compared with the solids in the biological reactor, clarifier solids sometimes are not included in the solids inventory. This is acceptable if the amount of clarifier solids is small compared with the amount of biological reactor solids, and the solids returned from the clarifiers to the reactors are relatively constant. If the solids returned from the clarifier cause large fluctuations in reactor MLSS, however, then the clarifier solids must be included.

If mixed liquor solids are wasted from the biological reactor instead of the RAS line (or clarifier) and the solids mass in the effluent is relatively small, a short-cut method can be used to calculate MCRT. Because both solids wasted and solids in the biological reactor are mixed liquor, the MCRT calculation reduces to

$$\text{MCRT} = \text{Biological reactor (liquid) volume} / \text{Waste mixed liquor flow per day} \quad (20.7)$$

Therefore, if 10 000 m^3/d (2.64 mgd) of mixed liquor is wasted from a 35 000-m^3 (9.24-mil. gal) biological activated-sludge reactor, the MCRT is 3.5 days.

The MCRT for a secondary activated-sludge process removing only BOD is typically 1 to 3 days, for a nitrifying process the MCRT is typically 4 to 10 days, and for an extended aeration process the MCRT is typically 20 days or greater.

Sludge Age, Solids Retention Time, and Mean Cell Residence Time. Confusing to many is the difference among sludge age, solids retention time (SRT), and MCRT.

This confusion becomes apparent after you ask different operators or consult a few textbooks and find that you get a variety of definitions for these terms. More important than the term itself is the concept behind the term and how it is applied to a particular activated-sludge process. Both sludge age and SRT are used to quantify the amount of time microorganisms stay in a particular activated sludge before being wasted, the same

as MCRT. Therefore, as long as the instructions provided in the previous discussion on MCRT are adhered to, you can assume that the terms are all the same, and as long as you are consistent you can use the one most comfortable to you. It is very important, however, that when discussing these terms with others (especially those working at different wastewater treatment plants [WWTPs]) that you make sure you are talking about the same thing. Ask them to define the term they are using before you use the data they give you.

Constant Mixed Liquor Suspended Solids. In smaller activated-sludge treatment plants, a third method typically used for maintaining adequate solids inventories is to keep a constant MLSS in the biological reactors. Often in this case, the MLSS concentration is approximated with the volume of sludge resulting after a mixed-liquor sample has been spun in a centrifuge (other methods are also used, such as handheld SS meters), eliminating the need for expensive and time-consuming laboratory analysis. The MLSS target concentration is determined individually for each activated-sludge process.

Selecting a Control Strategy. Many operators have a preferred method for calculating the amount of solids to waste to maintain an optimum solids inventory. Mean cell residence time (or SRT or sludge age) is most often the method chosen for municipal WWTPs. For a given target MCRT, the same portion of activated-sludge inventories is wasted every day regardless of the variations occurring in the influent wastewater. In contrast, wasting rates determined by F:M will depend on the variations of influent BOD, and wasting rates determined for a constant MLSS will depend on changes in activated-sludge growth rate (resulting from influent variations). Therefore, it is much easier for the operator to maintain a constant MCRT than a constant F:M or MLSS. This gives the operator more control and the process more stability when the MCRT method is used. Nonetheless, in some cases the MCRT method is not the most suitable.

In some cases in which WWTPs receive high BOD loads intermittently from a few industries (usually food processors with seasonal operations), the BOD loads are often predictable and, therefore, activated-sludge inventories can be built up in advance to accommodate these loads. In this case the F:M method is the only safe method to use of the three methods discussed. Strictly using the MCRT method would result in activated-sludge inventories critically insufficient to treat the higher BOD loads received.

For small WWTPs, the constant MLSS method is often used because the laboratory equipment and expertise needed to run the necessary tests for this method are minimal. If this is not a constraint for the operator, it is recommended that the MCRT method be used instead.

Temperature Effects. In cold temperatures, microorganisms tend to grow much slower. Therefore, if the wasting rate remains the same as in warmer weather, the amount of

microorganisms in the solids inventory to treat the BOD (and other constituents such as ammonia through nitrification) will decline, possibly resulting in a rise in effluent BOD (or ammonia). During cold weather, operators will often reduce wasting rates to increase the MCRT to a point where BOD (and ammonia) removal efficiencies are maintained. Then, when temperatures increase, the wasting rate is increased to maintain a more constant solids inventory and to reduce the cost of keeping these higher solids inventories under aeration.

Sudden temperature changes can also affect clarification, by producing temperature layers in the clarifier and reducing the active volume of the clarifier. This could result in short-circuiting and solids carryover from the clarifier.

AERATION AND DISSOLVED OXYGEN CONTROL. Aeration includes both a supply of oxygen and a method of mixing the oxygen into the activated sludge. Mixing can be accomplished in many cases with just the action of adding air to the process, if adequately distributed. However, because the gas flow rate of pure oxygen added to activated sludge is too low to provide adequate mixing, some type of mechanical mixing is always required with pure oxygen activated-sludge processes. When low-BOD wastewaters are treated using an air-activated-sludge process, the minimum air flow rate is based on mixing requirements rather than DO requirements. This is true for both mechanically aerated and diffused air systems.

As a rule, oxygen requirements are typically met when the DO in the biological reactor is 2 mg/L or more. But this is not always the case, large populations of low-DO filamentous organisms have been observed in pure oxygen activated-sludge systems with DO concentrations as high as 10 to 12 mg/L. When the DO concentration was increased to 16 to 20 mg/L, the low-DO filaments declined and activated-sludge settling improved (Jenkins et al., 1993). This demonstrates that the DO measured in pure oxygen activated-sludge plants cannot be compared with the DO measured in air-activated-sludge plants. It is best to experiment with each individual system to determine the DO concentration that will provide adequate oxygen. In the case of pure oxygen activated-sludge systems, vent gas purity may be a better indicator of whether oxygen demands are met.

Indicators of low-DO conditions, going from less to more severe, are as follows:

1. Significant presence of low-DO filamentous bacteria in the activated-sludge.
2. Turbid effluent.
3. Dark-gray or black activated sludge, often associated with putrid odor.

When the DO drops below optimal concentrations, the first indicator of a low-DO condition will be the growth of low-DO filamentous organisms. As the DO drops, the dominance of these filamentous organisms increases, adversely affecting the settleability of the activated sludge. Nonetheless, as long as the activated sludge can be successfully separated from the treated effluent in the secondary clarifier, good treatment will still occur. Filamentous organisms will be discussed later in this section.

As the DO continues to drop further, even low-DO filamentous organisms (which are strict aerobes requiring some level of oxygen for growth) will decline in both length and number (eventually washing out of the sludge), and treatment efficiencies will be severely affected. At this point, effluent turbidity will rise and permit violations may either occur or soon follow. In severe conditions, the activated sludge may turn a dark-gray or even black, and putrid odors (caused by anaerobic processes) may also occur. Visual observations are good as indicators, but actual measurements of both DO and effluent water quality should be taken before a determination of cause is made; for example, the black color may be the result of a dye from an industrial discharger.

Only well-maintained, clean, and adequately calibrated DO probes and meters should be used. Dissolved oxygen meters often come with electronic zeros for calibration. Zero calibration accuracy should be checked with an absolute zero solution composed of a saturated solution of sodium sulfite (see procedure in *Standard Methods* [APHA et al., 1998]).

To be safe, some operators keep the DO in the biological reactors at the highest concentration possible. Keep in mind, however, that the cost for power to run aeration equipment is typically one of the highest operating costs for a secondary WWTP, and overaeration would result in a significant waste of both energy and money.

SECONDARY CLARIFIER AND SOLIDS SEPARATION PROCESS CONTROL. Although the heart of the activated-sludge process is the biological reactor, the secondary clarifiers are necessary to allow the activated-sludge solids to separate from the treated effluent. Without proper operation of the clarifier, the activated sludge could not adequately remove BOD or suspended solids from the wastewater stream.

Control Parameters. There are five parameters that will have the most influence over the performance of a well-designed secondary clarifier: 1) MLSS concentration in the flow to the clarifier, 2) wastewater flow, 3) RAS flow, 4) surface area of the clarifier, and 5) settleability of the activated sludge (discussed later in this section). Except for sludge

settleability, all the other parameters mentioned are accounted for in the clarifier solids loading rate (SLR), calculated as follows:

$$\text{SLR} = (Q_{WW} + Q_{RAS}) \times (\text{MLSS}) \times \text{Conversion factor}/\text{SA} \qquad (20.8)$$

Where

SLR = solids loading rate, $kg/m^2 \cdot d$ (lb/d/sq ft);
Q_{WW} = wastewater flow, m^3/d (mgd);
Q_{RAS} = return activated sludge flow, m^3/d (mgd);
MLSS = mixed liquor suspended solids concentration, mg/L;
SA = clarifier surface area, m^2 (sq ft); and

$$\text{Conversion factor} = \frac{0.001 \text{ kg} / \text{m}^3}{\text{mg} / \text{L}} \left(\frac{8.34 \text{ lb} / \text{mil. gal}}{\text{mg} / \text{L}} \right)$$

Typical SLRs in the safe operating range are 171 $kg/m^2 \cdot d$ (35 lb/d/sq ft) or less (the maximum SLR at specific sludge volume indexes (SVIs) will differ for different WWTPs; it is best to determine the actual SLR limits for your plant). The poorer the activated-sludge settleability [measured with sludge volume index (SVI)], however, the lower the SLR should be.

Solids Blanket. Blanket depth should be measured at least one to three times per day. Typically, a long clear plastic tube that has a ball check valve at the bottom is used to take the measurement. The ball check allows water to flow into the tube as it is lowered vertically into the tank; but once the tube hits the bottom of the clarifier and is brought up, the ball check prevents the water in the tube from flowing back out again. Inspection of the tube's contents will typically reveal a clear water (secondary effluent) portion throughout most of the tube, while the bottom of the tube will have a layer of thickened activated-sludge solids (solids blanket). Ideally, there is always a distinct separation between the clear water layer on the top and the solids layer on the bottom. If the test is performed correctly, the depth of these layers in the tube will be the same as that in the operating clarifier. Measuring the depth of the solids layer in the plastic tube, then, will be the same as measuring the solids blanket depth in the clarifier. Other methods for determining blanket depth are also available.

Typically, clarifiers are operated so that the solids blanket depth is between 0.15 and 0.9 m (0.5 and 3.0 ft) up from the bottom, with optimal depths typically between 0.3 and 0.6 m (1 to 2 ft). A blanket depth allowed to increase too high could be picked up by a sudden hydraulic surge to the clarifier and sent over the clarifier weirs, resulting in ef-

fluent compliance violations. However, some blanket depth is desirable to allow solids to thicken in the clarifier and reduce the return of secondary effluent to the biological reactor; thereby reducing pumping costs by reducing the amount pumped from the clarifier back to the reactor. Keep in mind these are only guidelines, which will be true most of the time, but it may be necessary to occasionally operate differently. For example, in the case of highly denitrifying activated sludge (nitrogen bubbles that are produced float the sludge to the top of the clarifier and eventually over the clarifier weirs into the secondary effluent), it may be desirable to operate with no blanket in the clarifier to prevent solids loss to the effluent.

Return Activated-Sludge Control. The importance of RAS control can be illustrated by looking at the extremes. If there was no RAS being removed from the clarifier, the activated-sludge solids would build up and eventually spill over the clarifier weirs into the secondary effluent. Essentially no treatment would take place. If the RAS flow is too high, initially the liquid level in the clarifier would drop, but the RAS flow is pumped to the biological reactors where it eventually flows back to the clarifier. Too high a RAS flow will ultimately create a high hydraulic load on the clarifier, preventing activated-sludge solids from settling. This, at its extreme, will also result in activated-sludge solids loss to the secondary effluent, preventing treatment.

Although the RAS flow is also necessary to provide an adequate mixture of activated-sludge solids with the wastewater to be treated (this mixture is referred to as mixed liquor), the clarifier is the more sensitive part of the process to variations in RAS flow. Therefore, blanket depth should be the primary indicator of an optimum RAS flow rate.

The RAS flow is typically controlled at a percentage of the wastewater flow to the biological reactors. In short-MCRT systems, with low solids inventory, RAS flow is typically 25 to 50% of the wastewater flow rate (30 to 40% being most typical). In longer-MCRT systems with high solids inventories, the RAS flow may be 100 to 150% of the wastewater flow rate. This relationship can be understood by realizing that the higher solids inventories carried in the process at longer MCRTs will require higher pumping rates to remove solids from the clarifiers, compared with shorter-MCRT systems.

Sludge Settleability and Foaming. Activated sludge is composed of a variety of microorganism populations, and the specific microorganisms can differ from one activated sludge to another. The kind of microorganisms that grow in and dominate a particular activated sludge is determined by factors such as the composition of the wastewater treated (e.g., highly soluble with high sugar content, highly particulate with more fats and oils, or high sulfide content); whether the process is operated at long or short MCRT; and conditions in the biological reactors such as pH, temperature, and DO concentration.

The different microorganism populations can produce very different activated-sludge characteristics and treatment potential. This section will discuss settling and foaming characteristics, and how they are created by the type of microorganism that is allowed to dominate the process.

FILAMENTOUS ORGANISMS. If an activated sludge is not settling or compacting well, and the SVI is greater than 150 mL/g, chances are the problem is because of an overgrowth of filamentous organisms. Filamentous organisms are those microorganisms that grow with their cells lined up end-to-end to form long strings or filaments. When these organisms grow in the right amounts in activated-sludge flocs, they act as a kind of skeleton for the flocs and the result is a good-settling floc. If no filamentous organisms are present in the activated sludge, flocs will be weak, may break up, stay in suspension, and not settle well. If the flocs contain an overabundance of filamentous organisms, however, the activated sludge will settle poorly, if at all, and is referred to as a *bulking* sludge.

Filamentous organisms can be identified under a 1000X power, oil immersion, phase-contrast microscope. Different techniques used to stain the filamentous organisms with colored dyes provide a method for identifying certain specific filamentous organisms that are not easily identified otherwise while observing them at 1000X power (see Jenkins et al., 1993). A specific filamentous organism grows and dominates an activated-sludge process because specific conditions were such that the organism was able to outcompete other microorganisms for the food (usually BOD) available. In many cases, the conditions that promote filamentous organism growth include 1) low DO in the biological reactors, 2) highly soluble, high-sugar industrial wastewater making up a large part of the wastewater being treated (nutrient deficiencies can also play a role here), and 3) low pH (usually this is a filamentous fungus, while other filamentous organisms that grow under conditions 1 and 2 are typically filamentous bacteria).

Once the filamentous organism has been identified by microscopic examination, one of the three conditions can be identified as the cause of the bulking problem. Correcting conditions 1 and 3 are as easy as increasing the DO in the biological reactors (harder if the aeration equipment is not capable of this, in which case supplemental aeration or oxygen may be required), or increasing the pH in the reactors (a variety of chemicals such as lime, caustic soda, or bicarbonate could be used; however, caution must be used to not increase the pH above approximately 8.5). Condition 2 can be remedied with an aerobic, anoxic, or anaerobic selector. A selector is essentially a tank that is placed upstream of the reactor and is fed both RAS and the influent wastewater

to be treated. The selector creates a condition that allows floc-forming bacteria to outcompete filamentous bacteria for the soluble (typically sugar-based or short-chained fatty acids) BOD, resulting in good-settling floc with a controlled filament population. Contrary to previous beliefs, selectors are not capable of controlling all types of filamentous organisms (Gabb et al., 1989 and 1991). It is important to identify the actual effects on activated-sludge settleability caused by only those filaments that are controlled by a selector before an investment is made in selector construction and installation.

Another effective way to control filamentous organisms that grow under any of the three conditions is to chlorinate the RAS. Care must be used with this approach because overdosing chlorine could result in toxic effects, especially to nitrifiers. Typically, however, dosing below 4 g chlorine/kg MLSS·d (4 lb/d/1000 lb) is safe (important: make sure your calculations are correct before dosing), but this dosage may not be high enough to effectively control the filamentous population. The chlorine dosage can be carefully increased by 2 g chlorine/kg MLSS·d (2 lb/d/1000 lb), until an effect has been made. With experience, the correct dosage can be found quickly.

FOAM CONTROL. Foaming in an activated-sludge process can result from many causes. The white billowy foam coming off a biological reactor is typically caused by untreated surfactants (typically detergents or soaps, but other substances—such as some materials formed biologically—can also act as surfactants). Typically, longer MCRTs provide activated sludge with the slower-growing organisms to treat surfactants. This problem is magnified at shorter MCRTs. The more common foaming problem is caused predominantly by a branched filamentous bacteria called *Nocardia*. In some cases, other filamentous bacteria such as *Microthrix parvicella* have been claimed to cause foaming. These bacteria can be positively identified with a 1000X power microscope. Using the Gram-stain technique will assist in microscopic identification.

Foam caused by *Nocardia* is light-chocolate-colored and can be produced so abundantly that large masses of this foam have spilled out of biological reactors and covered nearby service roads. When waste activated sludge (WAS) is fed to digesters, foaming problems can be spread to the digesters. The foam can plug gas lines, leading to high digester-gas pressures.

Nocardia is controlled in many cases by keeping the MCRT very short (sometimes, typically in warm weather, to one day or less). *Nocardia* grows slow enough so shorter MCRTs will allow activated sludge to be wasted faster than *Nocardia* can grow, eventually eliminating *Nocardia* from the process (e.g., if a bacterial cell divides every two

days, but the MCRT is only one day, the bacteria's growth rate cannot keep up with the waste rate and the organism disappears from the process).

An effective method for *Nocardia* control is to physically remove the Nocardial foam from the biological reactor. Because most of the *Nocardia* is in the foam, *Nocardia* will be selectively removed from the system by removing the foam. Two cautions here are 1) once the foam is removed, do not put it back into the plant by sending it to the headworks of the plant or to the digesters; the foam should be sent to a drying bed (without decanting the bed and sending the liquid back to the WWTP), dried, and disposed in a landfill or by some other suitable method; and 2) if significant solids are removed from the process, check the effects on solids inventories: the actual MCRT may be shorter than the calculated MCRT. However, in some WWTPs (such as in large pure-oxygen activated sludge plants) this method may not be practical.

Chemical methods for *Nocardia* control include adding a cationic polymer to the RAS flow stream or mixed liquor channel (Shao et al., 1997), and spraying high concentrations of chlorine directly on the foam (care should be taken not to add toxic amounts of chlorine to the activated sludge). Note, although chlorine fed to the RAS line is effective for controlling filamentous organisms that cause bulking, feeding chlorine to the RAS line is not effective for controlling *Nocardia.* This is because most of the *Nocardia* is in the foam and not included in the RAS.

Membrane Processes for Solids Separation. More information is coming out suggesting the replacement of clarifiers with membranes for solids separation. An activated-sludge process using a membrane instead of a clarifier is referred to as a membrane bioreactor (MBR). The advantages claimed of using membranes over clarifiers are 1) membranes are not affected by poorly settling activated sludge (such as that discussed in the last section); 2) membranes remove more suspended solids, providing a higher-quality effluent; 3) membranes remove bacteria, providing a level of disinfection and possibly lowering the cost of subsequent disinfection processes; 4) membranes require much less space (and can even be immersed in existing biological reactors); and 5) membranes allow for higher SLRs, allowing higher mixed-liquor concentrations in the biological reactors and, therefore, lower reactor volume requirements (Davies et al., 1998; Engelhardt et al., 1998; and Nagoaka et al., 1998).

Conversely, clarifiers are one of the cheapest wastewater treatment processes to operate compared with all other wastewater treatment processes and will be significantly less expensive than membrane systems. Nonetheless, if overall treatment costs are considered, in some applications MBRs could be competitive. It is possible, therefore, that more of these systems will be used in the future.

PROCESS CONTROL FOR CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND REMOVAL

Biochemical oxygen demand is a measure of the amount of oxygen required to biochemically oxidize a variety of organic and inorganic substances in solution. Different substances in wastewater can result in different kinds of BOD. Biochemical oxygen demand can be classified based on the substance being oxidized and is typically separated into two basic groups. Carbonaceous BOD (CBOD) is the oxidation of organic carbon substances, such as sugars, fats and proteins, and nitrogenous BOD (NBOD) is the oxidation of inorganic nitrogen substances, almost always ammonia or nitrite. Secondary activated-sludge plants are designed to remove CBOD, while NBOD is removed by nitrification, typically referred to as a tertiary activated-sludge process. It is important to note that secondary treatment is defined by the U. S. Clean Water Act (40 CFR, Chapter 1, Section 133.102, [1993]) and includes discharge limits for BOD, total suspended solids (TSS), and pH. Although nitrification has become a common treatment practice in many areas, an ammonia limit is still not included in the definition of secondary treatment.

To create a control strategy for CBOD removal, the first step is to determine the target effluent CBOD or total BOD for the process. Typically this target is determined by the treatment plant's discharge-permit requirements, however, settling the target effluent BOD below permit requirements will allow for some process variation. Currently under the U.S. Clean Water Act, secondary activated-sludge plants are required to meet a 30 mg/L (5-day) BOD (includes both CBOD and NBOD) or a 25 mg/L CBOD over a 30-day average. These are U.S. federal regulations, but some WWTPs are regulated with more stringent state or local effluent requirements.

The CBOD can also be broken down into types. Typically, there is readily assimilated CBOD and slowly assimilated CBOD. The readily assimilated CBOD includes organic materials such as sugars and short-chained organic acids (e.g., acetic acid or vinegar), and the slowly assimilated CBOD includes longer-chained materials such as starches and fats. Note that slowly assimilated CBOD can be either soluble or particulate. Soluble is typically considered that which can pass through a 0.45-mm pore-sized filter and particulate is that which is trapped on a 0.45-mm pore-sized filter. Readily available CBOD is only in soluble form. Readily assimilated CBOD can be removed in very short MCRTs (1 to 3 days), while slowly assimilated CBOD requires longer MCRTs (4 to 20 or more days) for better treatment.

To enhance CBOD removal, many different process modifications have been tried. The next section discusses the more widely used modifications.

CHANGING PROCESS CONFIGURATIONS

The basic activated-sludge process has been modified many ways to obtain different performance outcomes. Most of these modifications were intended to fix a problem (such as high soluble-BOD loads or limited land for construction of treatment facilities) or to enhance the performance of the activated-sludge process. From its conventional configuration, the mixing patterns in the biological reactor have been modified, the locations where influent feed and RAS flows enter the process have been varied, and other treatment processes have been coupled to the activated-sludge process. A description of these process configurations can be found in Section 2. This section provides the operator with an understanding of how these configurations can be implemented in an existing WWTP to enhance activated-sludge process performance. In some WWTPs, the design of the activated-sludge process will allow the operator to easily change the configuration of the process. In other plants, design modifications will be needed to allow changes to the process configuration. If modifications are required, a cost–benefit analysis should be performed before the modifications are implemented.

CONVENTIONAL. The conventional activated-sludge process typically consists of a concrete biological reactor followed by a concrete clarifier. Wastewater and RAS enter together at one end of the reactor and leave mixed at the other end. This mixed liquor flows into the clarifier where it is allowed to settle and the treated effluent separates from the activated sludge. The effluent from the process flows over the clarifier weirs while the settled activated sludge is either recycled to the reactor or wasted out of the system. Process control of the conventional system, as just described, is rigid compared with other process configurations. This provides operational simplicity when everything works well, but fewer options for the operator to use to prevent potential upsets. The conventional activated-sludge process can be designed to operate as a complete-mix reactor or a plug-flow reactor. Configuration modifications to both of these options are discussed in this section.

Complete Mix. In a complete-mix configuration, the biological reactor has only one cube-like compartment, allowing the mixed liquor to be homogeneously mixed and aerated. This results in the concentrations of all constituents (e.g., BOD, TSS, or ammonia) to be the same at any point in the mixed liquor. An actual complete-mix system will not be this perfect, but if biological reactor mixing is adequate it should be very close. Because of this, the BOD and TSS in the complete-mix reactor will be the same as that leaving the reactor; which means the reactor BOD and TSS will be somewhat dilute.

The oxidation ditch can also be considered a complete-mix reactor, and a conventional activated-sludge process. It is an oval or circular racetrack-type biological reac-

tor, designed to move mixed liquor around this path with the use of brush aerators or pumps. Because the mixed liquor moves around the reactor in a short period of time (often 10 minutes or less), the reactor closely approximates a complete-mix reactor. (Note that some less traditional oxidation ditch designs include modifications that lengthen the flow path and can reduce the complete-mix effect). Although the mixed liquor is circulated many times around the reactor in one day, the average hydraulic detention in the reactor is typically approximately 18 hours or more. The oxidation ditch process is typically operated with an MCRT of 20 days or longer.

The advantage of the complete-mix configuration is that it promotes efficient aeration where DO levels are typically easy to keep above 2 mg/L; but this process configuration could also have problems.

One significant problem with the complete-mix configuration is that it can promote the growth of filamentous organisms under certain conditions. Some types of filamentous organisms (including type 021N, *Thiothrix* spp., and *Sphaerotilus natans*) are able to outcompete other microorganisms when there is a significant amount of diluted, readily assimilated BOD (such as sugars and short-chained organic acids common in some food processing wastewaters) available. Because all the soluble constituents in a complete-mix biological reactor should always be dilute, this type of filamentous organism will thrive if sufficient readily assimilated BOD is available in the mixed liquor. If the readily assimilated BOD is removed prior to the influent entering the complete-mix reactor, however, these filamentous organisms will not grow.

To prevent readily assimilated BOD from entering a complete-mix reactor, two process configuration modifications have been successful: 1) a fixed-growth biological system (e.g., a trickling–bio filter, which will always be an expensive modification to the process) installed upstream of the complete-mix reactor, and 2) a selector installed upstream of the complete-mix reactor (which can be relatively inexpensive). Selectors can be aerobic, anoxic, or anaerobic, but all are designed to allow non-filamentous bacteria to outcompete filamentous bacteria for the readily assimilated BOD.

Selectors. An aerobic selector is installed upstream of the main biological reactor and it can be one or more small biological reactors in series or it can be a long aerated channel. The selector receives both the wastewater and RAS flows before they enter the main reactor. The hydraulic retention times in aerobic selector systems are typically between 5 and 30 minutes, or the amount of time it takes for the activated sludge to remove the readily assimilated BOD from the wastewater. In these selector systems, the concentration of readily assimilated BOD is many times greater than that in the complete-mix reactor. The higher concentration of readily assimilated BOD allows non-filamentous bacteria to outcompete filamentous bacteria. The challenge to using an aerobic selector is to

build the selector large enough to allow readily assimilated BOD to be completely taken up before it enters the main biological reactor and small enough so the readily assimilated BOD is not too dilute to allow filaments to grow in the selector.

An anoxic selector also receives both wastewater and RAS flows before the flows enter the main biological reactor, but conditions in the selector are anoxic. Anoxic means that there is no oxygen present, but there is nitrate present. Non filamentous bacteria take up readily assimilated BOD while using nitrate instead of oxygen. Because filamentous bacteria can only take up readily assimilated BOD in the presence of oxygen, these non-filamentous bacteria are able to outcompete the filamentous bacteria for the readily assimilated BOD; and therefore filamentous bacteria do not grow.

An anaerobic selector is physically much like an anoxic selector, but even nitrate is absent. Bacteria capable of taking up readily assimilated BOD under anaerobic conditions outcompete filamentous bacteria that require oxygen to take up readily assimilated BOD. The anaerobic selector is actually the same as, or similar to, the anaerobic reactor in the phosphorus-removal process discussed later in this section. It is important to note, however, that selectors (regardless of type) can only control specific types of filamentous organisms, as discussed in the previous section on "Sludge Settleability and Foaming".

Plug Flow. Very long biological reactors are often called plug-flow reactors, but strictly speaking this is incorrect. These reactors come closer to achieving plug-flow than compete-mix reactors, but they do not achieve actual plug flow. Nonetheless, in many cases the degree to which they come close to being plug flow is good enough; and because these reactors have been called plug-flow reactors for many years, it is acceptable to continue to use the name.

Typically, mixed liquor flowing through plug-flow reactors will have higher concentrations of the waste to be treated (such as BOD or ammonia) and lower concentrations of DO at the front end of the reactor compared with these concentrations at the discharge end of the reactor. There are at least two advantages to this. First, having higher concentrations of readily assimilated BOD at the front end of the reactor will reduce the competitive advantage of filamentous bacteria as discussed above. Those reactors that poorly approximate plug flow may still require the assistance of a selector. The advantage of having a plug-flow reactor, however, is that a selector can be cheaply installed by placing a wall (e.g., a fabric or plastic curtain hung in the reactor) towards the inlet end of the reactor to create a small separate selector zone.

Second, an operator may be able to optimize the amount of air fed to a reactor by measuring DO along the length of the reactor and reducing airflow until there is a sharp increase in the DO concentration at the end of the reactor. If the DO concentration

jumps up a quarter of the way down the reactor and then remains constant to the end of the reactor, the last three-quarters of the reactor is probably not being used by the activated sludge for treatment. If this occurs when the reactor is receiving its highest BOD or ammonia loading (of the day, week, month, or year), the airflow could be reduced or, in a multi reactor system, one or more reactors could be taken out of service. Doing this could reduce operating costs; especially because aeration costs are typically one of the most significant costs of operating an activated-sludge process. Conversely, if the DO concentration in a reactor is still low at the discharge end of the reactor (see the previous section on DO regarding adequate DO concentrations in mixed liquor), this may indicate inadequate DO. It would be a wise operating strategy to correlate the level of treatment with the location in the reactor where the DO jumps up to an adequate concentration.

Step Feed/Contact Stabilization. Step feed is often provided as an option to a conventional plug-flow reactor, but is not available to a complete-mix reactor. (Note that activated-sludge systems consisting of three or more complete-mix reactors installed in series may be better referred to as plug-flow systems). The step-feed process provides the opportunity to feed wastewater to other points along the length of the plug-flow reactor besides the front end. Step feed allows the operator to make better use of the plug-flow reactor by better distributing the oxygen demand along the length of the reactor. The DO demand is typically greatest at the front end of the reactor because both the RAS and the wastewater are typically introduced at this point. If the DO demand is too high, the DO in the mixed liquor can be drastically reduced allowing the growth of undesirable microorganisms in the activated sludge. Because the RAS carries an oxygen demand with it already, reducing or eliminating the amount of wastewater added at the front end will allow the reactor to first satisfy the demand of the return sludge prior to treating the wastewater. Thereby, a higher DO is maintained in this part of the reactor.

Step feed also allows the operator to keep a large inventory of activated sludge under aeration (resulting in longer MCRTs) without affecting the solids load to the clarifier. This is desirable for operators who want to switch to complete nitrification or would like to have their process remove more slowly biodegradable BOD, but do not have the clarifier capacity to keep larger solids inventories necessary to obtain the longer MCRTs.

Contact stabilization is a type of step-feed process. It requires that the RAS from the clarifier is preaerated before being mixed and aerated with the wastewater to be treated. Stabilization refers to the process where the RAS is aerated without wastewater, and contact refers to the process where wastewater is included with the RAS in the biological reactor. The stabilization part of the process should be large enough to

allow the DO demand in the RAS to be reduced to that of endogenous respiration. This indicates that the BOD and ammonia associated with the RAS have been essentially oxidized.

The contact-stabilization process has been used to remove nitrogen in recycle streams from dewatering operations (Drury et al., 1995). Ammonia can be very high in these streams and can significantly affect activated-sludge systems that are required to nitrify. Returning these high-ammonia recycle streams to the stabilization zone of the contact-stabilization process will allow the system to nitrify the ammonia before it enters the contact zone. If the DO in the contact zone is kept low enough in the front end, denitrification of all, or some, of the nitrate produced in the stabilization zone with nitrification can be achieved.

OTHER CONFIGURATIONS AND MODIFICATIONS. The activated-sludge process has often been coupled with other processes to enhance the performance of the process or to fix a particular problem. Combinations include activated-sludge processes with fixed-growth systems, powdered activated carbon (PAC), and chemical addition.

Combining Fixed-Growth Systems. Because fixed-growth systems typically grow the same microoganisms as activated-sludge processes, adding a fixed-growth system is typically intended to supplement the activated-sludge biomass in some way. As mentioned previously, biofilters have been used to remove readily assimilated BOD upstream of the activated-sludge process to prevent the growth of filamentous organisms in the activated-sludge process. Fixed-growth systems have also been used as a low-cost way to upgrade the capacity of activated-sludge processes. Manufacturers of cord media immersed in the activated-sludge biological reactor have claimed that this media supports fixed-growth biomass that can cost-effectively increase the capacity of the activated-sludge process without the need for additional land.

Addition of Powdered Activated Carbon. Some activated-sludge systems receive wastewaters that contain organic compounds that, in high concentrations, can be toxic to the environment and humans. These compounds could also inhibit the performance of the activated-sludge process. In cases where this is a problem, operators have added PAC to the biological reactor to adsorb these toxic compounds. Use of PAC in activated-sludge processes can be costly, therefore, it is only used when absolutely necessary. Nonetheless, an operator may choose to use PAC on occasions when short-term discharges of a toxic organic is not otherwise controlled.

Chemical Addition. Coagulating and flocculating chemicals can be used to enhance settling when necessary. Coagulants, such as ferric chloride, are used to remove turbidity,

while flocculants are used to aid settling of activated-sludge flocs. Flocculants have also been shown to reduce *Nocardia* foaming. Chemicals, such as ammonia or phosphates, can be used for supplementing nutrients in nutrient-deficient wastewaters containing large quantities of industrial wastes. As discussed previously, chlorine added to the RAS can control filamentous organisms. Ferric chloride and alum can be used to help activated-sludge processes remove phosphorus.

PROCESS CONTROL FOR NITRIFICATION

The activated-sludge process can treat or remove more than just BOD. It can be operated to also remove nitrogen and phosphorus. Nitrogen and phosphorus are nutrients that can promote the growth of noxious algae in surface waters that receive treated wastewater. The activated-sludge processes used to remove nitrogen and phosphorus are referred to as biological nutrient removal processes.

Nitrogen removal is accomplished by combining two separate activated-sludge processes; nitrification and denitrification. Nitrification is an aerobic process that oxidizes ammonia and consumes alkalinity by producing a strong acid as a byproduct. Ammonia can be toxic to fish and other aquatic life and create an oxygen demand when discharged to surface waters.

Nitrification is a two-step process that features a specific bacteria in each step. In the first step, bacteria oxidizes ammonia to nitrite with the consumption of oxygen and production of a strong acid. *Nitrosomonas* is the bacteria typically associated with this first step; however, other bacteria, such as *Nitrosospira*, *Nitrosococus*, and *Nitrosolobus* (notice the "Nitroso-" in the name of each bacteria), are capable of oxidizing ammonia to nitrite in activated sludge. In the second step, bacteria oxidizes nitrite to nitrate. *Nitrobacter* is typically the bacteria that is attributed to performing this second step; however, other bacteria, such as *Nitrospina* and *Nitrococcus* (notice the "Nitro-" in the name of each bacteria), are also capable of oxidizing nitrite to nitrate, and have been identified in activated sludge (Bergey's Manual, 1993; Van Loosgrecht and Jetten, 1998; and Juretschko et al., 1998). The following equations illustrate these two steps

$$\underset{\text{Ammonia (Ammonium form)}}{2NH_4^+} + \underset{\text{Oxygen}}{3O_2} \rightarrow \underset{\text{Nitrite}}{2NO_2^{-+}} + \underset{\text{Water}}{2H_2O} + \underset{\text{Strong acid}}{4H^+} \qquad (20.9)$$

$$\underset{\text{Nitrite}}{2NO_2^-} + \underset{\text{Oxygen}}{O_2} \rightarrow \underset{\text{Nitrate}}{2NO_3^-} \qquad (20.10)$$

From these equations it is clear that the nitrification process requires a large amount of oxygen. The nitrification process consumes 4.57 kg of oxygen per kilogram of ammonia-nitrogen oxidized to nitrate, or approximately 25% of the oxygen required for both CBOD treatment and nitrification for a typical municipal wastewater. Note that some ammonia is used in cell synthesis and is not available to nitrification, while some ammonia is released through deamination (bacteria consume protein no longer required by the cell and release the ammonia associated with the consumed protein) and can be nitrified.

With the production of the strong acid in the first step, nitrification uses 7.14 kg of alkalinity (as calcium carbonate)/kg of ammonia-nitrogen oxidized. If the alkalinity is too low, the consumption of alkalinity in the first step may drop the pH low enough to shut down nitrification. It is best to retain at least 50 mg of alkalinity (as calcium carbonate)/L in the activated-sludge process effluent after nitrification is complete. If this is not possible with the alkalinity provided in the wastewater, the addition of alkalinity with lime, caustic soda, soda ash, or bicarbonate should be considered. The nitrifying bacteria grow best when the pH in the biological reactor is approximately 8.0 to 8.5 (although nitrification will occur at a pH as low as 6.5), and the temperature is between 15 and 30 °C (although nitrifiers will still grow at temperatures as low as 5 °C).

Nitrifiers also grow slowly (especially at low temperatures or low DO), therefore, the MCRT must be long enough to allow nitrifiers the opportunity to reach sufficient numbers to adequately nitrify the amount of ammonia and nitrites present in the wastewater. An MCRT as short as 4 days is sufficient for complete nitrification under optimum conditions, however, when complete nitrification is required, an MCRT of approximately 10 days or longer for cold weather is typically used.

Therefore, the factors necessary for good nitrification include

- Sufficient biological reactor DO;
- Adequate alkalinity to prevent inhibiting drops in pH;
- MCRT of at least 4 days, but preferably at least 10 days; and
- Suitable pH and temperature in the biological reactor.

TWO-STAGE OR TWO-SLUDGE NITRIFICATION. When designers were unfamiliar with achieving nitrification in activated-sludge processes, to be conservative they designed activated-sludge systems that would remove CBOD in one process and oxidize ammonia in a second. This resulted in building two completely separate activated-sludge systems to treat the wastewater. Now that we understand the activated-sludge–nitrification process much better, there is little reason for continuing this practice. Building these two-stage, two-sludge systems is costly (essentially building

twice the treatment plant necessary) and is a poor use of clarifier capacity. The two-stage system puts the first-stage clarifiers in series with the second-stage clarifiers. If instead these clarifiers were operated in parallel, the clarifier capacity of the overall activated-sludge process could double. For those plants still operating in the two-stage mode, careful evaluation of the process should be considered to determine if the process might instead be better operated in a single-stage mode.

PROCESS CONTROL FOR DENITRIFICATION

Denitrification takes the nitrification process and adds an unaerated zone in the initial part of the biological reactor. Both the RAS from the clarifier and wastewater to be treated are returned to this unaerated zone, but an additional RAS stream is also fed to this zone, this time from the discharge side of the biological reactor. This additional return line is intended to add more of the nitrate produced in the biological reactor to the unaerated zone, and thereby denitrify more nitrate. The nitrate fed to the unaerated zone is used by some bacteria instead of oxygen. The flow rate of the RAS from the clarifier in this process is approximately the same as the wastewater flow to the biological reactors, and the RAS flow from the biological reactor discharge to the unaerated zone is between one and four times the wastewater flow to the biological reactor. The basic equation for treating BOD with activated sludge is

$$\text{BOD} + \text{Oxygen} \rightarrow \text{Carbon Dioxide} + \text{Water} \tag{20.11}$$

The basic equation for denitrification is

$$\begin{gathered}\text{BOD} + \text{Nitrate (or Nitrite)} + \text{Strong Acid} \rightarrow \\ \text{Carbon Dioxide} + \text{Nitrogen Gas} + \text{Water}\end{gathered} \tag{20.12}$$

When oxygen is absent and nitrate is used as an oxygen source, the condition is called *anoxic*. This is in contrast to aerobic (with oxygen) or anaerobic (without oxygen and nitrate) conditions. Advantages to the denitrification process include use of nitrate instead of oxygen for BOD removal returning some of the extra equivalent oxygen needed to nitrify, and the replacement of some alkalinity lost during nitrification. The equivalent of 2.86 kg of oxygen/kg of nitrate-nitrogen denitrified is provided. Also, when strong acid is consumed during denitrification, some of the alkalinity consumed by the nitrification process is returned to the process. This step provides 3.57 kg of alkalinity (as calcium carbonate)/kg of nitrate-nitrogen denitrified.

The primary objective of the anoxic zone in the denitrification process is to remove nitrate, and not to remove BOD (although this is a convenient side benefit).

Therefore, it is preferred that the mixed liquor leave the anoxic zone with BOD and no nitrate than the other way around. Readily assimilated BOD is best for denitrification because it is promptly consumed and used by denitrifying bacteria. There may be plenty of BOD but insufficient readily assimilated BOD to denitrify all the nitrate before the mixed liquor leaves the anoxic zone. If this is the case, additional readily assimilated BOD must be added to the anoxic zone. Methanol has been used in the past, but table sugar or vinegar (vinegar being a weak acid, however, could significantly lower the pH in waters with insufficient alkalinity) can also be used, especially in small WWTPs. It is important that additional readily assimilated BOD is not overadded, because of the increased aeration costs that will result from treating this extra BOD in the aerobic zone and the potential for an overload in the aerobic zone leading to permit violations.

It is also important that the volumes of all unaerated reactors are excluded when calculating an MCRT. The 10-day MCRT required by the nitrification process might not be met if the anoxic zone is included in the MCRT calculations, leading to occasional periods of incomplete nitrification, especially in cold weather. Therefore, two MCRTs should be calculated—an aerated MCRT and an unaerated MCRT. The aerated MCRT should be sufficient to meet nitrification requirements (see nitrification discussion) and the unaerated MCRT should be sufficient to meet denitrification requirements. Unaerated MCRTs are often typical to those of secondary treatment, but it is best to determine the target unaerated MCRT for a specific activated-sludge process by comparing different MCRTs to process performance.

PROCESS CONTROL FOR PHOSPHORUS REMOVAL

When phosphorus is removed in the activated-sludge process, an unaerated zone at the start of the biological reactor like the denitrification process (and, therefore, the aerated MCRT should be calculated separately from the unaerated MCRT) is used. However, this time it is critical that neither oxygen nor nitrates are present in this zone. This zone is therefore called an anaerobic zone. Under anaerobic conditions, activated-sludge bacteria, referred to as phosphorus-accumulating organisms outcompete other organisms, for readily assimilated BOD.

Phosphorus-accumulating organisms store phosphorus in high-energy bonds and under anaerobic conditions phosphorus-accumulating organisms release this stored energy by breaking the phosphorus bonds. This gives the bacteria the energy to consume and store the readily assimilated BOD. Under anaerobic conditions phosphorus-accumulating organisms release phosphorus and consume readily assimilated BOD. The result in the anaerobic zone is that the phosphorus concentration increases while

readily assimilated BOD decreases. Then when the mixed liquor flows to the aerobic part of the biological reactor, phosphorus-accumulating organisms use their stored BOD to produce energy to reconsume the phosphorus the phosphorus-accumulating organisms released, plus more, to again form the high-energy bonds. The result is a net decrease in phosphorus, or phosphorus removal. If enough phosphorus-accumulating organisms can be grown in the mixed liquor, the effluent phosphorus concentration can be reduced to low levels. In the activated-sludge process, phosphorus-accumulating organisms have been identified by many to be predominantly a bacteria called *Acinetobacter*, but this claim has been recently challenged (Mino, 1998).

The process configuration can be simple when the MCRT is short and little nitrification takes place resulting in negligible nitrite and nitrate in the RAS. Under these conditions, phosphorus removal can be successful with an unaerated reactor followed by an aerated reactor. This process configuration is often referred to as the A/O™ process (WEF, 1998).

In the case of an activated-sludge process that is required to fully nitrify, the phosphorus-removal process becomes more complicated. Processes, such as the University of Cape Town process, would be required. In this process there are four stages. The first stage is anaerobic, the second and third anoxic, and the fourth aerobic. Return activated sludge is recycled to the second stage from the clarifier. The second stage is intended to reduce the nitrate in the RAS before it is recycled to the first (anaerobic) stage to mix with the incoming wastewater. The aerobic (fourth) stage recycles flow to the second anoxic (third) stage. This is to promote the denitrification of additional nitrate. Typically, the recycle flow rates from the clarifier to the second stage, and from the second stage to the first stage, are the same as the wastewater flow rate to the process. The recycle flow from the fourth stage to the third stage, however, is approximately 3 to 4 times the wastewater flow rate to the process.

PROCESS CONTROL FOR SEQUENCING BATCH REACTORS

In a sequencing batch reactor (SBR) the activated-sludge process (including clarification) takes place in a single reactor. A reactor is first filled with wastewater and activated sludge biomass (biomass is only added during the initial startup; otherwise thickened sludge will already be in the reactor from the previous treatment cycle). This period is referred to as the fill step. During the fill step, the contents of the reactor could be aerated if the process is not required to denitrify or remove phosphorus.

Once the reactor is full, flow to the reactor is stopped and the reactor is both aerated and mixed for a specified period of time. This period is referred to as the react step

(Note, if SBRs are used for nitrogen or phosphorus removal, the react step will be initiated with anaerobic or anoxic periods followed by an aeration period). Actual treatment takes place during the react step.

After the wastewater is treated in the react step, both aeration and mixing are stopped to allow the mixed liquor to settle. This step is referred to as the settle step. Once the sludge is settled and sufficiently thickened (the measuring tube discussed in the secondary clarifier section can be used to determine when the sludge blanket is sufficiently settled and thickened), most of the top-treated effluent layer in the reactor is decanted off. This step is known as the decant step. The settle and decant steps combined take the place of having a separate clarifier. With the remaining thickened activated sludge in the reactor (i.e., the RAS), the reactor is refilled with wastewater to start the fill step and restart the treatment cycle. Waste activated sludge is typically removed from the reactor toward the end of the react step while the mixed liquor is still being mixed. Because mixed liquor is wasted (not RAS), the shortcut MCRT method (discussed previously) can be used to determine the amount of sludge to be wasted.

The SBR fill and react cycles can be modified to mimic many activated-sludge process configurations. The nitrogen-removal and phosphorus-removal processes have already been discussed, but step-feed and contact-stabilization processes can also be approximated by delaying feed to the reactor until an aeration period during the react cycle to aerate the RAS has been completed. Similar to taking samples along the plug-flow biological reactor, samples can be taken at different time intervals during the react period and tested for BOD, ammonia, or DO to evaluate the efficiency of the treatment process. Based on these results, aerated and unaerated react times can be adjusted to increase the efficiency of the process.

TRACKING PROCESS PERFORMANCE

INTRODUCTION. With constant changes in the character of municipal wastewater (e.g., flow, BOD, ammonia, phosphorus, materials inhibiting activated-sludge microorganisms, temperature, etc.), along with changes in weather, aging treatment plant equipment (affecting capacity output), and a variety of other factors; variations in activated sludge performance should be expected. While these variations will typically be small and will not result in violations of effluent discharge standards, violations can sometimes occur. Proper tracking of process performance parameters can often alert the operator to these variations while there is still time to correct the problem and avoid discharge violations. Therefore, a good system for tracking process performance is essential to achieving good activated sludge process control.

PERFORMANCE PARAMETERS. Key to a good process performance tracking system is identification of the proper performance parameters to track. At a minimum, variation of those constituents that have permit discharge limitations for the WWTP, such as effluent BOD, TSS, ammonia, or phosphorus should be tracked. These particular parameters, however, may not always be the most sensitive indicators for predicting significant changes in process performance. Parameters that are often more sensitive to predicting process performance variations are trends (either increasing or decreasing) in activated-sludge inventories, biological reactor DO levels, clarifier sludge blanket depths, character changes in the incoming wastewater (such as, pH, alkalinity, BOD, ammonia, temperature, etc.), rain intensity, and air temperature. These and other parameters should be assessed for their appropriate use in tracking the performance of a specific treatment plant. The specific parameters selected for tracking will have a strong effect on the strength of the tracking system, so it is important to carefully consider those parameters that are ultimately selected.

Special Considerations. In addition to the specific performance parameters that are to be tracked, there are special considerations for performance monitoring. The BOD test takes five days, so results from this test will only be available after the event has taken place. Other methods for estimating the BOD will provide more timely information and should be considered. The chemical oxygen demand (COD) test takes approximately three hours to perform, so results can be obtained on the same day. But, operators may need to have results even faster, especially in the event of a process upset. In these conditions, the total organic carbon (TOC) analysis can be performed in 5 minutes. However, to provide a result in 5 minutes, the TOC instrument must be calibrated and ready to run the analysis. Also because of the cost of the instrument, many smaller WWTPs may not be able to afford this test. If the COD or TOC tests are used, they should be correlated to the BOD first for consistency. Note that the correlation factor will be different for each process stream. For example, the plant influent will have a different correlation factor (e.g., BOD:TOC) than the plant's effluent. Therefore, a separate correlation factor should be determined for each process stream.

Instead of an SVI test, the diluted SVI test should be used. When the 30-minute settling test for the SVI is performed, the resulting sludge portion should be less than 250 mL/L. If it is higher, the resulting SVI will be significantly over- or understated, because the sidewall effects of the cylinder used in the test will interfere with the sludge settling and compacting in the cylinder. The interference is negligible when the 30-minute settling test has a sludge portion less than 250 mL/L. Therefore, if the operator observes a sludge portion at 750 mL/L after 30 minutes of settling, the mixed liquor should be diluted proportionally with the activated-sludge process's effluent

and the test run again. If the dilution is correct, the 30-minute settling test should result in a sludge portion between 200 and 250 mL/L. Overdiluting will also produce inaccuracies. It is best to run 30-minute settling tests with 3 or 4 test cylinders simultaneously with different dilutions to obtain the correct result quicker. The results of the test would then have to be proportioned to account for the dilution. For example, if the mixed liquor was diluted with 850 mL/L of effluent and the 30-minute settling test result was 250 mL/L, the actual 30-minute settling result that should be reported and used in the SVI calculation should be

$$X = (250 \text{ mL/L})(1000 \text{ mL}) \div (1000 \text{ mL} - 850 \text{ mL}) = 1667 \text{ mL/L} \qquad (20.13)$$

In this case, the sludge at its original dilution could not settle at all and the 30-minute settling test would have been 1000 mL/L. The resulting SVI if the MLSS was 3500 mg/L would have been 285 mL/g at the original dilution, and 520 mL/g diluted, a significant difference. The diluted SVI is also discussed in Jenkins et al. (1993).

For activated-sludge plants that receive intermittent loads of readily assimilated BOD from food processors, or toxic loads from elsewhere in the collection system, oxygen consumption rates should be tracked. The oxygen consumption rate is determined by measuring the amount of oxygen (with a DO meter) that is consumed by a measured, aerated amount of RAS that has been fed an amount of activated-sludge influent (e.g., raw wastewater or primary effluent) at the same F:M as in the full-scale process. This DO uptake rate (in milligrams per liter of oxygen consumed per minute) is then divided by the suspended solids concentration in the test container (MLSS). For example, 2 mg/L·min of oxygen are consumed in a container of RAS and influent with an MLSS of 1000 mg/L (or 1.000 g/L). The oxygen consumption rate would be 2 mg O_2/g·min, or 120 mg O_2/g·h. This is considered a high oxygen consumption rate and may be caused by a high level of readily assimilated BOD in the wastewater. If the oxygen consumption rate is minimal (e.g., 2 mg O_2/g·h), toxic material would be a likely reason. At extremes such as those discussed it is easy to determine the cause; however, when the difference is small it is important that the operator have a record of oxygen consumption rates taken over time to distinguish between natural variation and pending problems. The oxygen consumption rate would be a good parameter to track with a control chart (see control chart discussion that follows).

DATA QUALITY. Tracking performance parameters with inaccurate data can be worse than not tracking performance parameters at all. It is not only a waste of time and effort, but it can mislead or confuse the operator as to the course of action that should be taken. Therefore, it is important that the integrity of the data is high. This

means good sampling and laboratory techniques are always used, and good quality assurance–quality control programs are consistently adhered to.

CONTROL CHARTS. The most important objectives to tracking process performance are to identify process variations and to distinguish natural variations from variations caused by a significant change to the process, which may include human error or significant equipment, season, or wastewater changes. An effective tool used in many industries for achieving these objectives is a control chart. A control chart is simply a time-series plot of one or more parameters, with three significant lines drawn parallel to the time line on the chart.

The first line, drawn through the middle of the plot, is the average of the individual values taken for a particular process parameter. For example, if the process param eter was the treatment plant's influent BOD concentration, the BOD concentration would be plotted over months or years. The first line would be a running average of those BOD values. With BOD values of 320, 380, 385, 335, 280, and 185 mg/L, this first line would be drawn parallel to the time line and at a BOD value of 314 mg/L (the average of the six BOD values, or X^m). This line is referred to as the center line. The other two lines are called the upper process limit and the lower process limit.

The upper process limit is calculated as

$$\text{Upper process limit} = X^m + (2.66 \times R^m) \tag{20.14}$$

where R^m = the average moving range.

In the above example $R^m = [(380 - 320) + (385 - 380) + (385 - 335) + (335 - 280) + (280 - 185)]/5 = 53$ mg/L. Note that in the above example the smaller of the two numbers is always subtracted from the larger number to give the relative difference or range between the two numbers, not the actual difference. So, in our example the upper process limit = 314 + (2.66 × 53) = 455 mg/L.

The lower process limit is calculated as

$$\text{Lower process limit} = X^m - (2.66 \times R^m) \tag{20.15}$$

In our example the lower process limit = 314 – (2.66 × 53) = 173 mg/L.

The control chart can now be constructed. The control chart will have a time scale on its horizontal (x-) axis, and (for our example) BOD values on its vertical (y-) axis. The BOD values will be plotted along the x-axis with a center line drawn at BOD = 314 mg/L, an upper process line drawn at BOD = 455 mg/L, and a lower process line drawn at BOD = 173 mg/L (Figure 20.20).

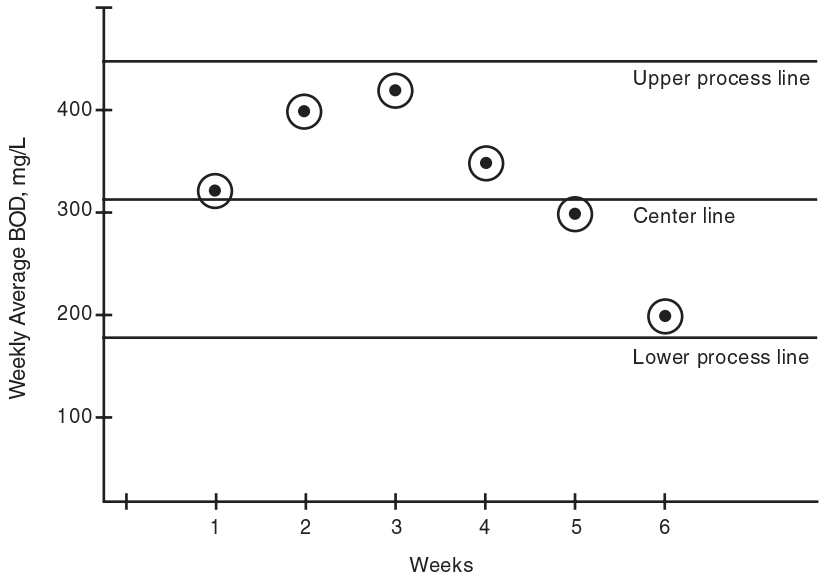


FIGURE 20.20 Control chart sample.

Using The Control Chart To Determine Process Problems. Once the control chart has been constructed, operators can use the following criteria to determine whether a process is out of control or at least deserves closer attention:

- One or more points are greater than the upper process limit or lower than the lower process limit (in our example this would be when the BOD exceeds 455 mg/L or drops below 173 mg/L),
- Nine consecutive points are on one side of the center line (X^m),
- There are six consecutive points increasing or decreasing, and
- There are fourteen points that alternate up and down.

(For more on control charts see Wheeler, 1993, and Brassard and Ritter, 1994)

COMPUTERIZED SPREADSHEETS AND DATABASES. Sophisticated computerized data management tools including spreadsheets and databases can be used to manage the large amount of data that are collected in the operation of a WWTP. These tools can be purchased as general applications that can be customized for a particular WWTP, or as applications already specialized for process control. Because of the frequency at which new applications become available, a review of these

applications is not included here; rather an Internet search is recommended to obtain updated information.

ACTIVATED SLUDGE MODELS

Considering the multitude of microbial and chemical processes that take place in the activated-sludge process, and potential variables that could be present in wastewaters treated by the process, the activated-sludge process is complex. To model the activated-sludge process with mathematical equations is not an easy task. Countless hours have been invested by hundreds of scientists around the world to develop a computerized model that can predict activated-sludge process performance given certain param eters. The early models were relatively simple and inaccurate. Activated-sludge modeling has since progressed to a great extent and now can be a useful tool to both the designer and the operator of activated-sludge processes.

The most well-known activated-sludge models are the International Water Association (IWA) family of activated-sludge models (ASM). The second model (ASM2) (Henze [Ed.], 2000) contains 71 stoichiometric and kinetic parameters, and has been successful in predicting the behavior of the conventional, nitrogen-removal, and phosphorus-removal activated-sludge processes. A third model in the IWA family (ASM3) has recently been released (Henze [Ed.], 2000). Other activated-sludge models are also available in various forms. It is important to ensure that data entered into any model are accurate. Nonetheless, even if the data entered into the model are accurate, the results obtained by the models should be considered as good estimates only. An operator should not expect the predicted outcomes from a model to exactly match actual outcomes.

Clarifier models have also been produced and can be used in conjunction with activated-sludge models.

AUTOMATED PROCESS CONTROL

Nearly every aspect of operating an activated-sludge process can be automatically controlled. Examples of functions that can be automatically controlled include,

- Adjusting the WAS or RAS flow rates to meet process objectives,
- Adjusting aeration systems to maintain a constant biological reactor DO,
- Putting multiple biological reactors in and out of service,
- Diverting more flow to one clarifier or biological reactor than another, and
- Balancing flows among clarifiers or biological reactors.

A wide variety of automated process control equipment and methods are commercially available to accommodate almost every level of need. Single loop controllers can provide good local control for one or more functions while distributed control systems (DCS) can provide for more sophisticated applications.

LOOP CONTROLLERS. Loop controllers are typically used to provide local control for elements within a process. The loop control will typically be fed a signal, or signals, that are compared to preselected settings in the controller. The controller will measure the difference between these settings and the signals received. Based on this difference the controller will send a signal to the process element in the control loop to make some change to reduce the difference between the controller's setting and the signals received by the controller. The method the controller will use to reduce this difference will be any combination of three approaches

1) proportional to the difference,
2) integral to the difference, or
3) based on the rate the difference between setting and incoming signal changes (derivative).

These three methods are called proportional, integral, and derivative; or PID. So, a loop controller is a PID controller. If a loop controller controls only one element of a process it is referred to as a single-loop controller, and if it controls more than one element it is referred to as a multiple-loop controller. An example of an application of a single-loop controller in the activated-sludge process would be the control of a RAS pump to continuously pump at 50% of the wastewater flow entering the biological reactors.

PROGRAMMABLE LOGIC CONTROLLERS. Programmable logic controllers (PLCs) can perform more complex control functions than loop controllers. A PLC is capable of controlling an entire activated-sludge process, taking in signals from measurement devices on different elements of the process, integrating these measurements into complex mathematical relationships, and sending out signals to control equipment to keep the process operating as intended. An example of a PLC application is the complete control of an SBR activated-sludge process. The SBR process relies on using one reactor for both aeration and clarification. Because of this, process steps (including aeration and mixing, and quiescent conditions allowing sedimentation) must be sequenced. These steps include filling the reactor with wastewater, stopping the wastewater flow when target reactor liquid height is reached, and turning on aerators to provide DO and mixing; then during the clarification stage turning off the aerators,

allowing the activated sludge to settle, decanting of the clarified effluent, and then again filling the reactor with wastewater. These steps along with activated-sludge wasting must be carefully timed, adding an anoxic or anaerobic period for nutrient removal adds to the complexity of the operation. This would consume large amounts of labor if performed manually. The PLC is a suitable method for efficiently controlling this process. The advantage over a loop controller is that it is able to control the whole activated-sludge process at a higher level of sophistication than the loop controller. The disadvantages, compared with a loop controller, are that it is typically more expensive and requires a higher technical level to operate.

DISTRIBUTED CONTROL SYSTEM. The distributed control system (DCS) is intended for monitoring and controlling of multiple processes at once. The DCS is composed of a number of separate computers that are distributed to the processes they control and monitor, and are linked to the other computers in the system to perform as an integrated system. An example of a DCS application is the control of an entire WWTP in which the activated-sludge process is one process in that plant. The advantage of a DCS over a PLC is that the activated-sludge process can be controlled in concert with the other processes in the wastewater process train, rather than being operated as a separate system. The disadvantages, compared with a PLC, are that it is typically more expensive and requires a higher technical level to operate.

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Section 4

Energy Management

INTRODUCTION

In recent years, the means of lowering energy costs have become more plentiful. Traditionally, emphasis was placed on demand-side management where the consumer outlined an energy plan to lower demand charges and tried to conserve energy (i.e., use less energy for a given unit of output). It is now possible in several states to choose electric or natural gas service from multiple suppliers. The transition of moving electric and natural gas service to open competition started in the 1980s, expanded rapidly in the 1990s, and will likely be complete by 2010. The states with high energy pricing moved rapidly to deregulate utilities, while the states with low energy pricing are not anxious to restructure the electric and gas service in their states. The passage of a federal bill could accelerate the progress of deregulation, but numerous attempts at the national level have not produced a consensus.

Historically, the major suppliers of energy were investor-owned utilities, municipally owned utilities, and cooperatives. Many states that have passed legislation require their public utilities commissions (PUCs) to make electric and natural gas service more competitive by implementing plans to have multiple suppliers. It should be noted that PUCs only have jurisdiction over the investor-owned utilities and the availability of customer choice is largely limited to former or existing customers of investor-owned utilities. Municipally owned utilities have their own form of governing that sets pricing. Electric cooperatives are likewise self-governed. Some legislation has allowed the municipal utility and the cooperative to be in the competitive energy market if they allow others access to their customer base; that is, they cannot sell to the customers of other suppliers without letting other suppliers compete for their existing customers.

Now, in most states, a complete energy management plan must include the integration of procuring energy in a competitive environment combined with a sound demand-side energy program.

ENERGY COSTS

For most wastewater treatment plants (WWTPs), electric power costs are a significant percentage (25 to 50%) of the plant's annual operation and maintenance (O & M) budget (WEF, 1997b). The activated-sludge treatment process alone typically accounts for 30 to 80% of these costs. This provides an opportunity for various energy conservation techniques and significant and effective cost reductions to be implemented.

Lowering energy costs requires a complete understanding of how energy is metered and billed. Using a sound approach to end-use profiling is fundamental to lowering energy costs. Such an approach must have a means of base-lining the pattern of plant energy consumption under the existing operating mode and a means of determining how operating, process changes, or energy efficiency initiatives in the plant affect each part of the energy bill. Some parts of the bill cannot be removed by new initiatives and may result in achieving less savings than expected when the change has been completed. New metering and supervisory control and data acquisition (SCADA) products should be used to provide real-time data for the total plant demand and for the individual pieces of equipment being studied. The implementation of additional instrumentation and sound end-use profiling can make cost reduction more understandable and easier to implement.

Electricity pricing is typically broken up into a customer charge, a demand charge, and an energy charge. Because of deregulation, some of the traditional items will be replaced or modified.

The customer charge is a fixed fee each month to administer the account. The customer charge reimburses the utility for operating a call center, reading the meter, and billing. Under deregulation this fee is gradually being phased out.

Demand charges are measured and billed on a kilovolt-ampere (kVA) basis for larger deliveries or a kilowatt (kW) basis for medium- and small-sized deliveries. Actual demands are metered and read on approximately 30-day billing cycles. Typically, the demand charges depend on time periods, although, some rate schedules do not differentiate for any time parameters. Often as many as four different pricing periods for demand billing are used. Billing for demand can depend on minimum billing provisions, some percentage of demand set in the last 11 months, or the actual demands set during the month. The service provider uses the larger of these variables to bill demand charges.

If the metering is done on a kilovolt-ampere basis, both the real and reactive energy is measured and billed to the customer. There will not be power factor penalties billed in this case. If the metering is done on a kilowatt basis, only the real energy is measured and the utility supplies the reactive energy without compensation. If the power factor or the supply of free reactive energy becomes unacceptable, the utility bills power factor penalties to correct for the loss of energy being left out of the metering.

Energy is billed on a megajoule (MJ) (kilowatt-hour, kWh) basis. In the traditional billing, energy costs include the variable production cost of providing energy and the fuel cost of providing energy. Fuel is a significant expense in providing energy and under the traditional monopoly arrangement utilities received direct reimbursement for this item. As utility deregulation moves forward, the fuel charge is being phased out of the energy pricing and the billing.

Under deregulation, pricing is expected to include generation services, transmission services, distribution services, marketing fees, and other necessary fees. Pricing for generation and marketing fees is likely to be flexible and will be established between the provider and the consumer. Pricing for transmission, distribution, and other necessary fees is likely to be based on megajoules and will be established by the U.S. Federal Energy Regulatory Commission and state PUCs.

During the transition to a deregulated energy market, the pricing of energy stabilized in the 1990s. Industry experts project improvements in pricing as more of the nation makes the transition to a competitive energy industry. Some experts predict as much as a 20% reduction in actual unit costs in the next decade. Energy costs in the past depended on cost-of-service criteria. In the future, energy pricing will be more market driven and will reflect a more commodity-based phenomenon. Because commodities widely fluctuate over time, knowledge of local energy pricing and use of good procurement practices to keep costs optimized is a must for plant management.

Deregulation in the energy industry has encouraged the development of new products and services to meet energy management needs. Retail electric or natural gas providers must be registered with the PUC in each state. Wastewater facilities can often obtain information from the PUC on whether a choice of energy suppliers is available to them and who those suppliers are.

Wastewater treatment plants can receive assistance with energy management, services, and products from consulting engineers, energy services companies, and manufacturers. Most of the participants in the energy industry have reinvented or modified their service offering or product line to make energy management easier and more cost-effective in a deregulated marketplace.

ENERGY USE IN WASTEWATER TREATMENT PLANTS

Energy use in WWTPs is significantly affected by

- Plant size,
- Location,
- Wastewater characteristics,
- Level of treatment,
- Energy conservation and recovery strategies used,
- Type of treatment processes selected, and
- Mode of operation.

Although it is difficult to define typical energy consumption values, average energy-use data provides a base line for comparison.

Figure 20.21 presents the range of energy consumption for different treatment processes in the western United States. The effect of treatment process on energy con-

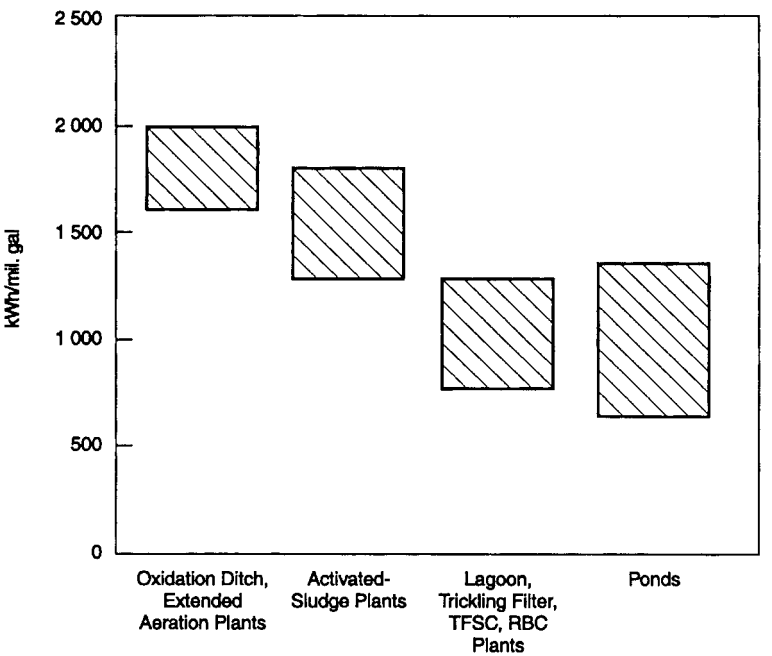


FIGURE 20.21 Typical energy consumption of various wastewater treatment processes (kWh/mil. gal $\times$ 951.1 = J/m^3)(TFSC = trickling filter solids contact and RBC = rotating biological contactor).

sumption is apparent. Typically, lagoons and attached-growth systems consume less energy than suspended-growth systems (WEF, 1997b).

A survey of 25 WWTPs, located on or near the eastern coast of the United States, provided average energy consumption presented in Table 20.2 (Hermann and Jeris, 1992). All were activated-sludge facilities that ranged in capacity from 9800 to 1.147×10^6 m^3/d (2.6 to 303 mgd). Of the 25 plants, 18 were conventional facilities, 3 were step-feed facilities, 3 included nitrification, and 1 used pure oxygen. The survey indicated that, regardless of the plant size, a base or minimum energy of 117 to 130 billion kJ/a (111 to 120 billion Btu/yr) was needed for space heating and lighting.

Figure 20.22 shows energy requirements for an activated-sludge system as a percentage of total plant energy consumption for various plant sizes. The activated-sludge system components include aeration, return sludge pumping, and secondary clarification.

As expected, nitrification facilities are associated with larger energy input because of increased aeration requirements. The data also reveal that for plants smaller than 57 000 to 80 000 m^3/d (15 to 20 mgd), the energy used by the activated-sludge system, expressed as a percentage of the total plant energy, is strongly affected by plant capacity. For larger plants, the fraction of the total energy consumed by the activated-sludge system is relatively constant.

ENERGY SAVING OPPORTUNITIES

PROCESS CONSIDERATIONS. ***General***. Informed and timely process control decisions could result in significant energy savings. Often, this entails alternative thinking to optimize the process and to overcome the temptation to continue current plant operation. In this section, key process considerations that could result in significant energy savings are discussed.

TABLE 20.2 Average total energy consumption.[a]

Basis	Value
Influent flow	1 394 kJ/m^3
Influent suspended solids	12 550 kJ/kg TSS
Influent BOD[b]	13 015 kJ/kg BOD
Air supply	331.6 kJ/m^3
Sludge production	793 645 kJ/m^3
	26 523 kJ/kg

[a]Includes pumping, aeration, heating, and lighting.
[b]BOD = biochemical oxygen demand.

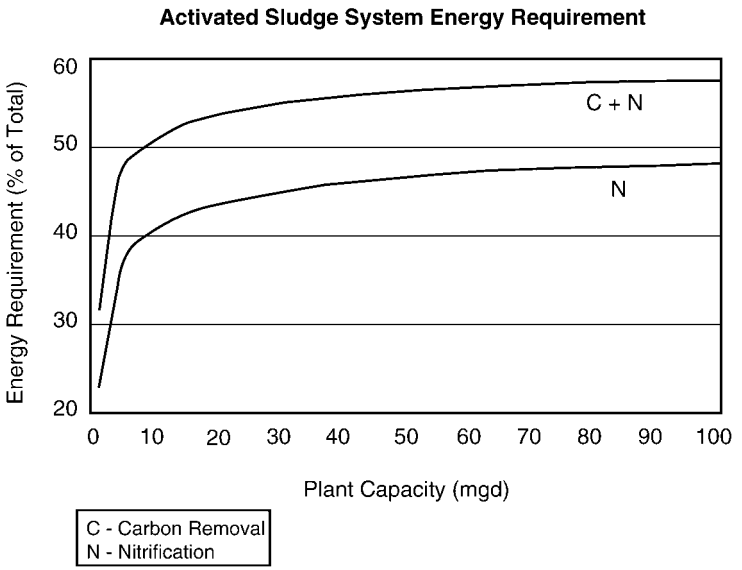


FIGURE 20.22 Activated-sludge system energy requirements (mgd $\times$ 3785 = m^3/d).

Number of Reactors. Plants are often placed online with excess capacity to accommodate future growth, allow for industrial loadings, or simply to provide the redundancy required for reliability. Consequently, activated-sludge systems are often underloaded. If the loadings to such facilities can be increased to optimum levels, significant energy savings may be realized.

If the plant has two or more biological reactors in service, an assessment should be made of the effect of taking one reactor out of service on the food-to-microorganism (F:M) ratio, mean cell residence time (MCRT), hydraulic retention time, waste sludge production, mixed liquor suspended solids, and the ability to maintain adequate dissolved oxygen (DO). Many plants can often function equally well by reducing aeration capacity.

Reactor Design. Based on waste-load distribution, the activated-sludge system may be complete mix, plug flow, or step feed. In complete-mix systems, the influent wastewater is instantaneously and uniformly distributed throughout the reactor tank. Plug-flow reactors receive the entire waste load at the upstream end. In step-feed configurations, the feed is distributed at several points along the length of the reactor tank. Accordingly, the concentration profiles and the degree of treatment will vary. The degree of treatment increases uniformly along the flow path in a plug-flow arrangement, increases in stages in a step-feed system, and remains uniform throughout the complete-mix reactor.

The field oxygen-transfer efficiency (OTE) improves with the degree of treatment. The field OTE has been observed to increase along plug-flow reactors, paralleling the improved degree of treatment. However, the increased potential for slimming of fine-bubble diffusers in plug-flow applications may decrease the OTE.

Operating in the step-feed or complete-mix modes may result in lower overall alpha factors (which account for the effects of process water characteristics on OTE) by distributing surfactants more uniformly throughout the biological reactor and achieving effective dilution. A study conducted in Madison, Wisconsin, demonstrated the benefit of improved alpha in step-feed systems (WEF, 1997b). Despite slimming potential, plug-flow systems have been credited with improved alpha along the length of the reactor (WEF, 1997a).

Nitrification. Unnecessary nitrification is probably the largest aeration system inefficiency. Typically, nitrification occurs when the system is operated at long solids retention times and a low F:M.

The potential effect of nitrification on oxygen requirement may be demonstrated by assuming nitrifying and nonnitrifying systems with F:Ms of 0.1 and 0.3, respectively, biochemical oxygen demand and an ammonia-nitrogen concentration equal to 10% of the biological oxygen demand (BOD) concentration. As shown in Table 20.3, the nitrifying systems will have, in addition to the nitrogenous demand, a carbonaceous demand that exceeds that of the nonnitrifying system. Consequently, for the example considered, the total oxygen demand of the nitrifying system is approximately 88% higher than the nonnitrifying system.

Partial nitrification is difficult to prevent, particularly in the warmer months. The most effective operating strategy is to maintain the highest possible F:M that will achieve the desired BOD removal while not allowing the mixed liquor DO to exceed 2 mg/L through proper DO control. However, few facilities are equipped with the necessary instrumentation and automation to accomplish this.

Denitrification. While nitrification exerts an oxygen demand, denitrification provides an opportunity for partial oxygen recovery. The oxygen credit that can be obtained is a

TABLE 20.3 Effect of nitrification on oxygen requirements.

		g O_2/kg BOD (lb O_2/lb BOD)		
Process	**F:M**	**Carbonaceous**	**Nitrogenous**	**Total**
Nitrifying	0.1	1 310 (1.31)	460 (0.46)	1 770 (1.77)
Nonnitrifying	0.3	940 (0.94)	0.00	940 (0.94)

function of denitrification efficiency, which is related to the internal mixed liquor recirculation (IMLR) and return activated sludge (RAS) ratios. For a predenitrification system (e.g., University of Cape Town [UCT], Virginia Initiative Process [VIP]), the following applies:

$$\text{Denitrification efficiency} = 1 - [1/(\text{IMLR} + \text{RAS})]$$

At a RAS ratio of 100%, the above expression reduces to

$$\text{Denitrification efficiency} = 1 - [1/(\text{IMLR} + 1)]$$

The practical limit on the IMLR rate is approximately 300 to 400%. At higher rates, the danger of DO transfer to the anoxic zone exists. The theoretical maximum denitrification efficiency at 300% IMLR rate is approximately 75%.

The above discussion does not consider denitrification that may occur in the final clarifiers and in the aerobic zone caused by low-DO conditions or in floc particles. As a result, higher denitrification efficiency than predicted by the above theoretical considerations is often observed in full-scale facilities.

As shown in Figure 20.23, the percentage of the total oxygen requirement that can be recovered from denitrification is a function of the denitrification efficiency. An influent BOD of 150 mg/L and oxidizable total Kjeldahl nitrogen of 30 mg/L were assumed

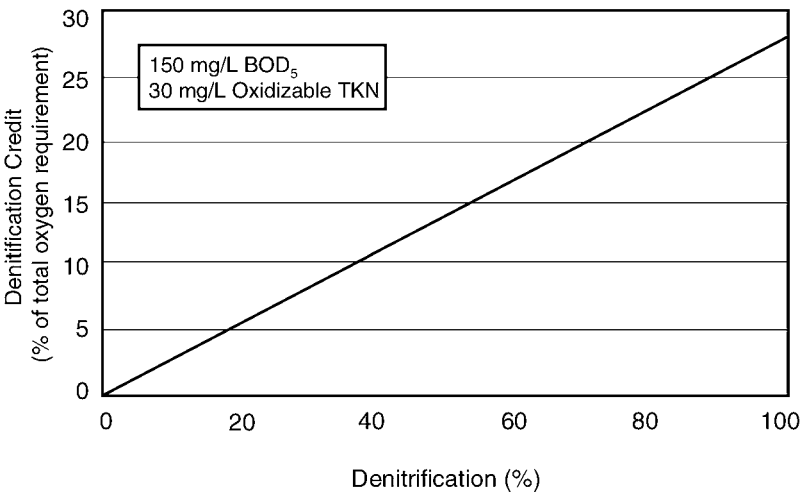


FIGURE 20.23 Denitrification credit as a function of denitrification efficiency (BOD_5 = 5-day biochemical oxygen demand and TKN = total Kjeldahl nitrogen).

in developing the total oxygen requirement. It should be noted that process configurations incorporating postdenitrification, such as the 4-stage Bardenpho™ process, are capable of achieving greater than 75 to 80% denitrification efficiencies.

Dissolved Oxygen Levels. Many facilities overaerate the mixed liquor because of a lack of automation or because it represents a safe practice. Overaeration results in energy wastage and poor sludge settleability. Figure 20.24 shows that it takes twice as much power using air to transfer a unit mass of oxygen to the mixed liquor at a DO of 5 mg/L as it does at a DO of 2 mg/L (Norris, 1982). This is because the driving force for oxygen transfer is the DO differential

$$\text{Oxygen transfer rate} \propto (DO_{sat} - DO_{actual})$$

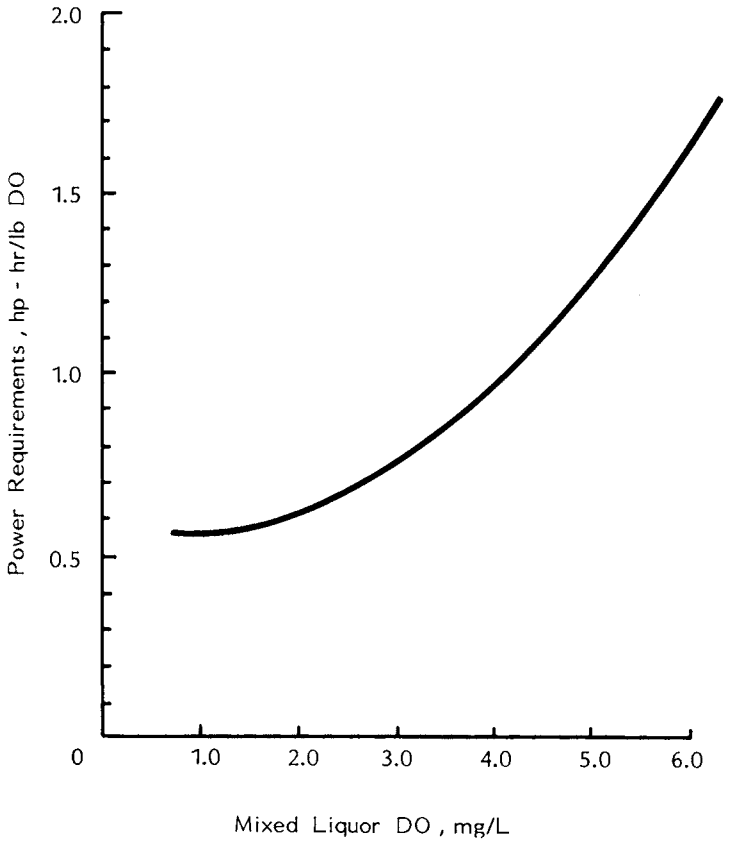


FIGURE 20.24 Power requirements as a function of mixed liquor DO (hp-hr/lb DO × 5.919 = mJ/kg).

If the mixed liquor DO (DO_{actual}) is higher, the differential will be lower, and the transfer rate will be slower. The figure also shows that minimum energy use is achieved by maintaining mixed liquor DO at the minimum value consistent with process needs. For a normal activated-sludge facility, this value is typically between 1.5 and 2.5 mg/L. Because daily variations in organic loading to the plant will be greater than daily variations in plant flow, air requirements may be substantially lower during the night and early morning hours than during the late afternoon and early evening.

Optimizing Mean Cell Residence Time. Unless nitrification is desired, it is essential to control the activated-sludge MCRT to realize associated energy savings. At MCRTs of 6 to 10 days and wastewater temperature of approximately 20 °C (68 °F), substantial carbonaceous BOD will be satisfied. Nitrification will be initiated as the MCRT approaches 8 to 10 days. The rate of nitrification will be faster in warmer climates and slower at colder temperatures, but at an MCRT of 20 days, nitrification will be substantially complete. The power required to satisfy the carbonaceous BOD is 30 to 40% less than the power required to satisfy both carbonaceous and nitrogenous demand. By maintaining the MCRT between 6 and 7 days, maximum carbonaceous BOD reduction can be achieved at moderate wastewater temperatures with minimum power.

Optimum MCRT varies from plant to plant and depends on wastewater temperature. By monitoring the nitrite and nitrate levels in the influent and effluent, it is possible to determine quickly and accurately when nitrification is taking place. The MCRT should be gradually reduced until nitrification stops and effluent limits with respect to BOD are met. This operating condition is associated with minimum aeration energy.

It is imperative to note that as the MCRT decreases, sludge production will increase and poor settling sludge (higher sludge volume index) will be encountered.

Volumetric Power Input. The amount of power input to the biological reactor must be sufficient to mix and transfer oxygen. As shown in Figure 20.25 (Grady et al., 1999), a minimum power input is required to keep the solids in suspension. Conversely, if the volumetric power input exceeds a maximum value, floc shear is likely, resulting in poor settleability. Typically, the downstream end of a biological reactor would be mixing limited if tapered aeration is provided and the air supply is turned down to maintain low-DO conditions.

Table 20.4 summarizes power-input guidelines for activated-sludge systems (Grady et al., 1999).

EQUIPMENT OPERATIONS. *Aeration System Components.*

The total capacity of aeration equipment in North America was approximately 1.3 million kW in 1982 (WEF, 1997b). Aeration consumes 40 to 70% of the energy used in an activated-sludge

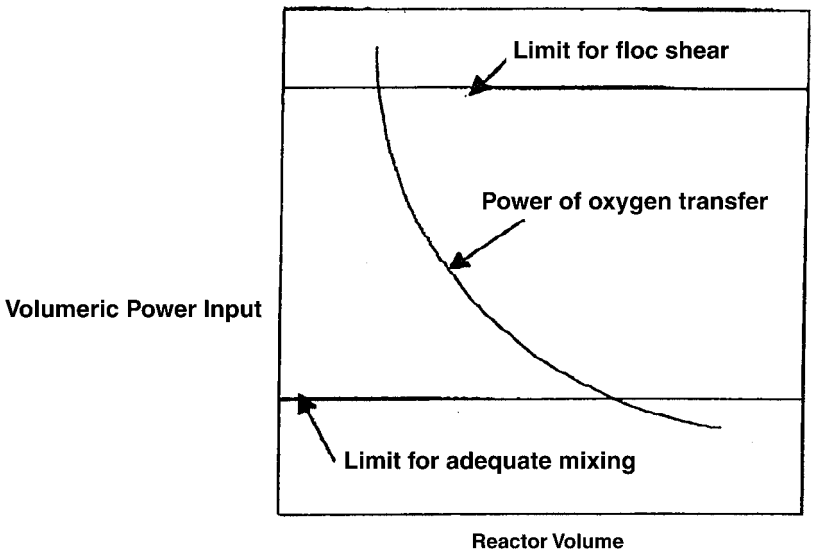


FIGURE 20.25 Volumetric power requirements (Grady et al., 1999).

plant. Effort and expense directed toward improving and maintaining aeration energy efficiency can be cost-effective.

The aeration equipment must provide adequate air to keep the mixed liquor suspended and the DO within the optimum range. The transfer of oxygen from air to wastewater is inefficient and energy-intensive. The ability of any equipment to dissolve oxygen in wastewater will depend on many factors, including diffuser type, basin geometry, diffuser depth, temperature, ambient air pressure, diffuser layout, and variations in wastewater characteristics.

MECHANICAL AERATORS. Unless variable-speed drives are provided, mechanical aerators have limited turndown capability. Consequently, energy-saving opportunities

TABLE 20.4 Volumetric power requirements.

System	Mixing (minimum per 1000 m^3)	Floc shear (maximum per 1000 m^3)
Diffused aeration (m^3/min)	—	90
Spiral roll	20	—
Full floor cover	27	—
Mechanical aeration (kW)	60	90

are not significant. Mechanical aerator output is typically adjusted by raising or lowering the biological reactor weirs to adjust impeller submergence. The power draw of the aerator will vary substantially as weir elevations change. Laminating and posting a plot of the amperage change in the aerator versus weir settings will be useful to the operators.

Although frequent weir adjustment is cumbersome, it is often worthwhile to lower the weirs at night or during weekends to coincide with low-loading periods, and raise them in the mornings or at the beginning of the week to cope with higher loadings.

Many plants have two-speed or variable-speed mechanical aerators. At these plants, operators should try to operate at low speed whenever possible, making coarse adjustments with aerator speeds and fine-tuning weir elevations.

Operating mechanical aerators on timers can be effective. Some negative results, however, include

- Solids settling and the inability to fully resuspend the settled solids,
- The possibility of developing anaerobic conditions if the loading is high or the aerator shutdown is too long,
- Increase in peak demand charge if several aerators are started in a short time, and
- The potential for increased wear on gear reducers because of frequent starts.

DIFFUSED AERATION SYSTEM. Diffused aeration is the most common method of delivering the required air at municipal WWTPs. Several factors affect the energy efficiency of diffused aeration systems.

Alpha. The alpha factor accounts for the effects of process water characteristics on OTE. Surfactants, such as detergents and dissolved and suspended solids, affect the alpha value. Iron and manganese also affect the alpha value (U.S. EPA, 1989).

Tank Depth. Deeper tanks enhance OTE by providing longer rise time and greater hydrostatic pressure on the bubbles, both of which hasten oxygen transfer. However, deeper tanks need larger compressors to energize the air. This increases capital and maintenance costs. In practice, site conditions determine tank depth more than energy efficiency. Figure 20.26 plots results of clean water tests of various aeration devices at different depths. Some devices show relatively constant energy efficiency with varying depth (WEF, 1997b).

Bubble Size. Diffusers with finer pores tend to produce higher values of standard OTE. However, reduction of the pore size may not always translate into overall energy savings

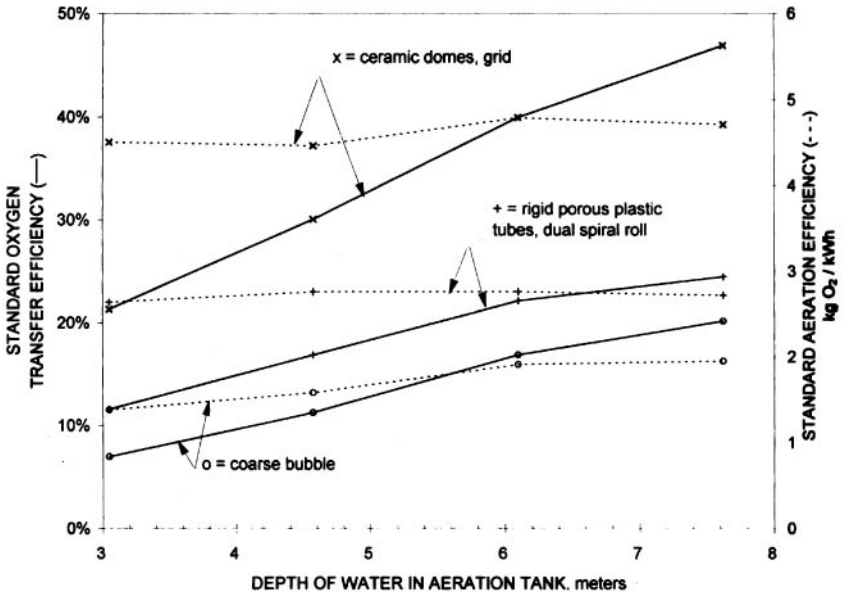


FIGURE 20.26 Comparative energy consumption for various diffusers.

because larger blowers would be required to overcome the associated increase in pressure differential across the fine-pore diffusers.

Airflow Rate. Airflow rate per diffuser is critical for all diffuser types. Insufficient airflow can cause clogging of the diffuser and solids-settling in the tank. Too high an airflow rate causes transfer efficiency to be lowered in fine-bubble diffusers. This is because of increased vertical velocity currents that result in faster rising bubbles. In addition, higher airflow rate corresponds to greater energy input. In the case of coarse-bubble diffusers, the OTE is substantially independent of the airflow rate. However, their OTEs are less than those for fine-bubble devices.

Diffuser Density. Diffuser density is expressed by the number of diffusers per unit area of basin (AD/AT factor). Typically, higher AD/AT values will result in higher OTE. This implies that densely packed and lightly loaded diffusers tend to be more energy efficient. For fine-pore diffusers, installing the maximum number of diffusers and operating them at or near constant optimum flow should be considered.

Fouling. Fouling of fine-pore diffusers is caused by biofilm growth and deposition of inorganic precipitates. Fouling alters the operating characteristics of the diffusers and

lowers the OTE. Airside fouling is caused by unclean air, which may contain dust, dirt, oil particles from blowers, and rust and scale from air pipes. Liquid-side fouling is caused by wastewater constituents. The most typical indicator of fouling is a rise in backpressure. However, it is possible to encounter a significant lowering of the OTE without a corresponding increase in the backpressure.

With diffused aeration, power can be reduced by turning off individual blowers, changing the blower speed or by throttling the inlet valve or vanes on centrifugal blowers. As shown in Figure 20.27 (Campbell, 1984), throttling valves on the outlet side of the blower consumes more energy than inlet throttling and may generate dam-

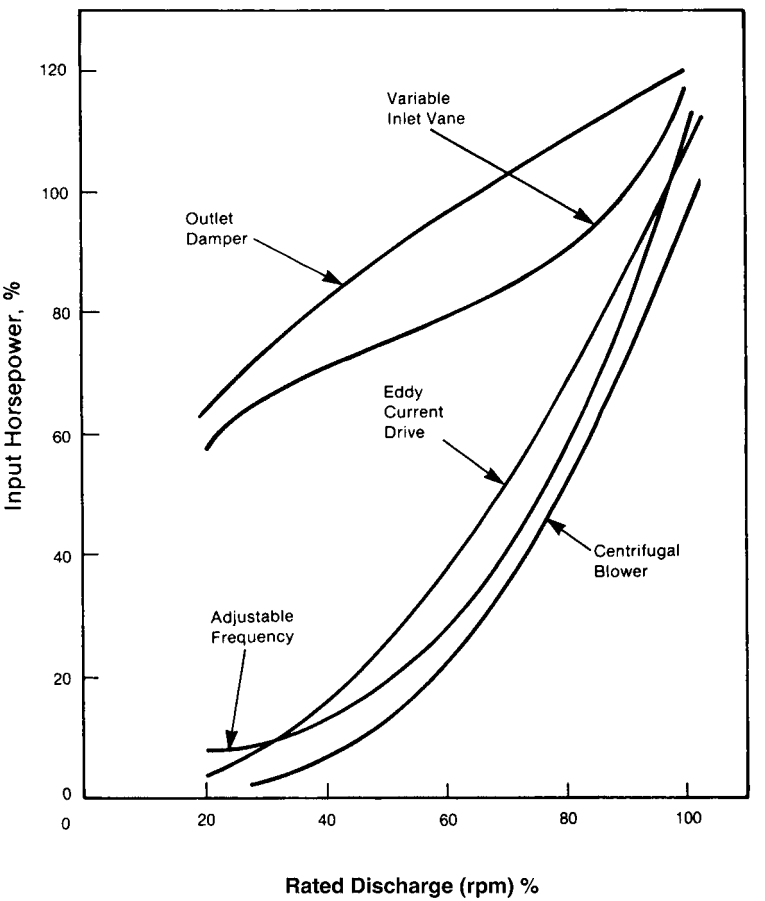


FIGURE 20.27 Typical power consumption for a variable airflow system (hp × 745.7 = W and rpm × 1.000 = r/min).

aging heat. Likewise, when variable-speed drives are DO-controlled, significant energy savings are possible while meeting process demands (U.S. EPA, 1976). A discussion on variable-speed drives can be found in the *Prime Movers* manual (WPCF, 1984a).

It is possible to provide supplemental mixing more efficiently with equipment specifically designed for that purpose (e.g., as submersible mixers) than with diffused air. Such combinations would allow the aeration device to be turned down, resulting in an overall decrease in power requirements.

Diffuser efficiency improvements can result in significant power savings. Factors affecting OTE were discussed previously. Oxygen transfer increases significantly with an increased amount of diffusers and their location in the biological reactor. Some plants have achieved significant cost savings by rearranging air diffusers to accommodate changes in process configuration, for example, from plug flow to reaeration and step aeration. Others have reduced air use by changing from spiral-roll to full-floor coverage.

Recent improvements in diffuser design make retrofitting of existing coarse diffusers with fine-bubble diffusers, both practical and cost-effective. In one plant the change over to new diffusers resulted in savings of more than $100,000 per year, and a payback period of less than 4 years for the initial investment (Finger, 1983).

Switching from coarse- to fine-bubble system requires the following considerations:

- Need of air filtration upstream from the blower,
- Effect of blower backpressure,
- Adequacy of the blower to meet increased head requirements,
- Need for piping modifications,
- Fouling potential,
- System monitoring for fouling,
- Need for routine cleaning, and
- Increased cost of operation.

Pumping Equipment. Pumping facilities associated with the activated-sludge process include

- Intermediate or primary effluent pumps,
- Return activated sludge pumps,
- Waste activated sludge (WAS) pumps, and
- Internal recycle pumps.

Typically, reducing the pump head by 0.3 m (1 ft) can save approximately USD $\$0.0304/m^3/d$ (USD $115/mgd) in annual power usage costs alone (at an electricity cost of USD 0.14/MJ [USD $0.5/kWh]) (Finger, 1983).

INTERMEDIATE OR PRIMARY EFFLUENT PUMPS. Intermediate pumps are typically designed to maintain a continuous variable liquid flow to the system. The method of achieving this variability, as shown in Figure 20.28, can be inefficient (discharge valve control or magnetic clutch slip control) or efficient (solid-state variable frequency control) (Campbell, 1984). Additional information on these drives can be found in the *Prime Movers* manual (WPCF, 1984a).

The following operating modes of the intermediate pumps may help to conserve energy use:

- Operate the pumps as close to design capacity as possible (e.g., attempt to run two pumps at 90% capacity rather than three at 60%).
- Adjust level controllers to minimize pump cycling and to smoothen the flow.
- Use capacitor correction (on larger pumps) to improve power factors.

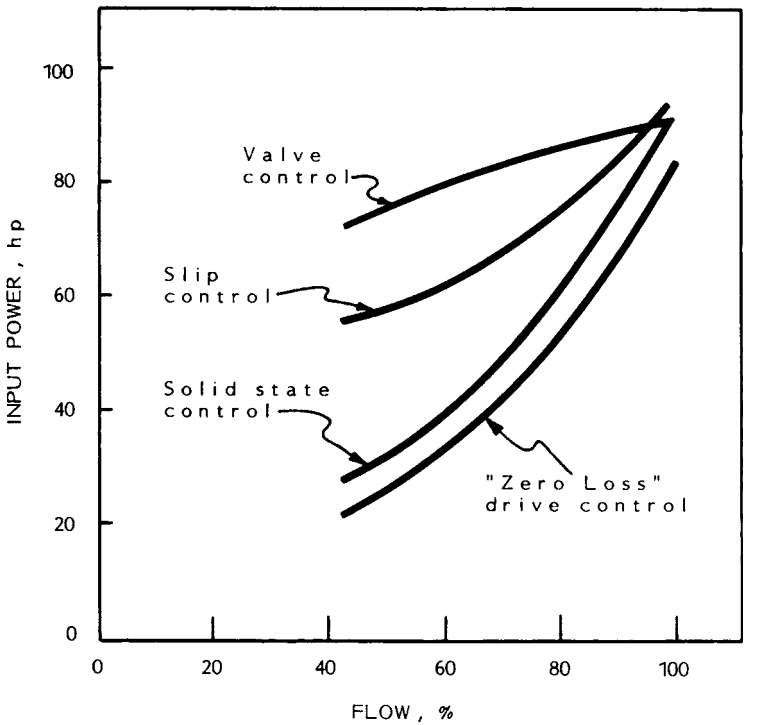


FIGURE 20.28 Typical power consumption for a variable liquid flow system (hp × 745.7 = W).

- Reduce impeller size if operating consistently at the low end of the capacity range.
- Use variable-speed drive or multispeed substitutions for fixed-speed installations where flows vary widely.
- Operate the pumps with minimum drawdown or maximum suction head from optimum upstream hydraulic flow conditions. Figures 20.29 and 20.30 show such an operation with a 1200-mm (48-in.) influent sewer that results in horsepower savings of 15 to 20% (Hermann and Jeris, 1992). The result is that the operating level of the wet well is raised, backing up flow into the influent sewers. Although significant energy can be saved if the sewer is flat, additional sewer maintenance problems may be caused by lower velocities.
- Replace inefficient motors with premium units. The power utility may have a rebate or grant program to aid in replacement.

Additional savings may be realized from associated fuel adjustment cost savings and peak power demand shaving.

RETURN ACTIVATED SLUDGE PUMPS. Typically, RAS pumps are not high-energy users because of their low heads. However, if they continuously operate at high return rates (70 to 100% of the influent flow), as would be the case with extended aeration

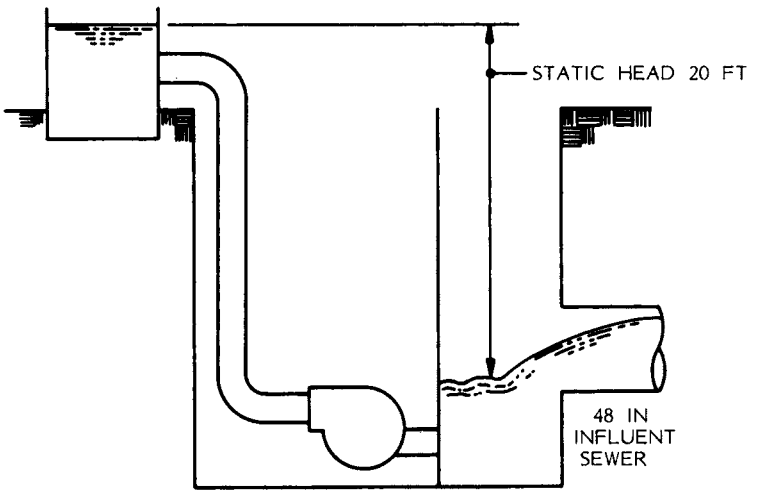


FIGURE 20.29 Influent plumbing—Original drawdown (ft × 0.3048 = m and in. × 25.40 = mm).

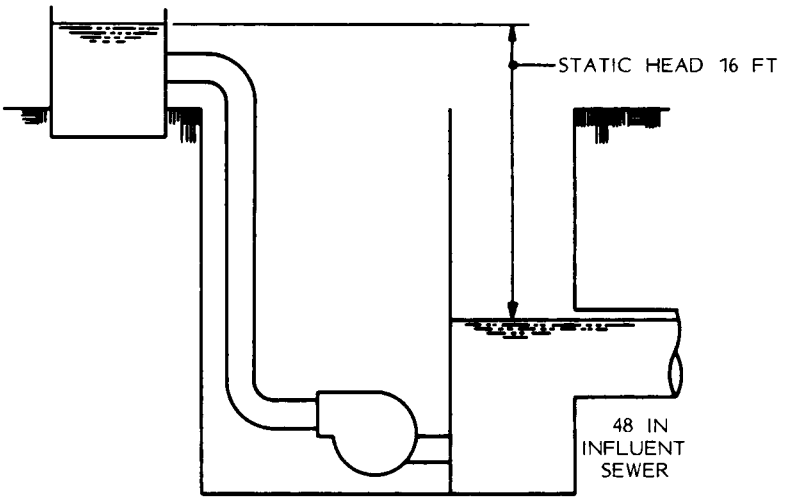


FIGURE 20.30 Influent plumbing—Modified drawdown (ft × 0.3048 = m and in. × 25.40 = mm).

processes, their energy use will be significant. Key factors for operating these pumps to conserve energy include

- Avoiding, where possible, operating with throttled discharge valves;
- Basing flow-paced RAS pumps on activated-sludge process influent flow rate. Use variable-speed drives where possible. Multispeed units are acceptable but will not provide the same level of flow control as variable-drive units;
- Reducing impeller size if operating consistently at the low end of capacity range;
- Using capacitor correction (for larger pumps) for power factor correction; and
- Using, where possible, individual RAS pumps for each clarifier so the pump can operate with the full tank head as its suction pressure. Such systems will work reliably with submerged hydraulic and plow-type sludge removal mechanisms in the clarifiers.

Some plants may use screw pumps for the RAS system. These pumps are efficient and if designed and operated correctly, would incur low maintenance costs.

WASTE ACTIVATED SLUDGE PUMPS. In an activated-sludge system, the amount of sludge wasted is typically 1 to 3% of the influent flow. However at many facilities,

wasting is not a continuous operation. Consequently, the wasting rate could be 10 to 15% of the influent flow if wasting is carried out for 5 minutes every hour.

The WAS pumps are associated with relatively low energy use. Efficient operation entails using variable-speed WAS pumps to draw waste sludge from common discharge headers off individual RAS pumps.

The WAS pumps are also good candidates for load shedding. Sludge wasting, if not detrimental to the process, can be accomplished during nonpeak hours when peak demand charges or ratchet clause effects are smaller. Priority load shedding reduces peak demand by turning off or keeping off loads that are not critical to the process or system operation.

INTERNAL RECYCLE PUMPS. The various biological nutrient removal (BNR) process configurations use IMLR pumps. These pumps are typically low-head, high-flow (100 to 400% of influent flow) pumps that operate continuously. Although energy savings can be achieved by using variable-speed motors, many facilities find the use of two-speed pumps to be adequate. Pump selection should be based on a life-cycle cost analysis.

Clarifiers. Clarifier drive motors are typically insignificant energy users in an activated-sludge process. Thus, a decision to place units in service or take them offline should be based strictly on maintenance or process control considerations and not on any anticipated energy savings. Variable-speed drives can provide more flexibility to operate sludge removal systems.

Equipment Start-Up Procedures. Careful equipment startup procedures can produce significant savings. For example, after transfer of power from normal to emergency service or viceversa, certain equipment (with maintained contact starting controls) will automatically restart. This can exert a high instant demand on the electrical system. Delayed and staggered restarting of other (nonautomatic restarting) equipment should be practiced where possible to minimize the peak demand (Smith, 1981). This may be achieved automatically by installing time delays, however, these units should be tagged as automatic start equipment for operation safety. While energy conservation may not be a high priority during emergency power transfers, it should be considered when periodically testing the emergency power service and routinely transferring lead equipment.

In most areas of the United States, plants pay a surcharge for peak power demand. This is especially true during periods coinciding with the utility's peak power demand (WPCF, 1984a). To minimize these surcharges, multiple large motors should not be operated together for any significant time. Often, even 10 to 15 minutes of peak power will be sufficient to affect power cost for the entire billing period (Norris, 1982).

AUTOMATIC SENSORS AND CONTROLS

GENERAL. Automatic sensors and controls can be key tools in conserving power. Earlier, under "Process Considerations", the monitoring of DO concentration, elimination of unnecessary nitrification, and incorporation of dentification were shown to be valuable methods of assuring minimum energy use. Under "Equipment Operation", methods for controlling mechanical aerator submergence, blower output, and pumping rates were also highlighted. All of these monitoring and control methods are adaptable to continuous automatic operation. Dissolved oxygen control loops for aeration blowers and mechanical aerators, and flow-matching or flow-pacing pump operations are examples of such control strategies.

Monitoring and control equipment can be extremely helpful, but must be properly installed, calibrated, debugged, and maintained; so there are trade-offs for the energy they save. Whenever a facility makes a decision to use automated systems or controls, it must also be prepared to give these controls an environment where they can function properly. For example, eddy current drive controls and variable-frequency drive components are solid-state, and like computer components they should not be installed under dusty or moist conditions, or in areas where hydrogen sulfide can cause erosion.

A facility must also devote the resources, either in-plant or by contract, to routine maintenance and system repair. Maintenance of this type of equipment requires highly skilled technicians and can be expensive. Some facilities have installed these devices in areas where necessary protection has not been given, resulting in severe problems. Conversely, where properly installed and adequately maintained, the equipment has given many years of trouble free and useful service.

DISSOLVED OXYGEN CONTROL. Dissolved oxygen control loops for aeration blowers have been effective. Some plants have had successful automatic sensors and control combinations working for more than 10 years (Finger, 1983). Routine maintenance is required to keep the sensors calibrated, and careful attention to instrument operation is necessary to ensure smooth transfer of the DO measurements to blower control. This is especially important when multiple biological reactor passes and multiple blowers are involved.

Biological reactor DO may be controlled by adjusting individual airflow control valves located on the aeration drop pipe. In this approach, reactor basin DO is measured at several locations and the corresponding air control valve is adjusted manually or automatically to maintain the established DO set point. Manual adjustment is simple and inexpensive but would result in overaeration or underaeration. Automatic control modulates the airflow on a continuous basis to match the demand. Consequently, overaeration and underaeration are avoided.

In conjunction with reactor DO control, aeration blowers may be operated in several modes that may be classified as manual or automatic control. In manual control, the operator opens or closes the inlet valves on centrifugal blowers. Typically, this is done on an as-needed basis and results in periodic overaeration. Automatic control of blower capacity (blower speed or number of online blowers) may be achieved based on main air header pressure. In the most common automatic mode, air capacity is varied around an operator-set air header pressure. For example, increased air demand will result in reduced air header pressure, which will trigger an upward adjustment of the airflow to reestablish the preset header pressure.

A more sophisticated automatic control strategy called most-open-valve control, which ensures the lowest possible air header pressure, is available (Vintor and Mace, 1998). Blower power is proportional to mass flow and differential pressure. Thus, to achieve energy savings, it is important to optimize both the discharge pressure and airflow. The valve position of each airflow control valve is transmitted to the blower control panel. The control panel then adjusts the set point of the air header pressure to the lowest pressure commensurate with the most-open valve position. Implementation of this strategy will require determination of minimum and maximum air header pressure, airflow, and valve positions during startup.

Positive displacement blowers can be adjusted by changing blower speed or by varying the number of blowers online.

Direct DO control of mechanical aerators has not been as successful. In most cases, DO monitoring and manual or computer strip plotting is used with adjustments made manually to the tank level, aerator speed, or number of aerators in service, based on this continuous information. However, some automatic systems have been installed.

Any type of DO control system depends heavily on the DO sensors for success. Fortunately, DO sensors have been improved. Some of the more recent units, equipped with continuous-cleaning mechanisms, have significantly reduced the need for routine maintenance and, more importantly, for energy conservation, have increased the accuracy of DO measurement. A study at the Renton plant in Seattle, Washington, indicates that the cost of retrofitting the plant with these newer sensors can be recovered in 3 years, based on maintenance costs. Savings in aeration blower operation as a result of the increased accuracy in DO measurement should reduce this payback period even further (Finger, 1983).

PUMP CONTROL. Flow-matching and flow-pacing sensors and controls have been used by industry and WWTPs for years. With the advent of highly efficient variable-frequency electric motor speed controls, an automatic sensor and control system should be used for intermediate, RAS and WAS pumping systems. Continuous,

smooth flow transitions through an activated-sludge process not only provides a better environment for the bacteria to grow, but less energy is required to maintain the process. Air-bubbler, capacitance-probe, or float-level sensors are all reliable and adaptable to the liquid involved in these pumping systems. A key element often underrated for these systems, however, is the flow measurement. Flow for most activated-sludge processes can best be measured with magnetic flowmeters, ultrasonic sensors, or open-channel flumes or weirs. Attention must be given to proper installation of the meter chosen, particularly the provision for the correct length of straight pipe runs upstream and downstream of the meter (WPCF, 1984b).

Where properly applied, RAS and WAS pumping control systems can ensure that pumping head is minimized and that sludge solids are not unnecessarily transferred back and forth between the biological reactors and clarifiers. This latter condition is achieved by pacing the RAS flow rate to the secondary influent flow rate, so that a 30 to 50% return rate applies to all flow rates and not only for the daily average flow rate.

OTHER SENSORS AND CONTROLS. Other automatic sensors and controls commonly used include timers, float switches, ammeters, and kilowatt-hour meters. While not as good as continuous-flow matching, timers can effectively control pumps and aerators. It is important to ensure, however, that peak power demand during startup from timer operation does not cancel out the downtime power saving.

Many plants use float switches for pump control, especially when multiple pumps of different capacities are used. If they are properly applied, these switches can help conserve energy in much the same way as flow matching.

On multiple-stage centrifugal blowers, ammeters can be used to measure blower output. They are simple and can typically be calibrated to be repeatable and accurate.

For all large motors, kilowatt-hour meters are highly desirable. They facilitate data logging, which is necessary in any ongoing plant energy-conservation system. Simple volts times amps calculations are inaccurate and should not be relied on.

For monitoring and controlling power demand, plantwide strip chart energy recorders are invaluable. To track total daily power use the main distribution switchboard must be monitored. Copies of the monthly power bills and meter charges should be obtained from the power company and plant use and demand, and the loads contributing to the total demand, should also be identified. If the use and demand are plotted from week to week, day to day, and, if possible, hour to hour, it will be possible to identify the operating conditions causing these loads.

In recent years, reliable inline nutrient monitoring equipment has been developed and used increasingly for BNR process control and monitoring. Like all inline equipment, the nutrient analyzers must be routinely cleaned and maintained to be effective.

Oxidation–reduction potential (ORP) may be used as a surrogate measurement for DO concentration. An ORP is a measure of easily oxidizable or reducible substances in a wastewater sample. An operator can control the process by knowing if the wastewater contains substances with high oxygen demand that will require the oxygen supply to be increased. The ORP measurement, although not specific, is instantaneous and can be used to help maintain the proper level of DO in the reactor. Use of ORP probes has been successful in nitrification–denitrification systems.

EQUIPMENT MAINTENANCE

The routine preventive maintenance tasks recommended in the plant's O&M manual or by the manufacturers should be performed as required, depending on usage and conditions. Cleaning items, such as air filters, fine-bubble diffusers, and aerator impellers, and properly servicing equipment in general will help sustain equipment operating efficiencies and identify potential problems.

In many cases, by monitoring various parameters, considerable energy can be saved if some devices are serviced ahead of time. This is especially true of the intake air filters and fine-bubble air diffusers. Routine monitoring and plotting of differential pressures across filters and pressures in aeration air headers can quickly indicate when these systems need to be cleaned. Swing-diffuser aeration systems are suitable for such monitoring because the fine-bubble diffusers can be removed from the biological reactor without the tedious and energy-wasting task of draining the reactor and transferring the biomass to other operating tanks.

ENERGY MANAGEMENT PLAN

Energy is one of the highest O&M costs in a WWTP alongside personnel costs. Many plant mangers have little or no control over personnel costs, but typically have absolute control over energy use.

An energy management plan (EMP) is a multifacetted approach to reduce energy use and realize associated cost savings. The EMP targets the entire plant operation, including the activated-sludge system, which is a major energy consumer. Key elements of the EMP are outlined here. See *Energy Conservation in Wastewater Treatment Facilities* (WEF, 1997b) for additional reading.

The EMP encompasses the following steps:

1. Initial Survey. A cursory survey to determine if, and where, there are excesses and abuses in energy use. This initial survey will identify if an EMP should be developed.

3. Energy Audit. The energy audit initiates the EMP and consists of two subsets—data gathering and data analysis. Together they define what exists, what current operating practices are, and where and how energy is being used. The energy audit establishes the basic information database required for the development of an effective and site-specific EMP.
3. Develop EMP. This step sets the direction for the program and determines whether additional spending is required for equipment replacement and professional consultation services.
4. Implement EMP. In this final stage, the EMP developed specifically for the WWTP is implemented and monitored.

CASE STUDIES

The following are examples of significant cost reductions that were achieved through the successful application of energy conservation programs.

PLANT A. This is a 4.91-m^3/s (112-mgd), high-purity oxygen, activated-sludge plant, with a secondary process divided in two independent systems. Each system includes biological reactors and six final clarifiers. Both systems are aerated with cryogenically generated high-purity oxygen. The hydraulic loading at the plant has been 97% of design flow, while 5-day BOD loading is 37% of design.

Energy Consumption. The main power components of the secondary treatment systems are described in Table 20.5. Annual electrical consumption in the early 1990s ranged from 86 to 100 MJ[6] (24 to 28 kWh[6]) (Figure 20.31) and annual electric costs were approximately USD $2 million (Figure 20.32) during the same period. Billed demand averaged 4193 kW.

TABLE 20.5 Plant A—Secondary treatment power components.

Cryogenic oxygen generation compressor	**746 kW**	**(1000 hp)**
Aeration systems (2)		
Stage 1 aerator/mixer	29.8 kW	(40 hp)
Stage 2 aerator/mixer	22.4 kW	(30 hp)
Stage 3 aerator/mixer	22.4 kW	(30 hp)
Stage 4 aerator/mixer	22.4 kW	(30 hp)
Oxygenation system purge blowers (4)	18.6 kW	(25 hp)

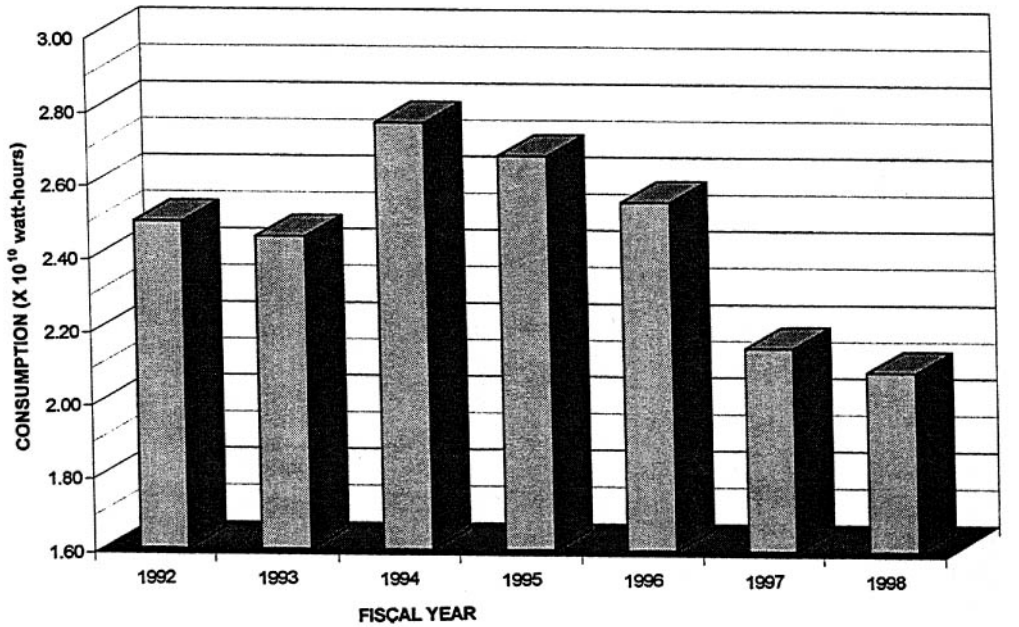


FIGURE 20.31 Plant A—Annual electrical consumption (W-hr × 3.600 = J).

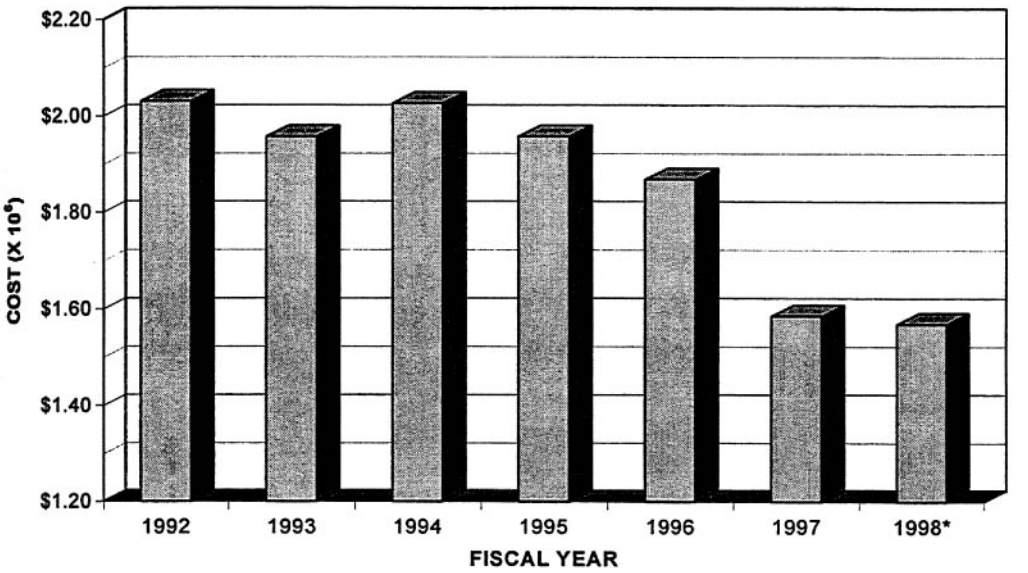


FIGURE 20.32 Plant A—Annual electrical cost.

Because of a consistently low power factor the plant had incurred penalties as high as $88,000 annually.

Conservation Program. High-purity oxygen was replaced with air in the secondary treatment process, and DO concentration in the biological reactors was maintained at 2.0 mg/L by seasonally adjusting the number of tanks and aerators and mixers in operation. The source of the poor power factor was identified and corrected with the installation of capacitor banks. Finally, nonessential equipment was shut down when wet-weather events occurred during peak flow hours to lower the billed power demand.

Because of these measures, annual electrical consumption decreased by 18% (Figure 20.31), billed demand decreased by 21% (Figure 20.33), and the power-factor penalty was eliminated. The annual electrical cost fell 20% from an average of USD $1.97 million in the five years before the conservation program was implemented, to an average of USD $1.58 million in the two years following.

PLANT B. This 7.9-m^3/s (180-mgd) plant is a conventional activated-sludge facility using coarse-bubble aeration in its secondary treatment. Two 3700-kW (5000-hp) single-stage blowers provided the air supply, and one or both were used according to system demand. The results of an energy audit on the plant's mechanical equipment and capital improvement costs are summarized in Table 20.6.

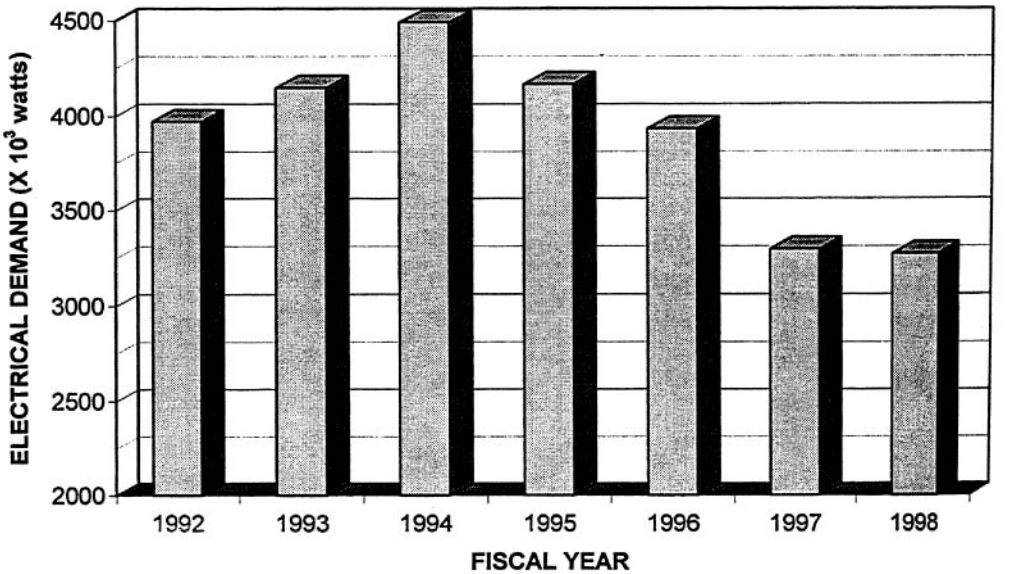


FIGURE 20.33 Plant A—Annual average billed demand.

TABLE 20.6 Results of identified energy conservation measures for Plant B (Bentivogli and Smith, 1998).

Energy conservation measure	Annual power cost (existing)	Annual power cost (proposed)	Capital cost	Simple payback (years)
Fine-bubble diffusion and new blowers	$2.4 million	$716,000	$5 million	3.1
Return solids pumps	$389,000	$352,000	$176,000	4.8
Untreated wastewater pumps	$365,000	$329,000	$132,000	3.7
Final effluent pumps	$186,000	$177,000	$ 60,000	6.7
Waste activated sludge pumps	$ 69,000	$ 38,000	$ 90,000	2.9
Air handling	$662,000	$464,000	$278,500	1.4

Energy Consumption. Prior to 1996, the plant's annual electric energy consumption exceeded 288×10^6 kWh). This represented an annual cost of more than USD $6 million, or more than a quarter of the plant's USD $21 million annual budget.

Conservation Program. The energy audit revealed that the largest savings could be realized by replacing the coarse-bubble diffusers with fine-bubble diffusers and replacing the two secondary blowers with smaller and more efficient 2200-kW (3000-hp) blowers. These replacements were carried out at a cost of USD $4.8 million. In the first full fiscal year following the conversion the plant consumed 193×10^6 kWh) at a cost of USD $4.1 million. The savings yielded a payback period of approximately three years.

PLANT C. This small 0.145-m^3/s (3.3-mgd) facility receives both municipal and industrial wastewater. The secondary treatment includes four biological reactors and two secondary clarifiers in a plug-flow configuration (Figure 20.34).

Conservation Program. As part of a multi-phase advanced wastewater treatment program, the biological reactors were reconfigured to modified contact stabilization processes with a stabilization zone, three-stage biological selector, and a downstream contact zone.

A study was conducted where two biological reactors were operated in plug-flow mode and two in modified contact stabilization mode (Figure 20.35). Oxygen-transfer efficiencies were evaluated concurrently in each mode. The results of the study showed that the modified contact stabilization system required less gas flow than the plug-flow system to maintain a DO concentration of 2.0 mg/L, representing an estimated cost savings of 18%.

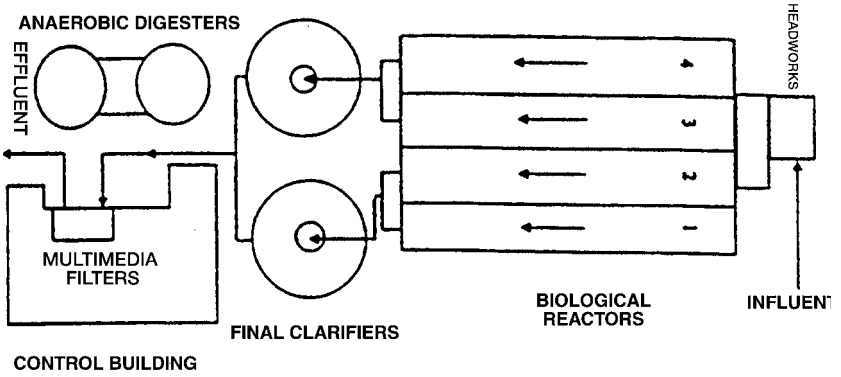


FIGURE 20.34 Schematic of Plant C.

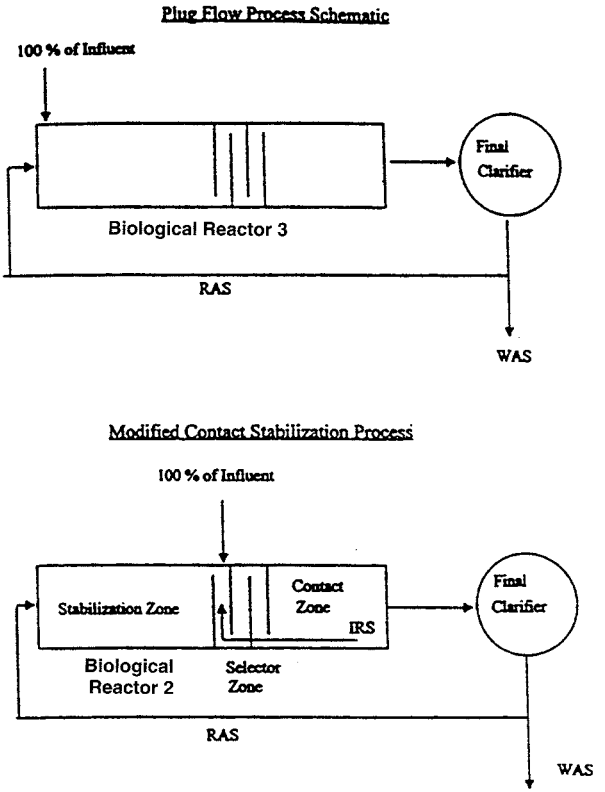


FIGURE 20.35 Comparison of conventional and selector modes of operation at Plant C.

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Section 5

Troubleshooting

INTRODUCTION

This section presents troubleshooting procedures for solving common operating problems. Troubleshooting tables are included and list problems, observations, probable causes, necessary checks to determine the cause, and suggested remedies.

To troubleshoot effectively, operators must determine the probable cause of a problem and select one or more corrective measures to restore the process to full efficiency with the least adverse effect on the final effluent quality and at the lowest cost. To do this, a thorough knowledge of the plant's activated-sludge process and the way it fits into the overall treatment plant operation is needed. In addition, familiarity with influent wastewater characteristics, plant flow rates and patterns, design and actual loading parameters, performance of the overall plant and individual processes, and current maintenance procedures is also needed. The topics on "Process and Equipment Description" and "Process Control" are recommended reading before using the troubleshooting guides. Many of these guides are based on the U.S. Environmental Protection Agency (U.S. EPA) manual titled *Process Control Manual for Aerobic Biological Wastewater Treatment Facilities* (1977).

When a problem or situation arises, first evaluate the problem and determine if it fits into one or a combination of the following areas:

- Hydraulic,
- Mechanical, and
- Process.

Hydraulic problems could be the result of several conditions. The first and foremost cause is rainstorms. This is especially true if the treatment facility is served from combined sewers.

Another hydraulic problem that could occur in the activated-sludge process is if, for example, there are not enough tanks in service because they are undergoing maintenance or repairs. Smaller facilities experience this more than larger facilities that have multiple tankage. Typically, a hydraulic condition is easy to detect because solids washout can be seen at the secondary clarifiers.

The second category is mechanical problems. A mechanical problem with a clarifier collector mechanism, return activated-sludge (RAS) pump, low-pressure air blower, or mechanical aerator could result in an effluent violation if it is not corrected or noticed immediately. For example, if a return sludge pump fails and this goes unnoticed, solids would not be removed from a secondary clarifier. This in turn could result in the clarifier filling up with solids until eventually solids flow over the weirs.

The third category the operator must be aware of is process problems. Process problems are typically the most difficult to identify and correct. A plant that maintains good records usually can see warning signs that alert the operator of an impending problem. A change in influent characteristics could result in a change in settling characteristics. In-plant sidestream changes, differences in dissolved oxygen concentrations, and other parameters and plant conditions are important aspects that an operator must know to effectively troubleshoot a treatment facility. Again, good plant records will help enable an operator to determine and correct the problem.

Another excellent process troubleshooting mechanism is microscopic examination of the activated sludge. Operators can determine the condition of the activated-sludge process by knowing and determining the predominance of various microorganisms. In addition, a microscopic examination of the mixed liquor will help operators identify the presence and type of filamentous organisms present in the facility, which in turn will help determine the best course of action to correct a process problem.

Troubleshooting requires several skills, including investigative thinking and logical use of all tools available to help solve a problem. It is important when troubleshooting to not perform numerous changes at once because that may result in further problems. If multiple corrective changes are made at once and the process does improve, it will be difficult, if not impossible, to identify which process change was the most effective. It is also important to realize that the activated-sludge system is a biological process so most responses will not be noticed immediately. It may take days or weeks before a process improvement can be seen.

KEYS TO TROUBLESHOOTING

As stated previously, the first step is to determine if the problem is related to hydraulics, mechanics, processes, or a combination of these factors. When a problem or situation is about to occur, or if it has already surfaced, it is important to take logical and methodical approaches to improving the process. The following seven areas are key to troubleshooting; they are critical for narrowing the search for solutions to most problems:

1. Know thoroughly the process being evaluated.
2. Know all plant flow patterns, including forward flow and sidestreams.
3. Know the plant's design parameters and how actual loadings compare to design values.
4. Know all maintenance procedures, including equipment maintenance considerations and staff responsibilities.
5. Know how to recognize an abnormal condition.
6. Know what alternatives are available when trouble develops.
7. Know the amounts and characteristics of any industrial waste that may be discharged to the plant.

It cannot be stressed enough that once a problem has been recognized, corrective actions should be kept to a minimum. This means not making too many changes at once because that may create additional problems. In addition, because the activated-sludge process is a biological process, adequate time must be alloted for corrective actions to take effect. Do not make rapid changes after a corrective action is implemented.

TROUBLESHOOTING TESTS

Several simple laboratory tests that can help solve or troubleshoot operational problems include the mixed liquor settleability test, sludge volume index (SVI), microscopic examination, mixed liquor respiration rate, dissolved oxygen (DO) measurement, and sludge blanket level. Some of these are briefly described here, while others are addressed in more detail in other sections of this manual.

MIXED LIQUOR SETTLEABILITY TEST. The mixed liquor settleability test, which shows mixed liquor settling characteristics under controlled conditions, is one of the most useful tools for understanding what is happening to the process. A benefit

of the test is that the results, which demonstrate how mixed liquor solids may react in secondary clarifiers, are available in 30 minutes. Figure 20.36 shows how to interpret and apply various settleability test observations. The test procedure is described fully in the U.S. EPA manual titled *Operational Control Procedures for the Activated Sludge Process, Part II Control Tests* (1974). Note that some operators use a 1-L graduated cylinder instead of a settleometer (a specially marked wide-mouth beaker for observing sludge settling) for this test, but the sidewall effects of the narrow graduate interfere with the settling.

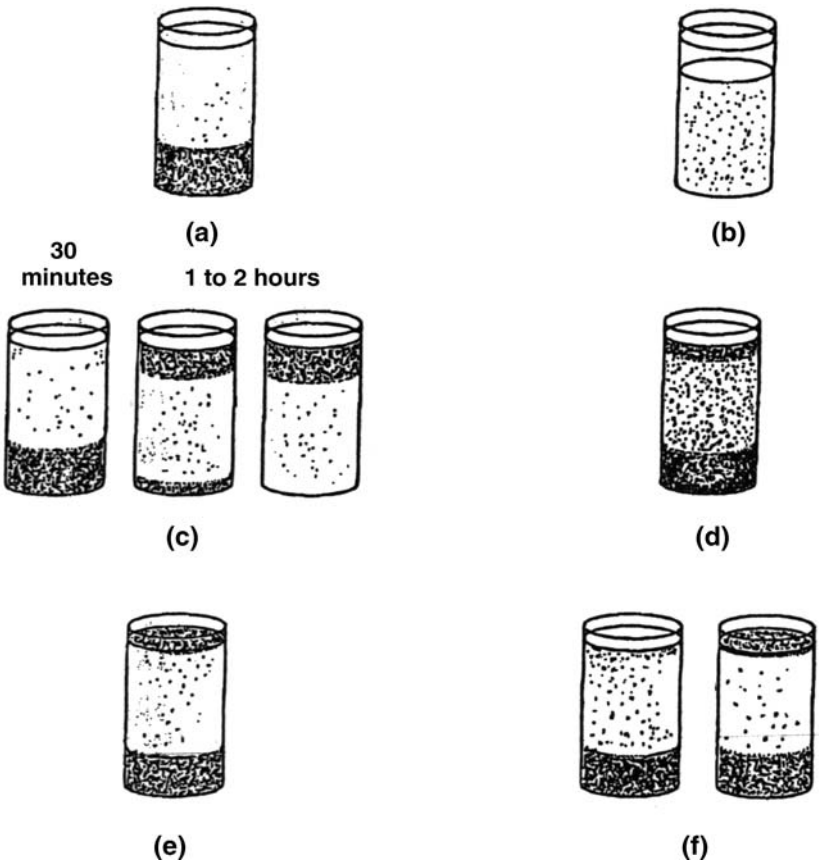


FIGURE 20.36 Index to troubleshooting guides based on settleability test results: (a) good settling sludge (effluent quality problem because of settling), (b) bulking sludge, (c) clumping/rising sludge (denitrification), (d) cloudy effluent, (e) ash on surface, and (f) pinpoint floc and stragglers.

When conducting this test, it is necessary to also observe the floc in the settleometer to determine if it is granular with well-defined edges and interspaces.

SLUDGE VOLUME INDEX. An extension of the mixed liquor settleability test is the SVI. The SVI is a better determination of the settling characteristics of sludge in secondary clarifiers than the mixed liquor settleability test by itself because the SVI takes into account the mixed liquor suspended solids (MLSS) concentration. The test is somewhat slower because the time required to determine the MLSS concentration is several hours. A normal range for the SVI of a properly operating activated-sludge system is in the range of 50 to 150 mL/g. However, because plants are different, slightly higher or lower valves do not necessarily mean poor operation. If the SVI becomes too high, say 300 mL/g, this indicates that the sludge is slow settling and may become caught in the effluent flowing over tank weirs. The lower the SVI number the faster the solids settle. If the solids settle too quickly (at SVI's of approximately 50 mL/g or less), they may not pick up some solids particles that will eventually flow over the clarifier effluent weirs. Note, where the mixed liquor settleability test is greater than 25% of the test cylinder (e.g., $>$ 250 mL in a 1000-mL cylinder), a diluted SVI should be run. This is where the mixed liquor is diluted with secondary effluent until the 30-minute settling is approximately 250 mL in a 1000-mL cylinder. The SVI is then calculated with a proportioned MLSS (Jenkins et al., 1993).

To ensure that SVI test results are accurate, *Standard Methods* (APHA et al., 1998) test procedures 2710 C and D must be carefully followed. For example, the sample must be stirred for several minutes with a proper stirrer at a speed not greater than 1 cm/s. A number of plants neglect this step when running the SVI test. This is especially true in treatment plants where the MLSS is high.

MICROSCOPIC EXAMINATION. By examining the mixed liquor with a microscope, much can be determined about the activated-sludge process. The presence of various microorganisms within the mixed liquor floc can quickly indicate good or poor treatment. It is not necessary to be a skilled microbiologist or to be able to identify or count individual species. Instead, it is important to be able to recognize significant groups of microorganisms such as

- Filamentous bacteria (Figure 20.37),
- Protozoa (amoebas, flagellates, and free-swimming or stalked ciliates (Figure 20.38), and
- Rotifers (Figure 20.39).

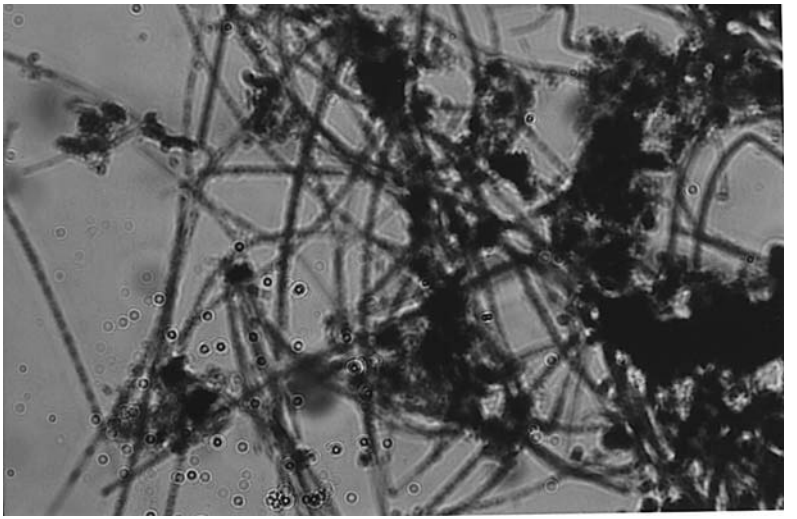


FIGURE 20.37 Filamentous bacteria.

Also, the microscope can be used to observe other important factors such as the presence or absence of filaments, floc characteristics, and supernatant characteristics.

The identification of filamentous microorganisms is important and can help narrow the investigative process during troubleshooting. In many cases, treatment facilities seek the assistance of colleges, universities, or commercial laboratories where proper staining techniques and stronger microscopes are used for a definitive identification of the type of microorganisms present at the plant. Most treatment plants have microscopes that can only determine the presence of excessive filaments but not the type of microorganism. Knowing whether a filamentous microorganism is, for example, *Nocardia*, *Microthrix*, *Thiothrix*, or type 0041 is important in pinpointing an activated-sludge settling problem. The specific type of filamentous microorganism will be an indication of whether the problem is caused by a low DO concentration, nutrient-deficient waste, a low food-to-microorganism ratio (F:M), or other conditions.

It is important that a wastewater treatment plant obtain a good phase contrast microscope that will meet its needs in identifying microorganisms and filaments. The microscope should have objective lenses at 100, 200, and 1000X. It is also important that the microscope be used carefully and maintained properly, including keeping the instrument clean.

MIXED LIQUOR RESPIRATION RATE. The mixed liquor respiration rate, also referred to as the specific oxygen uptake rate (SOUR), measures the rate that oxygen is

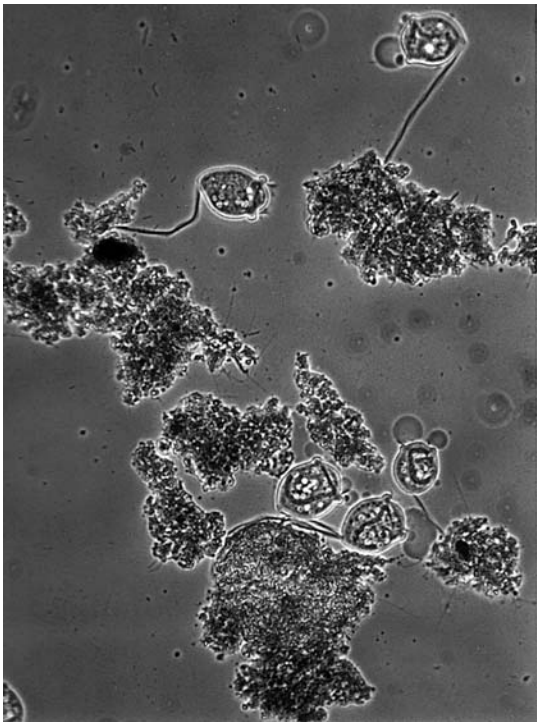


FIGURE 20.38 Stalked ciliates.

removed from the wastewater, thus providing an indication of the activated-sludge biomass. Because the activity level provides information that helps predict settling characteristics and sludge quality, the respiration rate can be used to predict the impact of a new wastewater; verify or refute the treatability of a given wastewater; indicate the need to increase or decrease biological reactors in service; assist in verifying changes in

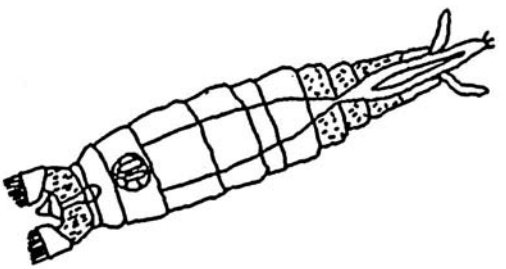


FIGURE 20.39 Rotifers.

mode of operation; and assist in determining or verifying trouble areas such as presence of toxics, excessive or insufficient mean cell residence time (MCRT) or F:M, filamentous bacterial overgrowth, organic overloads, or excessive in-plant recycles.

OPERATIONAL PROBLEMS AND POSSIBLE SOLUTIONS

INTRODUCTION. Operational problems commonly experienced in the activated-sludge process are discussed here. Because it is impossible to include all of the problems that may occur in the operation of the process, only the common problems that are encountered and may be corrected by operational changes are included. Generally, these problems can be classified by conditions that the operator can see in the biological reactor and secondary clarifier, such as ashing, pinpoint floc, and straggler floc.

Biological reactor and clarifier problems can be corrected by using reliable operational control practices applied logically and maintaining proper equipment operation. Troubleshooting guides that address these problems are provided later in this section. When troubleshooting operational problems, keep the following in mind: Do not try to correct a problem unless it is certain that the problem is the cause of, or will lead to, poor effluent quality.

Because of stricter effluent requirements, more treatment plants are required to limit the amount of nutrients leaving the plant and entering receiving streams. Therefore, more treatment plants are being constructed or modified to operate as biological nutrient removal (BNR) facilities. These facilities may be designed only to reduce phosphorus, nitrify, or to reduce phosphorus and nitrogen. Many variations of BNR processes are used to reduce nutrients; therefore, not every process can be discussed in this section with regard to troubleshooting needs. Instead general troubleshooting aspects to these processes are provided to help operators. Because BNR processes are mainly biological, some standard activated-sludge troubleshooting guidelines can apply to BNR problems.

Within this section and the troubleshooting guides that follow are lists of solutions that include

- Increasing or decreasing aeration,
- Balancing influent and return sludge flows,
- Adjusting return rates,
- Adjusting wasting rates,
- Adding chemical settling aids,

- Adding supplemental nutrients,
- Chlorinating return sludge or mixed liquor,
- Reducing or controlling recycle flows, and
- Rerouting recycled flows.

Some solutions produce quick results, some produce changes only after many days, and some can be drastic with potentially adverse side effects. The troubleshooting information presented here is typically oriented towards solutions that minimize the potential for overcorrection and adverse side effects. The stronger the recommended solution, the more judgment and experience required in applying it.

In most cases, aeration adjustments, flow balancing, and RAS flow rate adjustments will produce quick, mild results. Typically, the effect of altering sludge wasting takes longer and is less reversible, that is, more prone to overcorrecting. Chlorinating mixed liquor or return sludge produces quick results at moderate or greater application rates but poses significant risks if done improperly. (It is considered by some a solution of last resort, while others consider it a standard solution if applied properly). Applying polymers or metal salts (such as alum or ferric chloride) is typically effective quickly but can be expensive and may increase sludge-wasting requirements. Correcting nutrient deficiencies can produce quick, positive results but requires purchasing chemicals and chemical feed equipment. Reducing or controlling recycle flows produces quick, positive effects but may require changes in the operation of solids treatment processes or the addition of offline storage or treatment facilities.

It is important to take only one corrective action at a time to avoid confusing the effects of multiple changes. As troubleshooting expertise is gained, it may be possible to apply solutions in a more direct manner. The beginner, however, should be cautious. Significant changes may result in overcorrecting, which can create additional problems just as severe as the initial problems they were intended to cure.

If operating problems cannot be solved in-house, help should be obtained from others such as operators at other plants, state operators' associations, state and federal regulatory agencies, operations consultants, equipment manufacturers, and local colleges. Some problems are complex and difficult to solve because there may be several contributing factors. Only qualified individuals with firsthand knowledge and experience should be considered. Second guessing by well-intentioned people can waste time and money, divert attention from the correct solution, and possibly make matters worse. Also, solutions that worked once may not work again because conditions may have changed as a result of the biological nature of the process.

Before making a change, collect as many data as possible and experiment with possible solutions in the laboratory. If a mistake is made, the results can be easily dis-

carded and another solution tried. If a significant mistake is made within the plant, it is not as easily corrected.

When attempting to solve a problem, avoid treating only the symptoms. For example, chlorinating return sludge for a filamentous bulking problem will temporarily solve the problem, but the underlying cause (such as a nutrient deficiency or too low DO) must be corrected or the problem will return. However, in some cases the underlying cause cannot be readily corrected because of design deficiencies or budgetary restraints and it may be necessary to settle for treating the symptom (e.g., chlorinating return sludge) until the underlying problem can be permanently solved.

BIOLOGICAL REACTORS. ***Diffused Air and Mechanical Aeration Systems.*** Mixed liquor must be aerated so that aerobic microorganisms will get enough oxygen to remain active and healthy. In addition, biological reactor contents must be mixed to bring microorganisms into contact with all of the organic matter in the wastewater being treated.

Mixing in the biological reactor can typically be checked by observing the turbulence on the reactor's surface. Surface turbulence should be reasonably uniform throughout the reactor; violent turbulence should not be present because it wastes energy and shears floc.

DIFFUSED AIR SYSTEMS. Dead spots and nonuniform mixing patterns will typically indicate a clogged diffuser or that the diffuser header valves need adjustment to balance air distribution in the reactor. Violent turbulence typically indicates a broken pipe or diffuser. Illustrations of both uniform and violent turbulence in a biological reactor are shown in Figure 20.40.

For biological reactors with air diffusers, a DO profile should be made every 1 to 6 months or whenever the flow pattern is changed. The air distribution should be adjusted to maintain a DO concentration of no less than 0.5 mg/L (preferably 1.5 to 3 mg/L) throughout the biological reactor. Refer to Sections 2 and 6 for additional discussions regarding diffused air systems.

Some probable causes of nonuniform aeration include

- Air rates too high or low for proper operation of the diffuser,
- Valves needing adjustment or balancing of the air distribution,
- Diffusers needing cleaning or repair (masses of air rising over the location of the diffuser blowoff legs, if so equipped, typically indicate that the diffusers need cleaning or replacing or that there could be a line break),
- Mechanical equipment limitations, and
- Diffusers not at the same elevation.



a



b

FIGURE 20.40 Biological reactor surface turbulence: (a) violent turbulence and (b) good turbulence.

The following measures can be tried when applicable to correct aeration problems:

- Adjust airflow rate to maintain the DO in the proper concentration range (1.5 to 3 mg/L). Mixing requirements of a biological reactor are typically 0.5 to 0.7 $L/m^3 \cdot s$ (30 to 40 cfm/1000 cu ft). Fine-bubble diffusers typically require 0.36 to $0.61/m^2 \cdot s$ (0.07 to 0.12 scfm/sq ft) of reactor surface. However, oxygen-transfer requirements must also be met for either coarse- or fine-bubble systems.

- Adjust diffuser header valves to balance air distribution and eliminate dead spots.
- Check the blower preventive maintenance requirements, service record, design capacity, and present output if possible. The blower may need repair.
- Regularly check and clean the diffusers. Diffusers should be cleaned typically every 6 months to 1 year to maintain good aeration performance.
- If fine-bubble diffusers are extremely troublesome, investigate various air-cleaning devices, the airflow rate to each diffuser, and the type of clogging—internal by dirty air or external by biological fouling—so that use of fine-bubble diffusion can be continued. Testing has shown that most fouling is external, and acid gas systems for ceramic diffusers have been developed to correct this problem. Because fine-bubble diffusers are more energy efficient than coarse-bubble diffusers, every effort should be made to retain them. There are different types of fine-bubble diffusers, such as ceramic and membrane, that should be investigated to determine which type of diffuser is best for the plant. Only if all else fails should replacing them with a coarse-bubble type of diffuser be considered. Outside help should then be obtained.
- Relocate and/or increase the number of diffusers to properly mix and aerate the reactor contents. Before increasing the number of diffusers, the adequacy of the air supply must be checked. Outside help should be obtained.

MECHANICAL AERATION SYSTEMS. As with diffused air systems, inadequate mixing or aeration problems can occur with mechanical aeration systems. Additionally, mechanical aerators can be subjected to surging and impeller fouling problems.

Inadequate Mixing and Aeration. A DO profile of the biological reactor can be made to check the adequacy of mixing and aeration. Some probable causes of inadequate mixing and aeration are

- Aerator speed too slow,
- Impeller submergence inadequate,
- Impeller fouled with rags or ice,
- Aerator undersized, and
- Aerator flooding.

The following measures can be tried when applicable to correct for inadequate mixing or aeration:

- Increase aerator speed if the aerator has a two-speed motor that has been operating on slow speed,

- Raise weir setting and/or lower impeller to reach maximum allowable impeller submergence (do not exceed maximum allowable submergence because it could overload the motor),
- Remove rags or ice (if rags are a problem, check the headworks for screening efficiency),
- Consider replacing aerator with a larger or better-designed aerator,
- Reduce the airflow rate or turn the aerator on high speed, and
- Install a submersible mixer in the basin.

Hydraulic Surging and Flooding. Mechanical aerators can be subjected to hydraulic surging. Surging occurs when the impeller submergence is below the manufacturer's recommendation and a wave pattern is established in the biological reactor that causes the impeller to be alternately exposed to critical over- and undersubmergence. The aerator motor will be intermittently overloaded and may be shutdown. Surging is more likely to occur during low-flow conditions such as when an entirely new plant or additional biological reactor is put online.

The following measures can be tried when applicable to correct a surging problem:

- If the surging occurs during no-flow conditions, check the biological reactor effluent weir for leaks, especially if it is adjustable;
- Raise or lower the biological reactor effluent weir and/or lower the impeller to reach proper submergence (do not exceed maximum allowable submergence);
- Reduce the number of biological reactors online, if possible, to increase flow and, therefore, submergence in reactors;
- Investigate use of baffles, inlet draft tubes, and flow-straightening vanes to eliminate wave action; and
- Increase return rate as a last resort.

Mechanical aerators with draft tubes that use a downward flow pattern can experience a condition known as flooding. Flooding occurs when the flow of the column of water that typically travels downward in the aerator draft tube reverses and starts flowing upward. This condition typically occurs if the buoyancy of the entrained air is greater than the aerator can force downward. When an aerator is operating in a flooded condition, it reduces the oxygen-transfer efficiency and could damage the aerator. A flooded condition should be corrected as soon as possible. Care must be taken when making the correction, however, because equipment damage could occur if the column of water is forced to reverse direction too quickly. Typically, the equipment manufacturer recommends that during a severe case of flooding, the aerator be stopped and the air turned

off. After several minutes when the flow of the water through the draft tube stops, the aerator can be restarted and a correct flow pattern established. The air can then be restarted and regulated to the correct flow rate.

Impeller Fouling. Mechanical surface aerators can be subjected to impeller-fouling problems caused by rags and ice. Rags and ice interfere with aeration and mixing, may damage the gear box, and may cause a motor overload. Rags are most likely to accumulate in plants without primary clarifiers. Icing may result from heat losses in upstream tanks (such as aerated grit chambers and primary clarifiers), impeller and shroud design, and climate.

Rags and ice must be removed manually. Ice must be completely removed or it may cause a significant imbalance. It may be controlled by installing metal shrouds above the aerators to keep the spray in the reactor.

Biological Reactor Foaming. The presence of some foam (or froth) on the biological reactor is normal for the activated-sludge process. Typically, in a well-operated process, 10 to 25% of the reactor surface will be covered with a 50- to 80-mm (2- to 3-in.) layer of light-tan foam.

Under certain operating conditions, foam can become excessive and affect operations. Three general types of problem foam are often seen: stiff white foam, brown foam (greasy dark-tan foam and thick scummy dark-brown foam), and a very dark or black foam (Figure 20.41).

If stiff white foam is allowed to build up excessively, it can be blown by the wind onto walkways and plant structures and create hazardous working conditions. It can also create an unsightly appearance, cause odors, and carry pathogenic microorganisms. If a greasy or thick scummy foam builds up and is carried over with the flow to the secondary clarifiers, it will tend to build up behind the influent baffles and create additional cleaning problems. It can also plug the scum-removal system.

STIFF WHITE FOAM. Stiff white billowing foam, indicating a young sludge (low MCRT), is found in either new or underloaded plants. This means that the MLSS concentration is too low (low activated sludge solids inventory) and the F:M is too high. The foam may consist of detergents or proteins that cannot be converted to food by bacteria that grow in the mixed liquor at a high F:M.

Some probable causes of stiff white billowing foam include

- Activated sludge not being returned to the biological reactor;
- Low MLSS resulting from process startup;



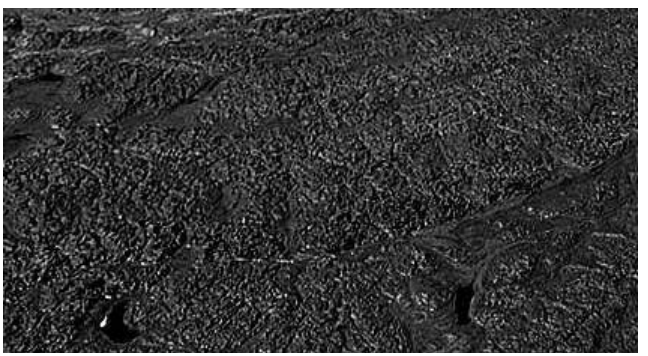
a



b



c



d

FIGURE 20.41 Foaming problems (a) stiff white foam, (b) thick scummy dark foam, (c) brown foam, and (d) very dark or black foam.

- Low MLSS for current organic loading, as caused by excessive sludge wasting or high organic load from an industry (typically occurring after low loading periods such as weekends and early mornings);
- The presence of unfavorable conditions such as toxic or inhibiting materials, abnormally low or high pHs (less than 6.5 or greater than 9.0), insufficient DO concentrations, nutrient deficiencies, or seasonable (summer to winter) wastewater temperature change resulting in reduced microorganism activity and growth;
- Unintentional loss of activated-sludge biomass in the secondary clarifier effluent caused by the following:
  —Excessive or shock hydraulic loads,
  —Biological upset,
  —High sludge blanket in secondary clarifier resulting in solids washout,
  —Mechanical deficiencies in the secondary clarifier (such as leaking seals or open dewatering valves), and
  —Improper distribution of flows or solids loadings to multiple clarifiers; and
- Improper distribution of the wastewater and/or RAS flows to multiple biological reactors.

The following measures can be tried when applicable to correct the foaming problem:

- Verify that return sludge is flowing to the biological reactor. Maintain sufficient return rates to keep the sludge blanket in the lower quarter of the clarifier, preferably between 0.3 and 0.9 m (1 and 3 ft) from the bottom.
- Stop the sludge wasting for a few days to increase the MLSS concentration and MCRT to target values.
- Control the airflow rates or mechanical aerator submergence to maintain DO concentrations of 1.5 to 3 mg/L in the biological reactor. This type of foaming is more likely to persist under otherwise acceptable conditions with fine-bubble than with coarse-bubble diffusers.
- Check dewatering valves and close them if they are inadvertently open.
- Consider seeding the process with activated sludge from a well-operating plant.
- Actively enforce sewer-use ordinances to avoid process upset and deterioration of the plant effluent.
- Modify the piping or structures as necessary to maintain the proper distribution (proportional to reactor volumes) of flows to multiple biological reactors and secondary clarifiers. The construction of some type of flow-distribution structure may be required.

- If flow meters are not provided, visually check the return sludge flow and compare the sludge blanket levels in each clarifier, the return sludge suspended solids (SS) concentration from each clarifier, and the MLSS concentration in each biological reactor. The corresponding measurements should be nearly equal if the wastewater, biological reactor effluent, and return flows are being properly distributed.
- If the biological reactors have water sprays for froth control, operate the water sprays when there is danger of the foam being blown onto walkways or other structures.
- If there are no water sprays, consider using defoamants or improvising a froth-control system using effluent water.

EXCESSIVE BROWN FOAMS. These foams are associated with plants operating at low-loading ranges.

Plants designed to nitrify and operating in the nitrifying mode will typically have low-to-moderate amounts of rich chocolate-brown foam.

Plants with the filamentous organism *Nocardia* (Figure 20.42) will have a strong greasy dark-tan foam that will carry over onto the clarifier surface. Scum-containing filamentous organisms should be wasted from the system rather than returned to the biological reactors. A heavy dark-brown greasy foam is often normal in the aeration stage of plants that practice sludge reaeration.



FIGURE 20.42 Nocardia.

Thick scummy dark-brown foam indicates an old sludge (long MCRT) and can result in additional problems in the clarifier by building up behind influent baffles and creating a scum disposal problem as shown in Figure 20.43.

Some probable causes of this sort of foaming problem are

- Biological reactor being operated at a low F:M, possibly because nitrification is required by a regulatory agency;
- Buildup of a high MLSS concentration as a result of insufficient sludge wasting. This condition could unintentionally occur when seasonal (winter to summer) wastewater temperature change results in greater microorganism activity and, consequently, greater sludge production;
- Operating in the sludge reaeration mode. A heavy dark-brown greasy foam is normal in the sludge reaeration tank, particularly if the process is being operated at a low F:M; and
- Improper wasting control program.

The following measures can be tried when applicable to correct the foaming problems:

- If nitrification is not required, gradually increase the wasting rate to increase the F:M and decrease the MCRT.



FIGURE 20.43 Dark foam in influent well of secondary clarifier.

- If the scum is not returned to the biological reactors, include the volatile solids removed in the scum in the waste sludge calculations. During normal operation, the amount of volatile solids removed with the scum is too small to matter. However, during heavy foaming, as much as 10% of the waste activated-sludge (WAS) solids may be removed with the scum.
- If filaments appear, try to identify the cause. Refer to the later section "Bulking Sludge—Filamentous Microorganisms Present" for further information.
- Implement a better program for controlling the wasting of activated sludge.
- If the foam contains filaments, remove it from the surface of the water and send it to the solids-disposal facilities. Ensure that the foam is not recycled back to the treatment plant.

VERY DARK OR BLACK FOAM. The presence of a very dark or black foam indicates either insufficient aeration, which results in anaerobic conditions, or that industrial wastes such as dyes and inks are present. The following measures can be tried when applicable to correct this foaming problem:

- Increase aeration (see "Aeration System Problems"),
- Investigate source of industrial wastes to determine if appearance is resulting from dyes or inks, and
- Decrease the MLSS concentration.

SECONDARY CLARIFIERS. ***Solids Washout.*** A solids washout condition can sometimes be quickly detected when good settling is observed in the mixed liquor settleability test (See Figure 20.36) but billowing, homogenous sludge solids are rising near the weirs in the clarifier (Figure 20.44), even though the sludge blanket is otherwise in the lower half of the clarifier.

Some probable causes of solids washout are equipment malfunction, hydraulic overload, solids overload, and temperature currents.

EQUIPMENT MALFUNCTION. Inspect all equipment in the clarifier to ensure proper operation. Equipment malfunctions can cause short circuiting or poor sludge collection. Specifically, check

- Flow meters
  —Return sludge flow meter may be reading high.
  —If return sludge flow is being flow-paced, influent flow meter may be reading low.
- Return activated sludge pumps and lines

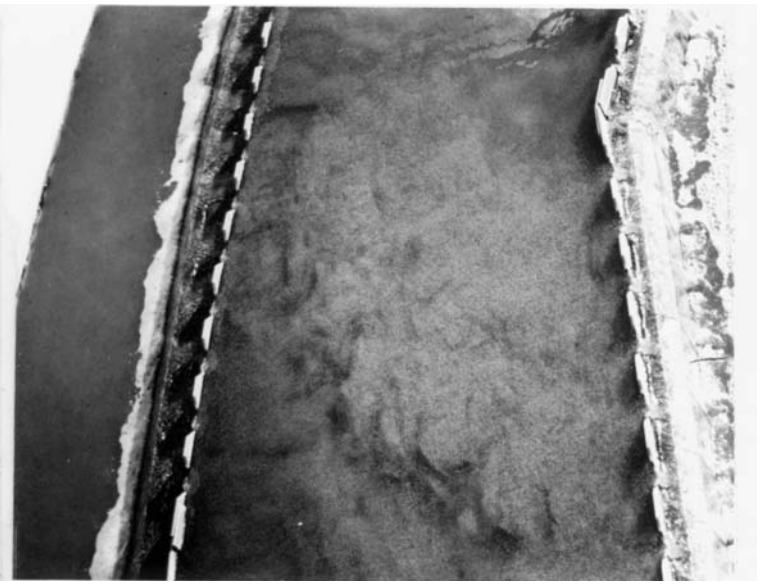


FIGURE 20.44 Solids washout in clarifier.

- Sludge collection equipment
  —Look for broken drives or support members.
  —Look for uneven blanket depth at several locations in the clarifier. An uneven blanket may indicate a plugged suction collector or broken plough.
- Baffles and skirts
  —Look for broken welds, bolts, or supports.
  —Look for holes in the baffle.
- Weir levels
  —Look for unbalanced flow over the weirs. If the weirs on one side of the clarifier are more deeply covered than those on the other side, they should be adjusted to an equal elevation.

HYDRAULIC OVERLOAD. If the plant is subjected to excessive inflow and infiltration (I/I), set up an I/I reduction program.

Check the hydraulic loading on each clarifier by either measuring the flow to each clarifier or estimating the flow balance between multiple units as indicated by the depth of flow over the weirs in each clarifier. Differences in depth of flow, however, will be hard to measure unless the differences in flow are excessive. If the head loss to

all clarifiers is the same, the clarifier overflow weirs should all be set at the same elevation. If not, the weirs should be adjusted to equalize the head loss to them. Overloading can result from excessive flow or unevenly distributed flow between multiple units.

The problem should be approached as follows:

- Determine if flows are being distributed equally to biological reactors and clarifiers. Weirs at the effluent end of the reactors must be adjusted to equally distribute the flow to each tank. Weirs or gates on the RAS distribution lines must be adjusted to properly distribute RAS flows. Weirs at clarifier distribution structures must be adjusted to uniformly distribute the flow. In addition, effluent weirs must be adjusted for optimum clarifier performance.
- After checking and correcting weir elevations where needed, determine the clarifier surface overflow rate at both average and peak flows. Compare the calculated surface overflow rate with the design rate. If the current rate exceeds the design rate, clarifiers may be hydraulically overloaded and additional clarifiers may be required in operation. Also, perform an SVI test to check settling characteristics. If results are unsatisfactory and all clarifiers are operating, plant expansion or flow equalization should be considered.

The clarifier surface overflow rate at average and peak flows can be calculated as follows:

Given:

Surface area, each clarifier = 729 m^2 (7850 sq ft)
Total surface area, two clarifiers = 1458 m^2 (15 700 sq ft)
Plant flow, average = 28 400 m^3/d (7.5 mgd or 7 500 000 gpd)
Plant flow, peak 2-hour = 56 800 m^3/d (15.0 mgd or 15 000 000 gpd)

Solution:

$$\text{Average surface overflow rate} = \frac{\text{Plant flow}}{\text{Clarifier surface area}}$$

In metric units:

$$\text{Average surface overflow rate} = \frac{28\,400\ m^3/d}{1458\ m^2}$$

$$= 19.48\ m^3/m^2 \cdot d$$

$$\text{Peak surface overflow rate} = \frac{56\,800\ \text{m}^3/\text{d}}{1458\ \text{m}^2}$$

$$= 38.9\ \text{m}^3/\text{m}^2 \cdot \text{d}$$

In English units:

$$= \frac{7\,500\,000\ \text{gpd}}{15\,700\ \text{sq ft}}$$

$$= 478\ \text{gpd / sq ft}$$

$$\text{Peak surface overflow rate} = \frac{15\,000\,000\ \text{gpd}}{15\,700\ \text{sq ft}}$$

$$= 955\ \text{gpd / sq ft}$$

SOLIDS OVERLOAD. A special case of clarifier overloading is solids overloading in which solids enter the clarifier faster than they can be settled. Solids overloading is related to the plant flow, return flow, and MLSS concentration. It becomes apparent when sludge settleometer readings are near normal, but clarifier blanket levels are high, return rates are high, and high effluent solids are observed (or threatening).

Whether the clarifier is overloaded with solids can be determined by increasing the return rate and watching how the blanket responds, or by checking the solids loading rate and comparing the results with established values. An initial settling velocity (ISV) dilution test may also be considered. The ISV test is a simple and quick process control test that helps determine the flow that a clarifier can adequately handle at a given MLSS concentration. It can also help determine the minimum required return rate (Wilson, 1983). Operators and engineers currently use flux curves to help them determine overloaded clarifiers, return rates, and settling characteristics.

Adjusting the return rate should quickly verify whether a solids overloading problem exists. If the return rate is increased and the blanket drops, the problem is not solids overloading and increasing the return rate has helped. If an increased return rate raises the blanket and keeps it up, the clarifier is probably overloaded with solids and higher return rates will only aggravate the problem. The return rate can then be reduced by 20%, but only if the blanket level, effluent and MLSS concentrations, and mixed liquor settleability are closely watched. The sludge blanket in clarifiers should be measured after 30 minutes and again after 60 minutes to check the effect. It should then be checked three times per shift to ensure that the blanket does not build up to an

excessive depth. This may only work for a short time because storing solids in the clarifier is not effective with high blankets. If a reduced return rate raises the blanket, other options can be tried as described later.

The solids loading rate can be determined as follows:

Given:

Surface area, each clarifier = 729 m^2 (7850 sq ft)
Total surface area, two clarifiers = 1459 m^2 (15 700 sq ft)
Plant flow, Q (peak hour) = 28 400 m^3/d (7.5 mgd)
Return flow rate, R (peak hour) = 14 400 m^3/d (3.8 mgd)
MLSS (peak hour) = 2500 mg/L

Solution:

$$\text{Solids loading rate} = \frac{(Q + R)\ (\text{MLSS})\ (\text{Conversion factor})}{(24\ \text{hours/day})\ (\text{Clarifier surface area})}$$

In metric units:

$$\text{Solids loading rate} = \frac{(28\,400\ \text{m}^3/\text{d} + 14\,400\ \text{m}^3/\text{d})\ (2500\ \text{mg/L})\left(0.001\dfrac{\text{kg/m}^3}{\text{mg/L}}\right)}{(24\ \text{hr/d})\ (1459\ \text{m}^2)}$$

$$= 3.1\ \text{kg MLSS/ m}^2 \cdot \text{h}$$

In English units:

$$\text{Solids loading rate} = \frac{(7.5\ \text{mgd} + 3.8\ \text{mgd})\ (2500\ \text{mg/L})\left(8.34\dfrac{\text{lb/mil. gal}}{\text{mg/L}}\right)}{(24\ \text{hr/d})\ (15\,700\ \text{sq ft})}$$

$$= 0.63\ \text{lb MLSS/ hr /sq ft}$$

For peak flow conditions, solids loading rates of approximately 7.08 and 9.28 $kg/m^2 \cdot h$ (1.45 and 1.90 lb/hr/sq ft) are practical upper limits for nitrification and normal secondary clarifier operations, respectively. For average flow conditions, a solids loading rate of 6.10 $kg/m^2 \cdot h$ (1.25 lb/hr/sq ft) is a practical upper limit for normal secondary clarifier operation.

Also, an ISV dilution test reportedly can determine the clarifier safety factor (CSF) and the minimum return rate required. If the actual return rate is more than the calculated minimum and the CSF is more than 1.5, the plant may not be overloaded (Wilson, 1983).

If calculated values and observations suggest an overload, the following approaches can be tried:

- Place another clarifier online, if possible.
- Place another biological reactor online, if possible, to reduce MLSS concentrations.
- Reduce the MLSS concentration by increasing the wasting.
- Change to sludge reaeration or contact stabilization, if possible.
- If necessary, temporarily add a settling aid such as polymer or alum until the MLSS is reduced. (This will not help if the problem is strictly the result of solids overload, but it may help if poor settling is a factor).
- Try to implement a step-feed operating strategy, if possible.

Using additional clarifiers increases the clarifier surface area, reducing the solids loading rate. This is a low-cost option and typically is easy to do.

Bringing another biological reactor online makes it possible to reduce the MLSS concentration without changing the F:M. The extra volume provided by additional biological reactors makes it possible to have the same volatile solids inventory with a lower MLSS concentration, which effectively reduces the solids loading rate. Placing another biological reactor online may increase power costs, therefore other corrective actions should be considered first.

If prior solutions do not improve the situation, MLSS concentration should be decreased by significantly increasing the wasting rate. Be aware that the F:M is increasing and MCRT is decreasing during this procedure because the solids inventory will decrease. If this is the last resort to reduce the solids overload on the clarifier, reduce the MLSS concentration 20% in one day, reduce an additional 15% the second day, and hold it at that level.

If no improvement occurs during any of these adjustments, high effluent SS concentrations are most likely not the result of solids overloading. Try to improve sludge settleability by changing process conditions through wasting or environmental changes. Adding polymer, alum, or iron salts will help if poor settleability is a factor by shortening the response time for improvements.

TEMPERATURE CURRENTS. Temperature currents occasionally occur in large, deep clarifiers in colder climates, most often in the spring and fall.

A temperature profile of the clarifier will identify the presence of temperature currents. The temperature probe on a DO meter is an excellent tool for this procedure. To make the profile, measure and record the temperature at the head, one-quarter, one-half, three-quarters, and tail end of a rectangular or square clarifier, or at quarter points across a circular clarifier. At each point, measure the temperature at the surface and

quarter points down to the reactor bottom. Be careful that the temperature probe and wires do not get entangled in the sludge-collection equipment.

If deeper temperatures are consistently cooler by 1 to 2 °C (2 to 4 °F) or more, temperature currents are present. If temperature differences are caused by surface warming from the sun, reducing the number of clarifiers online or rigging temporary covers over the clarifiers may help. Installing baffles may improve the settling by breaking up currents and stopping turbulence.

Bulking Sludge. The presence of clear supernatant above poorly settling sludge (See Figure 20.36) indicates that settling is being hindered by the presence of filamentous microorganisms. The presence of filamentous microorganisms is corrected by improving the treatment environment by adding nutrients such as nitrogen, phosphorus, and iron; or by correcting the DO concentration in the biological reactor; or by correcting a pH condition. The presence of a cloudy effluent above a poorly settling sludge indicates dispersed-growth bulking and either improper organic loading, overaeration, or toxics. Classic sludge bulking in the clarifier is illustrated in Figure 20.45.

Some probable causes of the bulking problem are

1. If filamentous microorganisms are present (filamentous bulking)
   - Low-DO concentrations in biological reactors,
   - Insufficient nutrients,
   - Improper pH—either too low or widely varying,
   - Warm wastewater temperature,
   - Widely varying organic loading,
   - Industrial wastes with high biochemical oxygen demand (BOD) and low nutrients (N and P) such as simple sugars or carbohydrates (for example, whey waste),
   - High influent sulfide concentrations that cause the filamentous microorganism *Thiothrix* to grow and produce filamentous bulking,
   - Very low F:M, allowing *Nocardia* predominance,
   - Massive amounts of filaments present in influent wastewater or recycle streams, and
   - Insufficient soluble 5-day BOD (BOD_5) gradient (as found in completely mixed biological reactors).
2. If few or no filamentous microorganisms are present (dispersed-growth bulking)
   - Improper organic loading—either too high or too low F:M,
   - Overaeration, and
   - Toxics.



FIGURE 20.45 Sludge bulking in clarifier.

The first step in analyzing this condition is to examine the mixed liquor under a microscope.

FILAMENTOUS MICROORGANISMS PRESENT. If a moderate to large number of filamentous microorganisms are present (Figure 20.36)

- Identify the type of filament. If the plant staff does not have the equipment or expertise, outside help should be used.
- Measure the DO concentration at various locations throughout the biological reactor.
- If the typical DO concentration throughout the reactor is less than 0.5 mg/L, there is insufficient DO in the biological reactor. Increase aeration until DO increases to 1.5 to 3 mg/L throughout the tank.
- If DO concentrations are nearly zero in some parts of the reactor but are higher in other locations, the air distribution system on a diffused air system may be off balance or the diffusers in an area of the reactor may need to be cleaned. Balance the air system and clean the diffusers. If a mechanically aerated system is used, increase aerator speed or raise the overflow weirs.
- If DO concentration is low only at the head of the tank, which is being operated in the plug-flow pattern, consider changing to the step-feed or complete-mix

flow patterns or using tapered aeration, if possible. However, a low DO concentration only at the head of the reactor may not be a problem as long as adequate reaction time is available in the rest of the reactor.

- Calculate the ratios of BOD_5 to nitrogen (use total Kjeldahl nitrogen [TKN] expressed as N), BOD_5 to phosphorus (expressed as P), and BOD_5 to iron (expressed as Fe). Generally, a proper nutrient balance in an activated-sludge system is 100:5:1 (BOD:N:P). Refer to Appendix A for procedures on checking nutrient levels and calculating how much nutrient to add if there is a problem. In general, anhydrous ammonia is used to add N, trisodium phosphate is used to add P, and ferric chloride is used to add Fe. The ratio of BOD_5 to required nutrients changes with MCRT. For example, high MCRTs produce less sludge and result in lower nitrogen and phosphorus requirements. Typically, 3 to 5 mg/L of nitrogen (3 mg/L at high MCRTs and 5 mg/L at low MCRTs) and 1 mg/L of phosphorus is needed for every 100 mg/L of BOD_5. Typically, a nutrient-deficient waste will not occur with domestic wastewater. However, if a plant is receiving industrial discharge, such as from a canning company, a nutrient-deficient waste could occur.

If there are insufficient nutrients in the wastewater, two things can happen:

1. Filamentous bacteria will predominate or take over the MLSS.
2. Organic materials will only be partially converted to end products; that is, there will be inefficient BOD_5 or chemical oxygen demand (COD) removal.

If excess nutrients are added to the wastewater to overcompensate for a nutrient deficiency, a large fraction of these nutrients may not be incorporated to the MLSS and may, therefore, pass into the effluent. Nutrients, if required, should be added at the head of the biological reactor. Mixed liquor settleability should be carefully observed to see if it is improving. If settleability improves, the nutrient dose can be reduced by 5% per week until settleability decreases. Then the dose should be increased by 5% and the settleability observed.

Nutrients are expensive and should be carefully applied. For example, adding excess ammonia may create a nitrification demand. Nutrient dosage should be increased as BOD concentrations increase, which takes into account the effects of the additional microorganism growth that will occur. If settleability does not improve readily, nutrient dosing should be continued until the actual problem is identified and solved because the problems that are causing poor settleability may be interrelated.

If pH in the biological reactor is less than 6.5 or is widely varying, mixed liquor settleability may be affected because bacteria that settle readily are inhibited. If the raw

wastewater pH is less than 6.5 and the water supply pH is higher, the low pH problem is probably a result of industrial waste, and a survey should be made to identify the industry that is violating its discharge permit. The best procedure, if possible, is to prevent the problem by controlling it at the source. A good industrial waste monitoring and enforcement program will avoid many difficulties in this area.

Also, nitrification destroys alkalinity and reduces the biological reactor pH. The nitrification process can be inhibited at pH's below 7.0 and could cease if the pH goes below 6.5. If this is the cause of the problem, raise the MLSS pH by adding sodium bicarbonate ($NaHCO_3$), caustic soda (NaOH), or lime ($Ca(OH)_2$) at the head of the biological reactor. If nitrification is required, the MLSS pH should be kept above 7.0 and held as constant as possible to encourage an acceptable rate of nitrification. Be sure that the treatment system is not shocked by high pH levels or overdosed to pH levels greater than 9.

When determining the amount of $NaHCO_3$, NaOH, or $Ca(OH)_2$ needed for pH adjustment to correct a filamentous-bulking problem, obtain and weigh (or measure) a small amount (1 to 2 g) of the actual chemical to be used in the treatment process. While stirring a measured sample, add small increments of the chemical until the pH is approximately 7.2. Then weigh (or measure) the portion not used to determine the amount used in the titration.

Adding $NaHCO_3$, NaOH, or $Ca(OH)_2$ to raise pH is expensive. Mixed liquor settleability should be closely monitored to observe changes to ensure that the chemical added is effective. If no improvement occurs within 2 to 4 weeks and nothing else in the process has changed in the meantime, then chemical addition should be stopped.

A uniform low concentration of soluble BOD, as found in completely mixed biological reactors, is considered by some to encourage the growth of some types of filamentous microorganisms that compete with floc formers to cause low F:M bulking. One technique suggested to control F:M filaments is use of a mixing zone for the wastewater and RAS. In this mixing zone, a high growth rate environment is provided to promote the growth of floc-forming organisms at the expense of filamentous organisms.

FILAMENTOUS FOAMING. Three filamentous organisms can cause activated-sludge foaming: *Nocardia* sp. (most common), *Microthrix parvicella* (less common), and type 1863 (rare) (Jenkins et al., 1993, and Richard, 1989). These three types of filamentous organisms can be distinguished from one another through microscopic examination and staining. *Nocardia* foaming seems to be the most common and severe. Little is known yet about foaming by the other filaments (Richard, 1989).

Filamentous organisms can produce a stable, viscous, brown foam on the biological reactor surface that can shift over onto the clarifier surface and may even escape in the effluent, violating permit limits. Foaming can range from being a nuisance to being

a serious problem. In cold weather, foam may freeze and have to be removed manually with a pick and shovel. In warm weather, it often becomes odorous. Because several species of *Nocardia* and *Mycobacterium* have been isolated from activated-sludge foams that can be opportunistic human pathogens, activated-sludge foaming should not be taken lightly because of possible harmful health effects. Samples of the foam and mixed liquor should be microscopically examined to determine if the foaming is in fact attributable to filamentous growths (Jenkins et al., 1993, and Richard, 1989). The following discussion focuses on *Nocardia* foaming.

The analysis of *Nocardia* foaming involves two factors:

- The factors that allow *Nocardia* to grow in activated sludge, and
- The conditions that cause foaming (Jenkins et al., 1993, and Richard, 1989).

Nocardia growth is typically associated with warmer temperatures, grease, oil, and fats present in treated wastes and longer solids retention times (SRTs) (typically more than 9 days), although it has been frequently encountered at SRTs of 2 days. Foam, however, typically has a longer SRT than the underlying MLSS, and calculations of retention time may be incorrect (Richard, 1989).

Nocardia foaming seems to involve the hydrophobic (water repellant), waxy nature of the *Nocardia* cell wall, which tends to cause flotation under aeration (Richard, 1989). *Nocardia* cells in the mixed liquor concentrate in the foam and continue to float even after they die.

Plants prone to *Nocardia* foaming often receive oil and grease wastes (for example, from restaurants without grease traps); have poor or no primary scum removal; recycle scum rather than remove it from the plant; and have biological reactor configurations such as submerged wall cut outs or effluent gates that trap foam.

The best way to deal with *Nocardia* foaming is to prevent the conditions that encourage *Nocardia* growth. Once established, *Nocardia* foaming can be extremely difficult to eliminate because

- Foam is difficult to break with water sprays.
- Foam typically does not respond to chemical antifoamants.
- Chlorinating RAS, although often helpful, does not eliminate *Nocardia* because most of it is in the floc and not exposed to chlorine.
- Increased wasting has its limitations because
  —Foam is not wasted with the WAS.
  —Even if foam and scum are removed from the process, they can cause problems in downstream units such as digesters and also can be recycled with decant or supernatant to the activated-sludge process.

—Reducing the SRT to fewer than 9 days (the classic cure for *Nocardia* growth and foaming) may be inadequate. Many plants must reduce the SRT to fewer than 2 days, which may conflict with other process goals, such as nitrification or sludge-handling capabilities. Numerous *Nocardia* species are involved in foaming. Of the two most dominant, one is slow growing and the other is fast growing. The SRT needed to control *Nocardia* foaming may depend on which species is involved (Jenkins et al., 1993, and Richard, 1989).

One proactive approach to dealing with *Nocardia* is to provide surface-wasting facilities to remove the foam and scum from the surface of the biological reactors or a convenient channel. The foam and scum should then be taken to a dissolved air flotation (DAF) thickening process (with the WAS) and removed from the system. Another is to provide a fine contained spray of a highly concentrated chlorine solution (0.5 to 1.0%) directly to the surface of the biological reactor where the foam is located.

A positive way to treat severe *Nocardia* foaming is to correct the cause (control greases and fats and increase wasting) while also physically removing (e.g., with a vacuum truck) the biological reactor foam and clarifier scum. Sometimes a cationic polymer can be used to correct a foam problem (Shao, 1997). Once removed, this material must be separated so it will not recycle through the plant.

FILAMENTOUS BULKING. A variety of influent and plant conditions can encourage the growth of filamentous organisms that cause filamentous bulking.

Table 20.7 is a general guide that relates bulking by specific filamentous organisms to various plant conditions. However, many of the associations shown are tentative and, for many filamentous organisms, as yet incomplete (Richard, 1989).

A practical approach to control filamentous bulking includes

- Confirming that the problem is indeed caused by filaments.
- Identifying the filaments involved.
- Determining the specific set of appropriate remedies (both short- and long-term) for the filaments involved:
  —Short-term solutions involve treating the symptoms (changing influent feed points, changing RAS rates, adding settling aids, and chlorinating); and
  —Long-term solutions involve treating the cause (controlling mixed liquor pH, controlling influent septicity, adding nutrients, changing aeration rates, and changing F:M).

Chlorination neither satisfactorily controls poor settling due to viscous activated sludge caused by nutrient deficiency nor controls dispersed-growth bulking. Chlorina-

TABLE 20.7 Filament types as indicators of conditions causing activated-sludge bulking (Jenkins et al., 1993).

Suggested causative condition	Indicated filament types
Low DO concentration (for applied organic loading)	*S. natans*, Type 1701 and *H. hydrossis*
Low organic loading rate (F:M) in completely mixed biological reactors	*M. parvicella*, *Nocardia* spp., *H. hydrossis*, and Types 021N, 0041, 0675, 0092, 0581, 0961, and 0803
Septic wastes and sulfides	*Thiothrix* spp., *Beggiatoa* spp., and Type 021N
Nutrient deficiency: nitrogen or phosphorus (industrial and mixed industrial–domestic wastes)	*Thiothrix* spp. and Types 021N, 0041, and 0675
Low pH (less than 6.5)	Fungi

tion exposes activated sludge to chlorine levels that damage filaments extended from the floc surface while leaving organisms within the floc largely untouched. Filamentous and floc-forming bacteria do not seem to significantly differ in their chlorine susceptibility (Richard, 1989).

One approach is to set a target SVI (or other measure of settleability) for satisfactory operation of secondary clarifiers and solids-processing units and chlorinate only when the target is significantly and consistently exceeded (Jenkins et al., 1993). This approach treats the symptom, not the underlying problem.

Location of the chlorine application point is critical. The point should be located where there is excellent mixing, where the sludge is concentrated, and where the wastewater concentration is at a minimum (to reduce unwanted reactions with the chlorine) (Richard, 1989). The three common application points are in the RAS stream, directly in the biological reactor at each aerator, and in an installed side stream that recirculates mixed liquor within the biological reactor.

Chlorine dose and the frequency at which organisms are exposed to chlorine are the two most important parameters. The dose is adjusted so that concentrations are lethal at the floc surface but not within the floc. The chlorine dose should be based on the solids inventory in the process (biological reactors plus clarifiers). This is called the *overall chlorine mass dose*, and effective dosages are in the range of 1 to 10 g/kg·d MLVSS (1 to 10 lb chlorine/d/1000 lb MLVSS). The dose must be accurately measured, preferably by using a chlorinator dedicated to this purpose. Initially, start at a lower dose and gradually increase the dose until it is effective (Richard, 1989).

Frequency of exposure is a measure of how often the entire solids inventory is subjected to an excessively high chlorine dosage. Required frequency of exposure depends on relative growth rates of filamentous and floc-forming organisms and the effectiveness of each dose. While the frequency of exposure is plant specific, three times or more per day were reported as sufficient (Jenkins et al., 1993), and success has been reported at frequencies as low as once per day (Richard, 1989). The actual dose applied at each exposure should be simply the total calculated dose per day divided by the number of exposure events.

Control tests should be performed during chlorination to assess the effects of chlorine on both filamentous and floc-forming organisms. The tests should measure settleability (e.g., SVI), effluent quality (turbidity), and activated-sludge quality (microscopic examination) (Jenkins et al., 1993). An adequate chlorine dose should start to improve settleability within 1 to 3 days (Richard, 1989). A turbid, milky effluent and a reduction in BOD removal are signs of overchlorination, although a small increase in effluent suspended solids and BOD concentrations are normal during chlorination for bulking control. The microscopically visible effects of chlorine on filaments include (in order)

- Intracellular sulfur granules (if present) disappear,
- Cells deform and cytoplasm shrinks, and
- The filaments break up and dissolve.

Chlorine does not destroy the sheath of sheathed filaments, and this causes poor sludge settling until they are wasted from the system. Chlorination should be stopped when only empty sheaths remain, not continued until the SVI falls (Richard, 1989). Adding chlorine beyond this point may overchlorinate. Because the effects of chlorine on filaments can be detected microscopically before settleability improves, microscopic examinations can provide an early indication of filament control.

FILAMENTOUS MICROORGANISMS NOT PRESENT. If few or no filamentous microorganisms are present, check the F:M to determine if the system is operating at a higher or lower than normal F:M. The presence of small, dispersed floc is characteristic of an increased F:M. If the F:M is higher than normal by 10% or more, the wasting rate should be decreased. The decrease in F:M should be reflected by the disappearance of the dispersed floc over a period of two to three MCRTs.

The amount of turbulence and DO in the biological reactor is also important. In most plants, DO concentrations greater than 4.0 mg/L indicate that excess air is being used, and the aeration rate should be reduced to lower the DO concentrations to the

1.5- to 3-mg/L range. (If the plant uses fine-bubble diffusers or pure oxygen, higher DO concentrations can be safely maintained). Excessive turbulence (overaeration) in the biological reactor may hinder MLSS floc formation and result in pinpoint floc being carried over with the clarifier effluent.

Toxics such as industrial wastes may also cause dispersed-growth buildup.

Clumping/Rising Sludge. Occasionally, sludge that has otherwise good settling characteristics may rise to the clarifier surface (Figure 20.46). This can occur even if settling aids such as polymer or alum are being fed as a coagulant. Floating clumps of solids and fine rising bubbles will be observed. The cause of this phenomenon is denitrification, which requires nitrification to occur first (unless industrial wastes are contributing nitrates).

For significant nitrification to take place, the mixed liquor temperature must be high and/or the MCRT must be long. Denitrification occurs in settled sludge under anaerobic conditions and in the presence of nitrate. Nitrogen gas is released and becomes trapped in the sludge mass. If enough gas is produced, portions of the sludge mass become buoyant and rise to the surface, typically in dark clumps, where they eventually flow over the weir.



FIGURE 20.46 Clumping in clarifier.

For denitrification to take place, not only must the activated-sludge process be nitrifying (unless industrial wastes are contributing nitrates), but three conditions must also be present within the sludge blanket

1. Low DO concentration (less than 0.5 mg/L). Removing the sludge too slowly from the clarifier may drive the DO down to this concentration.
2. High nitrate concentration (typically more than 5 mg/L).
3. Residual BOD_5 (typically more than 10 mg/L).

Long SRT in the clarifier can result in denitrification.

Thick sludge blankets (caused by a low RAS rate) and low mixed liquor DO concentrations are contributing factors.

Rise time in the mixed liquor settleability test (see Figure 20.36) is a key parameter to watch during warm-weather operations. When rise times drop below 2 hours, be alert for rising sludge problems.

High respiration rates on samples of mixed liquor taken at the clarifier inlet may also indicate that conditions are sufficient for denitrification in the clarifiers.

Some probable causes of sludge clumping are

- The process is being operated at a low F:M and, consequently, the process has slipped partly or completely into the nitrification zone.
- The sludge is being held too long in the clarifier and, consequently, all of the available DO has been used by the microorganisms.
- There is a higher than normal wastewater temperature, resulting in a higher rate of microorganism activity that causes the process to nitrify at a higher F:M. A higher rate of microorganism activity will also more quickly deplete the DO in the settled sludge and, consequently, pose a greater potential for denitrification.

The following measures can be tried when applicable to correct the sludge clumping problem:

- Increase the RAS rate to reduce detention time of sludge in the clarifiers. A periodic measurement of the clarifier sludge blanket depth will help determine the proper return rate.
- Where a suction-type sludge collector is used, check that all suction tubes are flowing freely with a fairly consistent SS concentration. Some of the suction tubes may be improperly adjusted or plugged, resulting in coning in some areas and a sludge blanket buildup in other areas.
- Where possible, increase the sludge collector speed.

- Reduce the number of clarifiers online to shorten the detention time.
- If nitrification is not required, gradually increase the WAS rate to shorten the MCRT and increase the F:M to stop nitrification. Initially, the solids inventory should be decreased by 20 to 30% over 1 week, and then the process operation must be observed to determine if nitrite and nitrate levels are dropping. If, after approximately 2 weeks, they have not dropped to below 5 mg/L, reduce the inventory by another 20 to 30%. As a guide, calculate the F:M or MCRT and compare it to published values for nitrification. In very warm waters it may be necessary to drop the MCRT to approximately 2 days (F:M greater than 0.6) and MLVSS less than 1000 mg/L.
- In severe cases and if nitrification is not required, chlorinate the RAS at low rates to stop nitrification.
- When nitrification is required, gradually decrease the WAS rate to increase the MCRT and lower the F:M to be sure nitrification is complete and soluble BOD concentrations are low.

Cloudy Secondary Effluent. During periods of high effluent SS concentrations, the mixed liquor settleability test should be run immediately and followed up with additional tests several times a day until the problem is identified and corrected. When the mixed liquor in the settleability test settles poorly, leaving a cloudy supernatant (see Figure 20.36), the next step is to examine the mixed liquor and RAS under a microscope. One of the important purposes of this examination is to determine the presence of protozoa and the status of their health.

PROTOZOA PRESENT BUT INACTIVE. When protozoa are present but appear to be inactive, it frequently indicates that a slug of toxic material, such as heavy metals, has recently entered the treatment system. Also, the type of protozoa and number of each type are important in troubleshooting the problem.

Check the respiration rate. If it is low, it is a further indication of a toxic sludge. Reduce the WAS rate, but otherwise maintain normal operation until the material passes through the treatment system, if it has not already. Then, try to identify whether toxics were actually present in the sludge by determining the presence of, for example, metals. Whenever evidence of toxics is found, thoroughly follow up to identify the pollutant and remove its source. Refer to Table 20.8 for information on inhibitory concentrations of inorganic pollutants.

PROTOZOA PRESENT AND ACTIVE. If protozoa appear normal and active (i.e., healthy), but the effluent is cloudy, the activated-sludge floc may be dispersed as a

TABLE 20.8 Concentrations of inorganic pollutants affecting activated-sludge treatment processes.

	Concentration, mg/L		
Pollutant	**No effect (less than)**	**Inhibitory**	**Upset**
Ammonia	100.0	—	480.0
Arsenic	0.1	0.1	0.1
Borate	0.1	1.0	0.1
Cadmium	—	1.0–100	50.0
Chromium (+6)	—	1.0–10	—
Chromium (+3)	—	50.0	—
Copper	0.2	0.5[a]	1.0
Cyanide	0.1	0.3–100	200.0
Iron	—	1.0–1000	1000.0
Lead	0.1	0.1	—
Manganese	10.0	20.0	60.0
Mercury	—	0.1	200.0
Nickel	—	1.0	20.0
Silver	—	9.0	30.0
Sulfide	—	20.0	—
Zinc	0.3	0.5	5.0

[a]The nitrification process would be inhibited at 0.05 mg/L

result of excessive turbulence (overaeration) in the biological reactor or excessive floc shearing at the clarifier inlet.

Also, there could be too many flagellates or amobae, which indicate a young sludge that may not settle well and leaves a cloudy effluent.

FEW OR NO PROTOZOA PRESENT. If few or no protozoa are present, there are two possibilities. First, the F:M could be too high and the system may be overloaded. In this case, the following measures can be taken when applicable to correct the problem.

- Calculate the F:M and compare it to F:Ms for periods of satisfactory operation. If the current F:M is greater than these values, reduce the WAS rate to increase the solids inventory.
- Increase the RAS flow to lower the sludge blanket level in the clarifier to the minimum. Increased RAS flow will increase the solids inventory by transferring the MLSS stored in the clarifier to the biological reactor.
- Consider letting the blanket build up. Sometimes this can produce a blanket-filtering effect, although this can be a complicated way to operate.

Second, the F:M may be lower than or in the normal range. This condition is frequently associated with one of the following:

- Low DO concentration in the biological reactor.
  —If the average DO concentration measured at several locations is less than 0.5 mg/L, aeration should be increased until the DO concentration is between 1.5 and 3 mg/L.
- A toxic waste in the treatment system.
  —Toxic waste adversely affects the health of the activated sludge. If metals are present in the mixed liquor, consider increasing the WAS rate for approximately 1 week to purge the system. A short-term solution would then be to add large quantities of healthy seed sludge from another plant to build up the volatile solids inventory. The long-term solution requires conducting an industrial waste survey to identify the source of the toxic material and strictly enforcing the sewer-use ordinance.

Table 20.8 shows U.S. EPA findings for inhibition of various pollutants on the activated-sludge process. There are many cases in which concentrations shown in the table overlap; that is, the concentration for "No effect" may be more than the concentration for "Inhibitory." This occurs because of the number of variables leading to a wide range of concentrations for observed effects. Key variables not accounted for in this table include treatment process mode (i.e., high rate, complete mix), pH, temperature, synergism, acclimation, and full-scale or pure culture at bench scale. Research reported in the literature indicates that activated-sludge systems may become acclimated to heavy metal levels considerably higher than those shown.

Except for the data [in Table 20.8] information on some organic chemicals is limited. Information on shock load sensitivity is also limited, but can be addressed in general qualitative terms. If other factors are equal, the inhibitory effect should be a function of concentration in relation to the active biomass (expressed as weight of pollutant per weight of biomass). If this assumption is used, the effect of a given influent pollutant concentration (expressed as milligrams per liter) can be evaluated for each treatment mode. For plug flow with zero intermixing, the shock load effect would be most intense. Systems using higher mixed liquor suspended solids concentrations would be affected less because the influent pollutant would be spread over more biomass. Similarly, the complete mixed system is considered more resistant to shock loads.

Ashing. The appearance of small ashlike particles floating on the surface of the secondary clarifier (Figure 20.47) is commonly referred to as ashing. The ash may be particles of

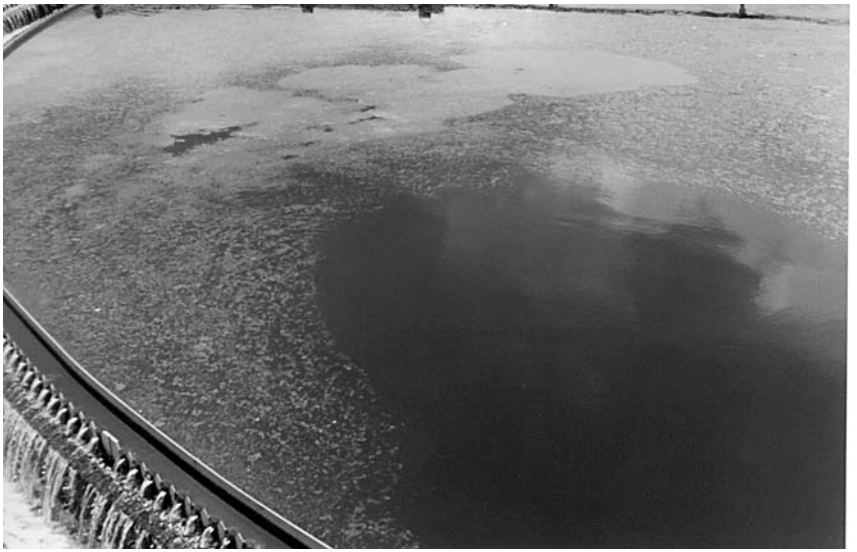


FIGURE 20.47 Ashing in clarifier.

dead cells, as well as normal sludge particles and grease. Some probable causes of ashing are denitrification beginning or occurring in the clarifier, extremely low F:M beyond normal extended aeration (less than 0.05), and unusually high grease content in the mixed liquor.

The ashing problem should be approached and solved as follows. First, stir the solids that float in the mixed liquor settleability test (see Figure 20.36). Proceed as follows:

- If floating solids release bubbles and then settle, this indicates that denitrification has begun. See the "Clumping/Rising Sludge" section earlier in this chapter for a solution.
- If stirred floating solids do not settle, there may be an overoxidized mixed liquor that has many higher microorganisms, few lower microorganisms, and many dead cells. This type of mixed liquor may settle quickly but will not flocculate well and leaves many particles behind. Some of the particles of dead cells that do not settle will accumulate on the water surface, forming an ash. If ashing is significant enough to affect effluent quality by increasing effluent SS concentrations, WAS rates can be increased by not more than 10% per day to increase the F:M and lower the MCRT to optimum values.

- If the floating solids do not settle, there may also be excessive amounts of grease in the sludge. Perform a grease analysis. If the grease content exceeds 15% by weight of the MLSS, the problem may be one of the following:
  —The primary tank scum baffles are malfunctioning because of hydraulic overloading or mechanical failure. Specific attention should be given to scum baffles and the scum collection system in the plant.
  —Too much grease is being put into the sewer by an industrial or commercial discharger. If too much grease is in the raw wastewater, an industrial waste survey must be conducted to identify the discharger and have the problem corrected.

Pinpoint Floc. The appearance of small, dense pinpoint floc particles suspended in the clarifier is a common problem seen in treatment plants operating near the lower end of the loading range (between conventional and extended aeration). This problem is typically related to a sludge that settles rapidly but lacks good flocculation characteristics.

Some probable causes of pinpoint floc are

1. The process is being operated at an F:M near or in the extended aeration range, resulting in old sludge with poor floc formation characteristics; and
2. Excessive turbulence (overaeration) in the biological reactor shears floc formations.

The following measures can be taken when applicable to correct the problem:

- If the sludge-settling characteristics observed during the mixed liquor settleability test (refer to Figure 20.36) indicate a sludge settling too rapidly with poor floc formation, the clarifier effluent quality can be improved by gradually lowering the MCRT by increasing the WAS rate. If nitrification is required, caution must be used to avoid decreasing nitrification by wasting too much sludge.
- If the settleability test indicates good settling with clear supernatant above the settled sludge, check for proper aeration and mixing in the biological reactor. If the average DO concentration in the reactor is more than 4 mg/L and nitrification is not required, consider reducing aeration until the DO concentration is between 1.5 and 3 mg/L.
- If there are facilities for feeding settling aids such as alum, ferric chloride, or polymer, determine the required dose and start feeding a settling aid as a temporary measure while correcting the source of the problem. Refer to Appendix E for a procedure on calculating how much settling aid to add.

Straggler Floc. The appearance of small, almost transparent, very light, fluffy, bouyant sludge particles rising to the clarifier surface near effluent weirs and discharging over the weirs is a problem often seen when the MLSS concentration is too low. When this type of straggler floc occurs while the secondary effluent is otherwise exceptionally clear, and particularly if it prevails even during relatively low surface overflow rates, the problem is typically related to a low MCRT (high F:M). At some plants, the floc is particularly noticeable during the early morning hours. In many plants, this problem is present but has no significant effect on effluent quality. Straggler floc is not a concern unless it causes an effluent quality problem.

Some probable causes of this problem are

- The biological reactor is being operated at an MLSS concentration that is too low. (This would typically occur during process startup until the proper MLSS concentration is reached). A WAS rate that is too high will result in low MLSS and a high F:M.
- Sludge is being wasted on a batch basis during the early morning hours, resulting in a shortage of microorganisms to handle the daytime organic loading.

The following measures can be taken when applicable to correct the problem:

- Decrease the WAS rate to increase the MLSS concentration and MCRT.
- If wasting sludge on a batch (or intermittent) basis, avoid wasting when the BOD load is increasing. Also, increase the RAS rate as peak flows start. All of the organisms are needed at this time to handle the daily increase in organic loading. Decrease the RAS rate at night.

Floating Sludge Due to Deep Tank Aeration. Treatment sites that have space restrictions have had to construct deep biological reactors (more than 6 m [20 ft] deep) to meet the necessary aeration volume to treat the wastewater. These deep reactors have resulted in problems at various wastewater treatment plants. Deep tank aeration systems can cause the MLSS to become supersaturated with gases (oxygen and nitrogen). When mixed liquor leaves the biological reactors and enters the clarifiers, these gases are released, causing the sludge to float to the surface similar to a DAF thickener. Studies conducted in the United States and Japan found that floating sludge, mechanical-aeration systems occurred both in pilot tests and full-scale operations (Fujii and Fukuda, 1974). Floating sludge from deep biological reactors can also be experienced at facilities using diffused-air systems such as occurred in New York City's North River Plant (Lu et al., 1990).

If a treatment plant is experiencing floating sludge on its secondary clarifiers because of deep biological reactor systems and not filamentous organisms, there are several alternatives for correcting the problem. The key is to strip out the gases from the mixed liquor before it reaches the clarifiers. This can be accomplished by

- Stripping the gases in an aerated mixed liquor channel to the clarifiers by increasing solids agitation;
- Installing diffusers in the biological reactors at the midpoint liquid elevation in the tank. (The lower level of the tank is continuously mixed by diffusers along the tank bottom or mixed by using mechanical aerators with draft tubes and air spargers);
- Installing a weir in the mixed liquor channel or at the effluent end of each biological reactor so that the spilling action causes a release of the gases; and
- Installing a shallow (3 to 5 m [10 to 15 ft]) biological reactor with a short hydraulic residence time (15 to 30 minutes) after the deep tanks, provided that sufficient area is available.

BIOLOGICAL NUTRIENT REMOVAL SYSTEMS

INTRODUCTION. Regulatory agencies are requiring treatment plants to produce cleaner effluents with fewer pollutants and nutrients such as phosphorus and nitrogen. More treatment plants are being converted or constructed as BNR facilities that are designed to control effluent phosphorus, nitrogen, or phosphorus and nitrogen. There are many variations to the biological phosphorus and nitrogen processes currently used at wastewater treatment plants and these variations are described in other sections of this chapter and manual, *Design of Municipal Wastewater Treatment Plants* (WEF, 1998), and *Biological and Chemical Systems for Nutrient Removal* (WEF, 1998).

Specialized processes for both phosphorus and nitrogen control use biological reactors that have baffles for creating zones with different environmental conditions. Several terms are used to describe these zones. Aerobic, or oxic, indicates a zone that contains DO. Anoxic refers to a zone that has a DO of less than 0.5 mg/L but has an input of nitrate nitrogen. An anaerobic zone has an input of organic substrate, contains no DO, and has no input of nitrate-nitrogen.

Other terms used are RAS recycle and internal recycle. Return activated sludge recycle is the return flow of biomass from the underflow of the secondary clarifier to the biological reactors. Internal recycle is flow directed from one reactor zone to another.

Processes have been developed for biological phosphorus removal only, nitrogen removal by biological nitrification and denitrification only, and removal of both nutri-

ents in dual or combined systems. Depending on the effluent residual requirements and reliability attainment goals, some chemicals may have to be added to supplement these processes.

This section highlights general troubleshooting aspects of these processes. The standard troubleshooting guidelines for activated-sludge systems can be used for some aspects of BNR processes; however, these systems have unique concerns that must also be addressed, such as, BOD-to-phosphorus ratios, nitrate concentrations in the anaerobic zone, internal recycle rates, and other process controls related to a particular BNR process.

BIOLOGICAL PHOSPHORUS REMOVAL PROCESSES. The basic concept of a biological phosphorus removal system is to cycle the activated-sludge microorganisms through an anaerobic zone and then an aerobic zone. In general, the hydraulic retention time through the anaerobic zone is 2 to 4 hours and through the aerobic zone is 4 to 6 hours. In addition, this system requires the proper soluble BOD to soluble phosphorus ratios to work. These ratios are typically in the range of 20 to 25 to achieve a 0.5-mg/L effluent total phosphorus concentration.

This process can also be affected by the type of in-plant sidestreams that are returned to the treatment process. Because this is a biological process, operators must watch various environmental conditions such as DO concentration in the aerobic zone, alkalinity levels, toxic materials entering the system, temperature, and other conditions that could affect the microorganisms.

Table 20.9 presents a troubleshooting guide for biological phosphorus removal processes. This guide will enable operators to help identify problems and their solutions.

NITRIFICATION SYSTEMS. Conversion between carbonaceous and nitrification treatment modes depends on the system used. The two basic types of nitrification systems are a single-stage system, in which both carbonaceous and nitrogenous uptake occur in the same tank and a two-stage system that is essentially two complete activated-sludge processes in series. In the two-stage system, the first stage, which has its own intermediate clarifiers, provides carbonaceous removal, while the second provides ammonia oxidation.

In either system, the basic feature enabling nitrification is a long SRT (or low F:M) of sufficient duration to allow the more slowly growing nitrifiers to develop. The necessary SRT or F:M values are temperature dependent. For single-stage systems, the SRT ranges from 8 to 10 days during the summer, when the wastewater

TABLE 20.9 Troubleshooting guide for biological phosphorus removal.

Observations	Solutions
Effluent soluble phosphorus >1 mg/L, total phosphorus >2 mg/L, and BOD <20 mg/L	Ensure that DO concentration in anaerobic zone is <0.2 mg/L and that nitrate concentration in anaerobic zone is <5 mg/L
Effluent soluble phosphorus <1 mg/L, total phosphorus >2 mg/L, BOD >25 mg/L, and SS >30 mg/L	Check SS frequently; use polymer or metal salt to control SS; find reason for high SS, such as high flow rates, high RAS rate, or bulking
Effluent soluble phosphorus <0.2 mg/L, total phosphorus <1 mg/L, and BOD >30 mg/L	Plant may be organically overloaded; check F:M
Effluent soluble phosphorus >1 mg/L, total phosphorus >2 mg/L, and BOD <30 mg/L	May not be enough low-molecular-weight acids in anaerobic zone; consider adding anaerobic digester supernatant to this zone
Thin-looking MLSS, effluent total phosphorus >2 mg/L, and BOD <30 mg/L	Sludge may be forming a blanket in secondary clarifier; check sludge blanket depth; adjust recycle rate if necessary
Effluent total phosphorus >2 mg/L, BOD <25 mg/L, and SS <25 mg/L	Start or increase dose of metal salt to assist in precipitating total phosphorus

temperature is 16 to 21 °C (60 to 70 °F), but may climb into the 12- to 20-day range as the temperature drops. When the wastewater temperature drops below 10 °C (50 °F), reestablishing a nitrifying culture, once lost, may not be possible, but typically it can be maintained once it is developed. Operating nitrifying systems at low temperatures is typically more difficult and requires considerable extra capacity in the biological reactor to provide the extended detention times needed to achieve acceptable nitrification levels.

Dissolved oxygen in nitrifying systems must remain at a higher concentration than in carbonaceous activated-sludge systems because of the aerobic nature of nitrifying organisms. A DO concentration of approximately 2.0 mg/L should prevent inhibition of the nitrifiers.

If a nitrification process is not capable of achieving the desired effluent ammonia-nitrogen concentration, there are various parameters to check and different controls that can be implemented to correct the process. Nitrifying organisms are sensitive, so slight changes in their environment will cause them to become inactive. Nitrifying organisms are affected by toxic material, temperature changes, pH, and SRT.

If a problem arises with the nitrification process, identify the cause of the problem and then make the following process changes to correct the situation:

- Maintain the DO concentration in the biological reactors between 2 and 3 mg/L;
- Reduce wasting to increase the SRT to the range necessary to develop nitrifying organisms; and
- Monitor the influent and effluent pH and ammonia, nitrite, and nitrate concentrations.

An indication that there is a problem with the nitrification process is if the chlorine demand on the plant effluent increases dramatically. This is an indication that nitrite is present and, therefore, that nitrification is incomplete. The nitrification process is only complete when ammonia-nitrogen is converted first to nitrite and then to nitrate. Again, the DO concentration in the biological reactor, the SRT, and other such parameters must be checked.

The nitrification cannot go to completion if the pH is significantly below 7.0. Nitrification produces acid, therefore reducing alkalinity and pH. For each 1 mg/L of ammonium-nitrogen oxidized to nitrate, 7.1 mg/L of alkalinity will be consumed. This affects process pH only if the alkalinity is insufficient. The nitrification reaction can be inhibited by low pH; therefore, it is necessary to ensure that there is adequate alkalinity in the wastewater. Alkalinity may have to be added if the influent wastewater has insufficient alkalinity to maintain the pH.

The optimum operating pH for nitrification is in the range of 7.0 to 8.3. The following example illustrates the procedure for checking if sufficient alkalinity is present and, if not, determining how much to add.

It is known that 7.1 mg $CaCO_3$ is consumed in the nitrification reaction per milligram of ammonia oxidized and that a minimum of 50 to 60 mg/L of residual alkalinity is required to maintain the optimum pH range.

Given:

Influent TKN concentration = 20 mg/L
Influent alkalinity = 130 mg/L
Plant flow = 37 800 m^3/d (10 mgd)

1. Calculate the amount of alkalinity required

Alkalinity to maintain optimum pH = alkalinity for ammonia oxidation + residual alkalinity

Alkalinity for ammonia oxidation = (20 mg/L NH_3–N) 7.1 mg $CaCO_3$ required/mg NH_3–N oxidized)

= 142 mg/L $CaCO_3$

Alkalinity required = 142 mg/L $CaCO_3$ required + 50 mg/L of residual alkalinity
= 192 mg/L $CaCO_3$

2. Calculate the amount of alkalinity needed

Alkalinity needed = Alkalinity required − Alkalinity available
= 192 mg/L alkalinity required − 130 mg/L available in influent
= 62 mg/L $CaCO_3$

3. Calculate the amount of alkalinity to be added

Alkalinity to add = (Alkalinity needed) (Plant flow) (Conversion factor)

In metric units:

$$\text{Alkalinity to add} = (62 \text{ mg/L } CaCO_3)\,(37\,800 \text{ m}^3\text{/d})\left(0.001\frac{\text{m}^3\text{/d}}{\text{mg/L}}\right)$$

$$= 2344 \text{ kg/d } CaCO_3$$

In English units:

$$\text{Alkalinity to add} = (62 \text{ mg/L } CaCO_3)\,(10 \text{ mgd})\left(8.34\frac{\text{lb/mil. gal}}{\text{mg/L}}\right)$$

$$= 5171 \text{ lb/d } CaCO_3$$

Careful control of alkalinity is important. By the time the pH decreases to less than 7.0, inhibition of the nitrifying organisms has already occurred.

BIOLOGICAL NITROGEN REMOVAL. Biological nitrogen removal involves two processes—nitrification and denitrification. When designed properly, biological nitrogen removal can be achieved in standard-designed biological reactors, oxidation ditches, sequencing batch reactors, and other process modifications.

To determine the success of biological nitrogen removal processes, the clarifier effluent is tested for ammonia-nitrogen, total nitrogen and nitrate. Typically, ammonia-nitrogen should be less than 1.0 mg/L, TKN at approximately 5 mg/L, and nitrate between 7 and 10 mg/L.

Biological nitrogen removal processes are typically controlled by

- Adjusting DO in the aerobic zone. Depending on process modifications, DO concentrations will range from 0.5 to 2.0 mg/L. If free oxygen (DO) is available, then nitrite (NO_2^-—N) and nitrate (NO_3^-–N) are available, therefore, the micro organisms will use DO first. It is only in the absence of DO that microorganisms will use NO_2^-–N and NO_3^-–N and complete the denitrification process. Therefore, it is critical to minimize the DO concentration in the recycle stream before it enters the anaerobic zone.
- Adjusting the return sludge rate and the internal recycle rate.

It is important that proper conditions be maintained in the anaerobic, anoxic, and aerobic zones of the treatment process. Refer to the "Process Control" sections of this chapter for further definitions and controls of these zones and the beginning of "Biological Nutrient Removal Systems" of this section. If the nitrate concentration gets above 10 mg/L in the anaerobic zone it can affect the process. The nitrate concentration in the anaerobic zone is controlled by the RAS flow rate. The addition of an anoxic zone helps control the nitrate that would typically be returned to the anaerobic zone. It is best to keep the nitrate concentration below 1 mg/L for efficient biological phosphorus removal.

Table 20.10 presents a troubleshooting guide for nitrification and denitrification processes.

Table 20.11 presents a troubleshooting guide for dual nutrient removal processes.

DESIGN AUDIT

Various studies and publications have found that many factors limiting wastewater treatment plant performance were attributed to inadequate plant design. These include deficiencies in sludge wasting capability, process flexibility, process controllability (inability to measure or adjust the process), secondary clarifier design, sludge treatment capacity or operating ease, and aeration capability.

Before troubleshooting a problem, it is important to determine the plant's capabilities and limitations. Design limitations may make it impractical to fully implement some of the more typical solutions to plant problems. Although operator ingenuity has overcome many minor plant limitations, certain design conditions will be difficult or

TABLE 20.10 Troubleshooting guide for nitrification and denitrification processes.

Observations	Solutions
Effluent BOD <25 mg/L, and ammonium >3 mg/L	Ensure that SRT is sufficient for design temperature
Effluent ammonium varies erratically, >3 mg/L, <3 mg/L, and <2 mg/L, in short period of time	Waste sludge operation is not stabilized; stop wasting until ammonium is <2 mg/L for 3 consecutive days; restart a careful sludge-wasting operation
Effluent ammonium >3 mg/L, and dark-brown or black MLSS	Check aeration zone DO; concentration should be >2 mg/L; check MLSS solids balance; SRT may be too long
Brown clumps of sludge floating on final clarifier surface; effluent ammonium <2 mg/L, and BOD <30 mg/L	Nitrogen gas bubbles being produced in stagnant sludge in clarifier; check RAS rate; increase frequency of cleaning of clarifier walls and weirs
Effluent ammonium >10 mg/L, and BOD >25 mg/L	Check SRT and mixed liquor DO and MLSS concentrations. If all seem to be satisfactory, the plant may be receiving an inhibitor of nitrification from industry; check pretreatment program.
Effluent nitrate 7 mg/L, and ammonium <2 mg/L	DO in anoxic zone; concentration should be less than 0.2 mg/L

TABLE 20.11 Troubleshooting guide for dual nutrient removal processes.

Observations	Solutions
Effluent total phosphorus <2 mg/L, ammonium <2 mg/L, and NO_3^-–N >7 mg/L	Check the recirculation rate between aerobic zone and anoxic zone, increase rate if necessary; check DO in anoxic zone, concentration should be <0.2 mg/L
Effluent total phosphorus <2 mg/L, ammonium <2 mg/L, nitrate <2 mg/L, and BOD >30 mg/L	Check feed rate of optional chemical dosing pump for adding organics to second anoxic zone
Effluent total phosphorus <2 mg/L, ammonium >3 mg/L, nitrate <5 mg/L, and BOD <25 mg/L	Check DO in aerobic zone, concentration should be >2 mg/L

impossible to correct without plant modifications. In some cases, design limitations may be so severe that proper operation under normal conditions will be difficult. It is important, therefore, to make a design audit of the plant.

Questions that must be asked include the following (items of major importance are printed in *italic type*)

Wastewater characteristics

- Is the plant protected against shock loads (e.g., with a flow equalization basin)? If not
  —What type of shock load is experienced: organic, toxic, or hydraulic?
  —How often does a shock load occur?
  —What is its duration?
  —What is its source?
- Is there industrial waste? If so
  —What percent of influent flow is industrial waste?
  —What percent of influent BOD_5 and total suspended solids (TSS) load is from industrial waste?
  —Does the city or agency have industrial waste pretreatment regulations and are they enforced?
  —Is industrial waste flow sampled?
  —How often is the flow sampled?
  —*Is the influent flow free of toxic concentrations of industrial waste?*
  —Was industrial waste considered in the plant design?
  —*Are there provisions for adequate pH control?*
  —*Are there provisions to feed supplemental nutrients if needed?*
- Do septic waste trucks discharge to the plant? If so
  —Is the septage analyzed for pH and BOD (and TSS if there are no primary clarifiers)?
  —Is there a septage handling facility to control the discharge to the plant?
  —Is septage a significant load on the activated-sludge process (more than 15% of the BOD_5)?
  —Is there a program to regulate receiving septage?
- Is in-plant recycled flow routinely measured for flow and BOD and SS concentrations? If so
  —Is it high-strength?
  —Is it variable rate?
  —Is it a significant load on the activated-sludge process (more than 15% of BOD_5)?

Plant layout

- *Are there two or more of each biological reactor and pump for operating flexibility?*
- Do reactors, if covered, allow for ready observation of the process?
- Do biological reactors and clarifiers have the flexibility to operate either as parallel process trains, or as a single process train?
- Can flow be accurately split and measured to parallel reactors?
- Is the influent sampler, if located outside, weather protected?
- Is the plant easily accessible during bad weather?
- Is there adequate piping flexibility so that a biological reactor need not be shut down if a clarifier is out-of-service?
- Are there bypasses around individual treatment units, such as biological reactors and secondary clarifiers? If so
  —Where do these bypasses discharge?
  —How are they controlled?
- Are bypasses listed in the discharge permit?

Influent flow measurement

- *Is the flow meter properly sized for low and peak flows?*
- Does the flow meter have a chart recorder and does it adequately show flow variations?
- Is the flow meter unaffected by upstream and downstream hydraulic conditions?
- Are the flow meter and recorder routinely and properly calibrated?
- Are recycle flows included in the plant flow measurement? If so, are they subtracted from influent flow?
- If a Parshall flume is used, is it free of grit deposits?

Biological reactors

- Do the biological reactors have adjustable weirs?
- Do outlet pipes remain free of rags?
- Is there adequate piping to operate in the step-feed or contact-stabilization modes as well as the plug-flow mode?
- Can the influent flow be accurately split and measured among multiple biological reactors?

- Can the RAS flow be accurately split and measured among multiple biological reactors?
- Is there a toxic-element sensing device ahead of, or in, the biological reactor? If so
  —Where?
  —What type?
  —What is the flow travel time between the sensor and biological reactor?
- Do in-plant recycle side streams discharge at the headworks rather than directly to the biological reactor? Also
  —Where do flows originate?
  —Are they measured for flow, pH, and BOD and SS concentrations?
  —Are there facilities for adjusting the pH?
- Are the biological reactors sized for secondary influent plus recycle loads?
- Is the design F:M indicated and appropriate?

Aeration equipment

- Are the blowers properly sized?
- Are there leaks in the air piping?
- Do air diffusers need only normal cleaning, and can they be cleaned with reasonable effort?
- Do surface mechanical aerators operate without overheating or shutting off under increased flows?
- Can the speed of mechanical aerators be varied?
- Do cables on floating aerators withstand intermittent operation?
- Are submerged turbine aerator bearings and shafts reliable?
- Is there adequate freeboard to contain splashing from surface mechanical aerators?
- Are surface mechanical aerators free of icing problems? If not, what are the frequency and extent of the problems?
- Are the surface mechanical aerators free of rag problems? If not
  —What are the frequency and extent of the problem?
  —Are there upstream screening devices?
- Are there provisions for removing rags from surface mechanical aerators?
- How is mixed liquor DO concentration controlled?
- Do the aeration devices meet their design oxygen-transfer efficiencies?
- Can DO concentrations of at least 1.0 mg/L be maintained under all conditions?

Secondary clarifiers

- Is there accurate flow splitting and measurement among multiple clarifiers?
- Are clarifier sidewall depths (SWD) sufficient?

Tank diameter (m) (ft)	up to 12 (up to 40)	12 to 21 (40 to 21)	21 to 30 (70 to 100)
SWD (m) (ft)	3.4 (11)	3.7 (12)	4.0 or deeper (13 or deeper)

(Note: A number of state regulatory agencies stipulate that the minimum secondary clarifier depth shall not be less than 3.7 m (12 ft).

- Are solids retained even during peak flows?
- Do clarifiers remain free of ice during cold weather?
- Is scum removed from the process and disposed properly?
- Are the overflow weirs unaffected by downstream hydraulic restrictions?
- Is short-circuiting prevented by adequate inlet baffle construction?
- Are the weirs on a single launder balanced to pull evenly from each side?

Return sludge system

- Are the RAS pumps properly sized?
- *Can RAS flows be varied over a wide range (25 to 100% of influent flow)?*
- Is the RAS pumping capacity adequate to control sludge-blanket depth?
- Is the RAS flow visible?
- *Is the RAS flow measured?*
- Does the RAS flow meter respond to flow changes?
- Can RAS flows be easily balanced with multiple clarifiers?
- Do telescoping valves remain free of rags even at lower flows?
- Is piping symmetrical on multiple clarifiers to avoid imbalances in RAS flows, both from the clarifiers and to the biological reactors?
- Is the RAS returned near the inlet of the biological reactors?
- Does the piping allow for step-feed operation?
- Is the valve controlling air to an air-lift pump the regulating type rather than the shut-off type?

- Do valves used for RAS flow control remain clear from obstructions?
- *Can the RAS be chlorinated?*

Waste sludge system

- *Are there provisions for wasting sludge?*
- *Are the WAS-treatment facilities adequately sized to prevent wasting restrictions?*
- *Are the WAS-treatment facilities reliable enough to prevent wasting restrictions?*
- Is there sufficient sludge-wasting capacity?
- *Can the WAS flow rate be varied?*
- *Can the WAS flow rate and volume be measured?*
- Can sludge be wasted continuously?
- Can the WAS pumping rate be reliably used to calculate waste volume if necessary?
- Does the WAS pump have taps for measuring pressure if checking the pumping rate with a pump curve?

Miscellaneous

- Are *process tanks adequately sized, with recycle flows included?*
- *Are actual peak flows, including infiltration and inflow, less than or equal to design peak flows?*
- *Is there a reasonable design hydraulic gradient so tanks are not surcharged and weirs are not submerged?*
- Are there facilities for feeding settling aids such as alum, ferric chloride, and polymer? If so, are they operating properly?
- Are there facilities for feeding chemicals for adjusting the pH?
- Are there facilities for feeding supplemental nutrients?
- Can the plant influent be chlorinated?
- Are there automated control systems, such as programmable-logic controllers, supervisory control and data acquisition (SCADA), and distributed control systems (DCS)?

Laboratory facilities

- *Is there an on-site process control laboratory?*
- *Is there sufficient equipment to run necessary operational control and National Pollutant Discharge Elimination System tests?*

- Is the balance unaffected by vibrations?
- Do the sampling point locations allow representative samples to be taken?
- Does the heating, ventilation, and air conditioning system provide comfortable working conditions and the proper environment for equipment?
- Is there good lighting?
- Is there sufficient flow and bench space?

TROUBLESHOOTING GUIDES

Several problems that frequently occur in operating the activated-sludge process were just described in detail. These problems and their suggested solutions are summarized in the tables that follow. The preceding sections of this chapter, in particular the sections on "Process and Equipment Description" and "Process Control", should be consulted before attempting to use these tables.

Table Number	Process Area	Problem Indicator
20.12	Biological reactor	Aeration problems
20.13	Biological reactor	Foaming problems
20.14	Secondary clarifier	Solids washout
20.15	Secondary clarifier	Bulking sludge
20.16	Secondary clarifier	Clumping/rising sludge
20.17	Secondary clarifier	Cloudy secondary effluent
20.18	Secondary clarifier	Ashing, pinpoint floc, and straggler floc

Note that problems are categorized between the biological reactor and secondary clarifier. Troubleshooting guides for the secondary clarifier are associated with activated-sludge characteristics and quality, as can be observed when conducting the mixed liquor settleability test. However, all observations made during the settleability test do not necessarily show conditions in the secondary clarifier. In all the guides presented, the probable causes given for the observation should be looked at simultaneously because one problem may often be the result of several causes.

Figure 20.36 presents a convenient pictorial index to the troubleshooting guides for typical settleability test results.

Refer to the beginning of the "Operational Problems" discussion of this section for general guidance on applying corrective remedies to problems.

TABLE 20.12 Troubleshooting guide for aeration system problems in biological reactors.

Observation	Probable cause	Necessary check	Remedies
1. Boiling action, violent turbulence throughout biological reactor surface. Large air bubbles, (0.5 in.) or greater, apparent.	A. Overaeration resulting in high DO concentration and/or floc shearing	1. Typically, DO concentration should be in range of 1.0 to 3.0 mg/L throughout reactors	1. Reduce air flow rate to maintain DO concentration in proper range
2. Uneven surface aeration pattern. Dead spots or inadequate mixing in some areas of the reactors	A. Plugged diffusers	1. Check maintenance records for last cleaning of diffusers	1. If diffusers have not been cleaned during past 12 months, do so
		2. Spot check diffusers in reactor for plugging	2. If several are plugged, clean all diffusers in reactor
	B. Underaeration resulting in low DO concentration and/or septic odors	1. Check DO concentration, should be in range of 1.0 to 3.0 mg/L throughout the reactor	1. Increase the air flow rate to maintain DO concentration in proper range
		2. Check for adequate mixing in biological reactors	2. Calculate the air flow rate per meter (scfm/ft) of diffuser header pipe. The minimum requirement is 5 L/m·s (3 scfm/lin ft). Adjust the air flow rate as necessary to maintain adequate DO concentration and mixing.
		3. Check RAS rates and sludge-blanket depth in clarifier	3. Adjust the RAS rate to maintain a blanket depth of 0.3 to 0.9 m (1 to 3 ft) in the clarifier

(*continued*)

TABLE 20.12 Troubleshooting guide for aeration system problems in biological reactors (*continued*).

Observation	Probable cause	Necessary check	Remedies
3. Excessive air rates being used with no apparent change in organic or hydraulic loading. Difficult to maintain adequate DO concentrations.	A. Leaks in aeration system piping	1. Check air pipe and joint connection; listen for air leakage or soap test flanges and watch for bubbling caused by air leaking	1. Tighten flange bolts and/or replace flange gaskets
	B. Plugged diffusers. Air discharging from diffuser header blow off pipes causing local boiling to occur on surface near diffuser header pipe	1. Check maintenance record for last cleaning of diffusers 2. Spot check diffusers in reactor for plugging	1. If diffusers have not been cleaned during past 12 months, do so 2. If several are plugged, clean all diffusers in reactor
	C. Insufficient or inadequate oxygen transfer	1. Check aeration system performance a. Diffused aeration system should provide between 50 and 94 m^3/kg (800 and 1500 cu ft air/lb) BOD removed b. Mechanical aeration system should provide between 1000 and 1200 g O_2/kg (1 and 1.2 lb O_2/lb) BOD removed	1. Replace with more effective diffusers or mechanical aerators 2. Add more diffusers or mechanical aerators
	D. High organic loadings BOD, COD, and/or suspended solids from in-plant sidestream flows	1. Check to see if organic loading from sidestream flows contributes significantly to overall process loading	1. If loads are greater than 25%, optimize operational performance or upgrading of other in-plant processes will be required

TABLE 20.13 Troubleshooting guide for foaming problems (*continued*).

Observation	Probable cause	Necessary check	Remedies
1. White, thick, billowing or sudsy foam on biological reactor surface	A. Overloaded biological reactor (low MLSS concentration) because of process startup. Do not be alarmed: this problem usually occurs during process startup.	1. Check biological reactor BOD loading kg/d (lb/d) and kg (lb) MLVSS in biological reactor. Calculate F:M to determine kg/d (lb/d) MLVSS inventory for current BOD loading.	1. After calculating the F:M and kg MLVSS needed, if the F:M is high and the MLVSS inventory is low, do not waste sludge from the process or maintain the minimum WAS rate possible if wasting has already started
		2. Check secondary clarifier effluent for solids carryover. Effluent will look cloudy.	2. Maintain sufficient RAS rates to minimize solids carryover, especially during peak flow periods
		3. Check DO concentration in biological reactor	3. Try to maintain DO concentrations between 1.0 and 3.0 mg/L. Also be sure that adequate mixing is being provided in the biological reactor while attempting to maintain DO concentrations.
	B. Excessive sludge wasting from process causing overloaded biological reactor (low MLSS concentration)	1. Check and monitor for trend changes which occur in the following: a. Decrease in MLVSS concentration b. Decrease in MCRT c. Increase in F:M d. DO concentrations maintained with lower air rates	1. Reduce WAS rate by not more than 10% per day until process approaches normal control parameters 2. Increase RAS rate to minimize effluent solids carryover from secondary clarifier. Maintain sludge-

(*continued*)

TABLE 20.13 Troubleshooting guide for foaming problems (*continued*).

Observation	Probable cause	Necessary check	Remedies
		e. Increase in WAS rates	blanket depth of 0.3 to 0.9 m (1 to 3 ft) from clarifier floor.
	C. Highly toxic waste, such as metals or bacteriocide, or colder wastewater temperatures, or severe temperature variations resulting in reduction of MLSS concentrations	1. Take MLSS sample and test for metals and bacteriocide, and temperature	1. Reestablish new culture of activated sludge. If possible, waste sludge from process without returning it to other in-plant systems. Obtain seed sludge from another plant, if possible.
		2. Monitor plant influent for significant variations in temperature	2. Actively enforce industrial-waste ordinances
	D. Hydraulic washout of solids from secondary clarifier	1. Check hydraulic residence time in biological reactor and surface overflow rate in secondary clarifier	1. Refer to Table 20.14, Observation 1
	E. Improper influent wastewater and/or RAS flow distribution causing foaming in one or more biological reactors	1. Check and monitor for significant differences in MLSS concentrations among multiple biological reactors	1. MLSS and RAS concentrations, and DO concentrations among multiple reactors should be consistent
		2. Check and monitor primary effluent and/or RAS flow rates to each biological reactor	2. Modify distribution facilities as necessary to maintain equal influent wastewater and/or RAS flow rates to biological reactors
2. Shiny, dark-tan foam on biological reactor surface	A. Biological reactor approaching underloaded (high MLSS concentration) condition because of insufficient sludge	1. Check and monitor for trend changes which occur in the following:	1. Increase WAS rate by not more than 10% per day until process approaches normal control parameters and a

(*continued*)

TABLE 20.13 Troubleshooting guide for foaming problems (*continued*).

Observation	Probable cause	Necessary check	Remedies
	wasting from the process	a. Increase in MLSS concentration b. Increase in MCRT c. Decrease in F:M d. DO concentrations maintained with increasing air rates e. Decrease in WAS rates	modest amount of light-tan foam is observed on biological reactor surface 2. For additional checks and remedies refer Tables 20.16 and 20.17 3. For multiple reactor operation refer to Observation 1, Probable cause "E" of this table.
3. Thick, scummy dark-tan foam on biological reactor surface	A. Biological reactor is critically underloaded (MLSS concentration too high) because of improper WAS control program	1. Check and monitor for trend changes which occur in the following: a. Increase in MLVSS concentration b. Increase in MCRT c. Decrease in F:M	1. Increase WAS rate by not more than 10% per day until process approaches normal control parameters and a modest amount of light-tan foam is observed on biological reactor surface 2. For additional and remedies refer to Table 20.16 and 20.18 3. For multiple tank operation refer to Observation 1, Probable cause "E" of this table

(*continued*)

TABLE 20.13 Troubleshooting guide for foaming problems (*continued*).

Observation	Probable cause	Necessary check	Remedies
			3. For multiple tank operation refer to Observation 1, Probable cause "E" of this table
4. Dark-brown, almost blackish sudsy foam on biological reactor surface. Mixed liquor color is dark-brown to almost black. Detection of septic or sour odor from biological reactor.	A. Anaerobic conditions occurring in biological reactor	1. Refer to Table 20.12, Observations 2 and 3	

TABLE 20.14 Troubleshooting guide for solids washout/billowing solids.

Observation	Probable cause	Necessary check	Remedies
1. Localized clouds of homogenous sludge solids rising in certain ares of the clarifier. Mixed liquor in settleability test settles well with a clear supernatant.	A. Equipment malfunction	1. Refer to Table 20.12, Observations 1-A, 2-A, and 2-B	
		2. Check the following equipment for abnormal operation: a. Calibration of flow meters b. Plugged or partially plugged RAS or WAS pumps and transfer lines c. Sludge collection mechanisms, such as broken or worn out flights, chains, sprockets, squeegees, and plugged sludge withdrawal tubes	2. Repair or replace abnormally operating equipment
		3. Check sludge removal rate and sludge-blanket depth in clarifier	3. Adjust RAS rates and sludge collector mechanism speed to maintain sludge-blanket depth at 0.3 to 0.9 m (1 to 3 ft) from clarifier floor
	B. Air or gas entrapment in sludge floc or denitrification occurring	1. Perform settleability test and gently stir sludge when settling to see if bubbles are released	1. If the process is not nitrifying, refer to Probable cause A above, and Table 20.18, Observation 2
		2. If bubbles are released, check nitrate concentration in secondary effluent to see if the process is nitrifying	2. If the process is nitrifying, refer to Table 20.16, Probable cause A

(*continued*)

TABLE 20.14 Troubleshooting guide for solids washout/billowing solids (*continued*).

Observation	Probable cause	Necessary check	Remedies
	C. Temperature currents	1. Perform temperature and DO profiles in clarifier	1. If temperatures differ by more than 1 to 2 deg between top and bottom of clarifier, use an additional biological reactor and clarifier, if possible.
		2. Check inlet and outlet baffling for proper solids distribution in clarifier	2. Modify or install additional baffling in clarifiers
			3. Refer to Probable cause A-1, and A-2 above
	D. Solids washout due to hydraulic overloading	1. Check hydraulic residence time in biological reactor and clarifier, and surface overflow rate in clarifier	1. If hydraulic loading exceed design capability, use additional biological reactors and clarifiers, if possible
			2. Reduce RAS rate to maintain high sludge-blanket depth in clarifier
			3. If possible, change process operation to sludge-reaeration or contact-stabilization mode
			4. Refer to Probable causes B-1, B-2, and C-2 above

(*continued*)

TABLE 20.14 Troubleshooting guide for solids washout/billowing solids (*continued*).

Observation	Probable cause	Necessary check	Remedies
2. Localized clouds of fluffy homogenous sludge rising in certain areas of the clarifier. Mixed liquor in settleability test settles slowly, leaving stragglers in supernatant.	A. Overloaded biological reactor (low MLSS concentraton) resulting in a young, low-density sludge	1. Check and monitor trend changes which occur in the following: a. Decrease in MLVSS concentration parameters b. Decrease in MCRT c. Increase in F:M d. Lower air flow rate to maintain DO concentration	1. Decrease WAS rates by not more than 10% per day to bring process back to optimum

TABLE 20.15 Troubleshooting guide for bulking sludge.

Observation	Probable cause	Necessary check	Remedies
1. Clouds of billowing homogenous sludge rising and extending throughout the clarifier. Mixed liquor settles slowly and compacts poorly in settleability test, but supernatant is fairly clear.	A. Improper organic loading or DO concentration	1. Check and monitor trend changes which occur in the following: a. Decrease in MLVSS concentration b. Decrease in MCRT c. Increase in F:M d. Change in DO concentrations e. Sudden SVI increase from normal, or decrease in sludge density index	1. Decrease WAS rates by not more than 10% per day until process approaches normal operating parameters 2. Temporarily increase RAS rates to minimize solids carryover from clarifier. Continue until normal control parameters are approached. 3. DO concentration throughout biological reactor should be greater than 0.5 mg/L, preferably 1 to 3 mg/L
	B. Filamentous organisms	1. Perform microscopic examination of mixed liquor and return sludge. If possible, try to identify type of filamentous organisms, either fungal or bacterial.	1. If no filamentous organisms are observed, refer to Probable cause "A" above
		2. If fungal organism is identified, check industries for wastes that may cause problems	2. Enforce industrial waste ordinance to eliminate wastes. Also see Remedy 4 below.

(*continued*)

TABLE 20.15 Troubleshooting guide for bulking sludge (*continued*).

Observation	Probable cause	Necessary check	Remedies
		3. If bacterial organisms are identified, check influent wastewater and in-plant sidestream flows returning to process for massive filamentous organisms	3. Chlorinate influent wastewater at 5- to 10-mg/L dosages If higher dosages are required, use extreme caution. Increase dosage in 1- to 2-mg/L increments. 4. Chlorinate RAS at 2 to 3 g/kg (lb/d/1000 lb) MLVSS 5. Optimized operational performance or upgrading of other in-plant unit processes will be required if filamentous organisms are found in sidestream flows
	C. Wastewater nutrient deficiencies	1. Check nutrient concentrations in influent wastewater. The BOD-to-nutrient ratios should be 100 parts BOD to 5 parts total nitrogen to 1 part phosphrous to 0.5 parts iron.	1. If nutrient concentrations are less than average ratio, field tests should be performed on the influent wastewater for addition of nitrogen in the form of anhydrous ammonia, phosphorus in the form of trisodium phosphate and/or iron in the form of ferric chloride

(*continued*)

TABLE 20.15 Troubleshooting guide for bulking sludge (*continued*).

Observation	Probable cause	Necessary check	Remedies
		2. Peform hourly mixed liquor settleability tests	2. Observe tests for improvement in sludge settling characteristics with the addition of nutrients
	D. Low DO concentration in biological reactor	1. Check DO concentration at various locations throughout the reactor	1. If average DO concentration is <0.5 mg/L, increase air flow rate until the DO concentration level increases to between 1 and 3 mg/L throughout the reactor
			2. If DO concentrations are nearly zero in some parts of the reactor, but 1 mg/L or more in other locations, balance the air distribution system or clean diffusers. Refer to Table 20.12, Observation 2.
	E. pH in biological reactor is less than 6.5	1. Monitor plant-influent pH	1. If pH is less than 6.5, conduct industrial survey to identify source. If possible, stop or neutralize discharge at source.
			2. If the above is not possible, raise pH by adding an alkaline agent such as caustic soda or lime to the biological reactor influent

(*continued*)

TABLE 20.15 Troubleshooting guide for bulking sludge (*continued*).

Observation	Probable cause	Necessary check	Remedies
		2. Check if process is nitrifying because of warm wastewater temperature or low F:M loading	1. If nitrification is not required, increase WAS rate by not more than 10% per day to stop nitrification 2. If nitrification is required, raise pH by adding an alkaline agent such as caustic soda or lime to the aeration influent

TABLE 20.16 Troubleshooting guide for sludge clumping.

Observation	Probable cause	Necessary check	Remedies
1. Sludge clumps (from size of a golf ball to as large as a basketball) rising to and dispersing on clarifier surface. Bubbles noticed on clarifier surface. Mixed liquor in settleability test settles fairly well, however a portion of and/or all of the settled sludge rises to the surface within 4 hours after test is started.	A. Denitrification in clarifier	1. Check for increase in secondary effluent nitrate concentration	1. Increase WAS rate by not more than 10% per day to reduce or eliminate level of nitrification. If nitrification is required, reduce to allowable minimum.
		2. Check loading parameters	2. Maintain WAS rates to keep process within proper MCRT, Gould sludge age, and F:M
		3. Check DO concentration and temperature in the biological reactor	3. Maintain DO concentration at a minimum (1.0 mg/L). Be sure adequate mixing is provided in the biological reactor.
		4. Check RAS rates and sludge blanket depth in clarifier	4. Adjust RAS rates to maintain sludge blanket depth of 0.3 to 0.9 m (1 to 3 ft) in clarifier
	B. Septicity occurring in clarifier	1. Refer to Table 20.12, Observation 2 2. See 3 and 4 above	

TABLE 20.17 Troubleshooting guide for cloudy secondary effluent.

Observation	Probable cause	Necessary check	Remedies
1. Secondary effluent from clarifier is cloudy and contains suspended matter. Mixed liquor in settleablity test settles poorly, leaving a cloudy supernatant.	A. MLSS concentration in biological reactor is low because of process startup	1. Refer to Table 20.13, Observation 1	
	B. Increase in organic loading	1. Perform microscopic examination on mixed liquor and return sludge. Check for presence of protozoa.	1. If no protozoa are present, possible shock organic loading has occurred
		2. Check organic loading on process	2. Reduce WAS rate by not more than 10% per day to bring process back to proper loading parameters and increase RAS rates to maintain 0.3 to 0.9 m (1 to 3 ft) sludge blanket in clarifier
		3. Check DO concentration in biological reactor	3. Adjust air flow to maintain DO concentration within 1.0 to 3.0 mg/L
	C. Toxic shock loading	1. Perform microscopic examination on mixed liquor and return sludge. Check for presence of inactive protozoa.	1. If protozoa are inactive, a recent toxic load on process is possible
			2. Refer to Table 20.13, Observation 1-C
	D. Overaeration causing mixed liquor floc to shear	1. Perform microscopic examination on mixed liquor. Check for dispersed or fragmented floc and presence of active protozoa.	1. Refer to Table 20.12, Observation 1-A
	E. Improper DO concentrations maintained in biological reactor	1. Refer to Table 20.12, Observation 2	

TABLE 20.18 Troubleshooting guide for ashing and pinpoint/straggler floc.

Observation	Probable cause	Necessary check	Remedies
1. Fine dispersed floc (approximately the size of a pinhead) extending throughout the clarifier with little islands of sludge accumulated on the surface and discharging over the weirs. Mixed liquor in settleability test settles fairly well. Sludge is dense at bottom with fine particles of floc suspended in fairly clear supernatant.	A. Biological reactor approaching underloaded conditions, (high MLSS concentration) because of old sludge in system	1. Check and monitor trend changes which occur in the following: a. Increase in MLVSS concentration b. Increase in MCRT c. Decrease in F:M d. DO concentrations maintained with increasing aeration rates e. Decrease in WAS rates f. Decrease in organic loading (BOD:COD in primary effluent)	1. Increase WAS rates by not more than 10% per day to bring process back to optimum control parameters for average organic loading
		2. Check for foaming in biological reactor	2. Refer to Table 20.13 for any foaming which may be occurring in biological reactor
			3. Adjust RAS rates to maintain sludge blanket depth of approximately 0.3 to 0.9 m (1 to 3 ft) in clarifier
			4. Refer to Table 20.12 for additional observations
2. Small particles of ash-like material floating on clarifier surface	A. Beginning of denitrification	1. Stir floating floc on surface of mixed liquor settleability	1. If floating floc releases bubbles and settles, see Table 20.16, Probable cause A
			2. If it does not settle, refer to Probable cause B, below

(*continued*)

TABLE 20.18 Troubleshooting guide for ashing and pinpoint/straggler floc (*continued*).

Observation	Probable cause	Necessary check	Remedies
3. Particles of straggler floc 6.4 mm (0.25 in.) or larger, extending throughout the clarifier and discharging over the weirs. Mixed liquor in settleability test settles fairly well. Sludge does not compact well at the bottom with chunks of floc suspended in fairly clear supernantant.	A. Biological reactor slightly underloaded (low MLSS concentration) because of organic load change	1. Check and monitor trend changes which occur in the following: a. Decrease in MLVSS concentration b. Decrease in MCRT c. Increase in F:M d. Lower aeration rate used to maintain DO concentration e. Increase in WAS rates f. Increase or decrease in organic loading (BOD:COD in primary effluent)	1. Decrease WAS rates by not more than 10% per day to bring process back to optimum control parameters for average organic loading
		2. Check for foaming in biological reactor	2. Refer to Table 20.13 for any foaming which may be occurring in biological reactor
			3. Adjust RAS rates to maintain sludge blanket depth of 0.3 to 0.9 m (1 to 3 ft) in clarifier
			4. Decrease air flow rates to maintain minimum DO concentration of only 1.0 mg/L in biological reactor. Refer to Table 20.12 for additional observations.

(*continued*)

TABLE 20.18 Troubleshooting guide for ashing and pinpoint/straggler floc (*continued*).

Observation	Probable cause	Necessary check	Remedies
	B. Excessive amounts of grease in mixed liquor	1. Perform a grease analysis on MLSS, and check scum baffles in primary tank	1. If the grease content exceeds 15% by weight of the MLSS, repair or replace scum baffles as needed
		2. Check grease content in raw wastewater	2. If grease content is excessive, implement an industrial-waste monitoring and enforcement program

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Section 6

Aerobic Digestion

Aerobic digestion is a biological treatment process that uses long-term aeration to stabilize and reduce the total mass of organic waste by biologically destroying volatile solids. This process extends decomposition of solids and regrowth of organisms to a point in which available energy in active cells and storage of waste materials are sufficiently low to permit waste sludge to be considered stable. Waste sludge consists of suspended solids (SS) that have been removed during clarification and solids that are a result of the growth of the biological mass during the treatment process. The aerobic digestion process renders the solids less likely to generate odors during disposal and reduces bacteriological hazards. Properly designed, the aerobic digestion process should easily meet the U.S. Code of Regulations (40 CFR Part 503) for Class B biosolids.

Because of its similarities to the activated-sludge process, aerobic digestion is covered briefly here. For detailed process control and operations information, refer to Chapter 31, Aerobic Digestion.

DESCRIPTION OF PROCESS

During aerobic digestion, aerobic and facultative microorganisms use oxygen and obtain energy from the available biodegradable organic matter in the waste sludge. However, when the available food supply in the waste sludge is inadequate, the microorganisms begin to consume their own protoplasm to obtain energy for cell maintenance. Eventually, the cells undergo lysis, which releases degradable organic matter for use by other microorganisms. This phenomenon is called endogenous respiration.

The cellular material is oxidized aerobically to carbon dioxide, water, and ammonia. Approximately 75 to 80% of the cell material can be oxidized; the remaining amount is composed of nondegradable components. The ammonia from this oxidation is eventually oxidized to nitrate as digestion proceeds (Metcalf & Eddy, 1991).

Typically, aerobic digesters are used to treat waste activated sludge (WAS) from treatment systems that do not contain a primary settling process, or contain WAS only or trickling filter sludge or mixtures of WAS and trickling filter sludge. Many variations of the process exist, including conventional, high-purity oxygen, thermophilic, and cryophilic aerobic digestion. Conventional aerobic digestion is the most typically used and is the focus of this discussion. For details on process variations, see Chapter 31, Aerobic Digestion.

Conventional aerobic digestion aerates waste sludge for an extended period of time in unheated tanks, using air diffusers or surface aeration equipment. The waste sludge that has been removed from the main biological process is transferred to the digester units, where the oxygen for microbial metabolism is provided either by mechanical aerators or through a diffused aeration system. Each tank has a waste sludge feed line above the high water level, a solids draw-off line at the bottom of the tank, and a flexible, multilevel supernatant draw-off line to remove liquor from the upper half of the tank (California State University, 1991). Depending on geographical location and climatic conditions, these tanks might not have covers. Covers are used in colder climates to help maintain the temperature of the process. Covers should not be used if they reduce evaporative cooling too much and the liquid contents become too warm. When the liquid becomes too warm offensive odors may develop and the process effluent will have a poor quality (California State University, 1991). Following digestion, the remaining solids are separated from the liquid for dewatering or disposal.

Typically, an aerobic digester is operated by continuously feeding raw sludge with intermittent supernatant and digested sludge withdrawals. Supernatant is the clear liquid that forms above the settled solids in the digester. The digested solids are continuously aerated during filling and for the specified digestion period after the tank is full (Hammer, 1986).

In some operations the aeration system is shut down for 1 to 2 hours to allow the solids to settle and the supernatant to form. The supernatant is then decanted, allowing additional waste sludge to be added; thus, the solids concentration typically increases. For example, if solids wasted from the activated-sludge process are pumped to the aerobic digester at a concentration of 0.5 to 1.0% solids, the solids concentration in the digester may increase to 1.5 to 2.0%. If primary sludge is also delivered to the digester, the solids concentration in the digester may be in the 2 to 4% range or higher. The increase of solids concentration results from the decanting process. Decanting during digestion allows the

solids to settle and the clear supernatant to be returned to the treatment process. This supernatant can cause additional biochemical oxygen demand (BOD), solids, and nitrogen loadings to the plant. Staff should be aware of the effect of returning the supernatant to prevent plant upset.

OPERATIONAL PARAMETERS

The important factors in controlling the operation of aerobic digesters are similar to those for other aerobic biological processes, and include waste sludge characteristics, oxygen requirements, pH, temperature, mixing, and solids retention time (SRT). These parameters either affect or are used to monitor the operational performance of the process. Although controlling and monitoring of these parameters is important, the degree of control that can be exercised on each parameter varies. Monitoring helps control process performance and serves as a basis for future improvements.

WASTE SLUDGE CHARACTERISTICS. The characteristics of the waste sludge to be digested will be determined by the raw influent to the treatment system and by treatment processes that precede aerobic digestion. The waste sludge concentration is important to consider. Increasing the feed concentration by thickening will result in longer SRTs with subsequent increased levels of volatile solids destruction, and will reduce the frequency of supernatant decanting (WEF, 1992). Solids concentrations that are too high can cause the process to attempt to go autothermal and can reduce decanting effectiveness.

The organic strength of the waste sludge significantly affects the digestion process. Although organic loading rates vary, they typically range from 0.3 to 2.2 kg/m^3·d (0.02 to 0.14 lb VSS/d/cu ft). Higher loading rates may result in higher oxygen demand and, in some cases, can exceed the oxygen-transfer capacity of the aeration system. This leads to anaerobic conditions and undesirable odors.

OXYGEN REQUIREMENTS. The most critical parameter in the aerobic digestion process is dissolved oxygen (DO). Maintaining adequate oxygen concentrations allows the biological process to take place and prevents objectionable odors. In aerobic digesters, DO concentrations typically range from 0.5 to 2.0 mg/L. Inadequate DO levels result in incomplete digestion and, more importantly, odor problems. Also, if air is used for mixing, the air must never be reduced below the mixing requirements regardless of the DO concentration.

The rate of oxygen use by the microorganisms depends on the rate of biological oxidation. The oxygen uptake rate (OUR) is expressed as milligrams of oxygen per gram of

volatile suspended solids (VSS) per hour (mg O_2/g VSS·h). The OUR is used to determine the level of biological activity and the resulting solids destruction occurring in the digester. Typical OURs are shown in Figure 20.48.

pH. Two products of aerobic digestion that tend to lower the digester pH are carbon dioxide and hydrogen ions. A pH drop can occur when ammonia is oxidized to nitrate if the alkalinity of the wastewater is insufficient to buffer the solution. In situations where the buffering capacity of the sludge is insufficient, it may be necessary to chemically adjust the pH (Metcalf & Eddy, 1991). Carbon dioxide will dissolve in the liquid in an amount proportional to the partial pressure of carbon dioxide in the gas phase above the tank. For an open tank this is typically negligible. For a closed digester, however, the amount of carbon dioxide in the headspace below the cover may exceed 40% by volume, and the pH may subside to 6.0 under such conditions.

As with other biological systems, the aerobic digestion process performs better at either a neutral or slightly higher pH. The results suggest that either pH adjustment or increased alkalinity will improve performance and dewaterability. If pH adjustment is necessary, the proper chemical dosage can be determined by performing a bench-scale jar test and proportioning the chemical dosage from the jar test to the digester volume.

TEMPERATURE. The liquid temperature in an aerobic digester significantly affects the rate of volatile solids reduction that increases as temperature increases. As with all biological processes, the higher the temperature, the greater the efficiency. At temper-

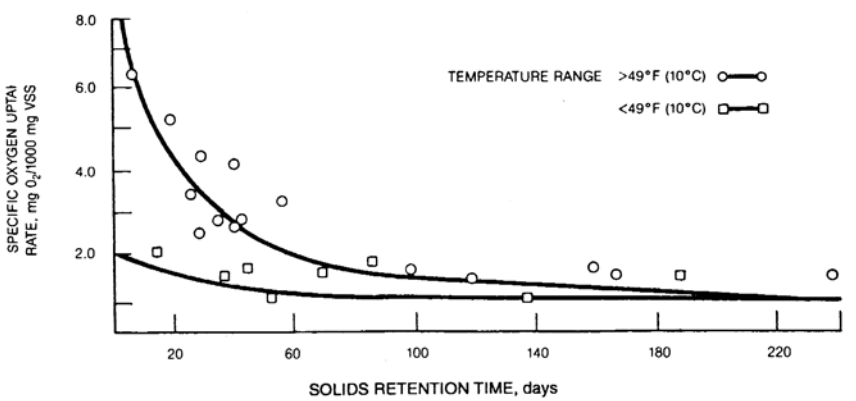


FIGURE 20.48 Influence of solids retention time and liquid temperatures on the oxygen uptake rates in aerobic digestion.

atures lower than 10 °C (50 °F) the process is less effective. In most aerobic digesters temperature is a function of ambient weather conditions and is not controlled.

MIXING. Mixing is essential in aerobic digesters. A well-mixed biomass ensures adequate contact between the organisms and their food supply and ensures uniform distribution of oxygen throughout the digester. The aeration system typically supplies the mixing. Adequate mixing is provided when the diffusers supply air at a rate of 0.3 to 0.6 $L/m^3 \cdot s$ (20 to 35 cu ft/min/1000 cu ft). Supplemental mixing is required when the rate of aeration or oxygenation needed to meet the OUR is less than the rate needed to keep the organisms in suspension. Either mechanical mixer or mechanical aerator requirements may be used to supplement mixing needs.

SOLIDS RETENTION TIME. The SRT is a significant factor in the effective operation of aerobic digesters. It is defined as the total mass of biological solids in the reactor divided by the mass of solids removed from the process on a daily average.

$$\text{SRT} = \frac{\text{Total sludge mass, kg}}{\text{Solids removed per day, kg/d}} \tag{20.16}$$

Typically, increased SRT results in an increase in the degree of solids reduction. Figure 20.49 shows the relationship between SRT and solids reduction. This relationship can vary depending on the characteristics of the waste sludge being digested. Figure 20.50 illustrates the relationship between SRT and solids reduction for several waste sludge types.

Equation 20.16 helps predict digester performance after trends have been monitored at various SRT values. The overall SRT typically ranges from 10 to 40 days. Note that higher retention times reduce dewaterability of the digested solids; therefore, if dewaterability is an important consideration, SRT values should be kept on the low end of the range.

DESCRIPTION OF FACILITIES

TYPES OF REACTORS. Most aerobic digesters are constructed to allow the liquid level to fluctuate. Some aerobic digesters are designed with sloped floors so that digested solids are drawn off the bottom; others have a constant, weir overflow design.

Aerobic digesters are constructed of reinforced concrete and steel. In cold climates, steel tanks that are above the ground should be insulated. If the steel and concrete tanks are below the ground, they are well-insulated by the soil if the groundwater is drained from the exterior of the tank walls.

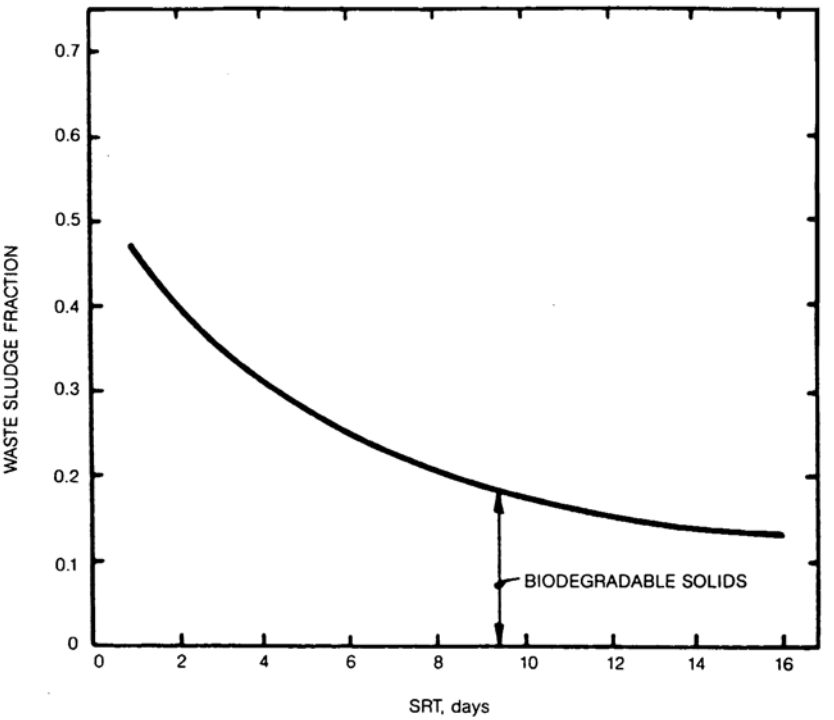


FIGURE 20.49 Effect of solids retention time on reduction of biodegradable solids by aerobic digestion.

At least two tanks are typically installed to allow flexibility for maintenance or repair. Increasing the aerobic digester size to produce an operating safety factor may create operational problems because of a loss of heat and increased energy requirements for mixing (WEF, 1992).

AIR AND OXYGEN SUPPLY EQUIPMENT. Either air or pure-oxygen-transfer equipment, such as conventional mechanical aerators, coarse-bubble diffusers, fine-bubble diffusers, or jet aerators, supply the oxygen needs for aerobic digestion. The best device not only should be capable of developing the required oxygenation and mixing, but should also provide flexibility (WEF, 1992).

Air diffusers typically are found near the bottom of the digester toward one side to induce a spiral or cross-roll mixing pattern. The most widely used air diffusers are the

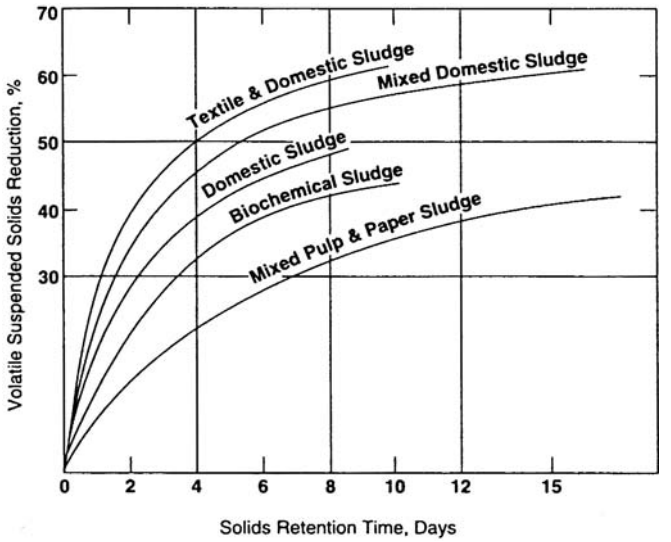


FIGURE 20.50 Relative solids destruction of several sludges by aerobic digestion.

small-bubble and large-bubble types. Blowers supply the air for mixing and aeration. Diffused-air systems tend to add heat to the digester, are not greatly affected by foaming conditions, and require the entire assembly to be removed for cleaning if it becomes clogged or plugged.

Both low- and high-velocity mechanical surface aerators, in either free-floating or fixed installations, are efficient in transferring oxygen (amount of oxygen fed by the aerator that has been absorbed by the biomass). Typically, mechanical surface aerators supply oxygen efficiently at approximately 0.5 kg/MJ (4 lb/kWh) have minimal maintenance requirements, are greatly affected by foaming conditions, and are greatly affected during cold weather by ice buildup.

Submerged mechanical aerators include a rotating submerged impeller mounted on a drive shaft extending vertically into the biological reactor. Compressed air is supplied beneath the impeller, where it is sheared into bubbles and pumped into the reactor (WEF, 1992). Typically, submerged mechanical aerators are unaffected by foaming and icing conditions, and tend to be more expensive than mechanical surface aerators.

Air requirements typically range from 0.5 to 0.6 L/m^3·s (30 to 40 cfm/1000 cu ft) for the treatment of secondary biological sludges, and from 0.75 to 1.1 L/ m^3·s (45 to 70 cfm/1000 cu ft) for the treatment of primary sludges.

PROCESS CONTROL

Aerobic digesters can be operated as either batch- or continuous-flow reactors.

BATCH OPERATION. Batch operation involves manually decanting digested solids. Originally, aerobic digestion was operated as a draw-and-fill process, a practice still being used at many facilities. Solids are pumped directly from the clarifiers to the aerobic digester. The time required for filling the digester depends on the tank volume available and the volume of waste sludge. When diffused-air aeration is used, the solids undergoing digestion are aerated continually during the filling operation.

When the solids are removed from the digester, aeration is discontinued and the stabilized solids are allowed to settle. The clarified supernatant is then decanted and returned to the treatment process. Another current mode of operation is batch feed and withdrawal without supernating, but with separate thickening with a belt thickener.

For batch-feed digesters the typical operating steps are as follows:

1. Turn off the aeration equipment and allow the solids to settle. To avoid anaerobic conditions, limit the solids–liquid separation to several hours.
2. Decant as much supernatant as possible. For quality control, analyze a sample of the supernatant for pH and SS, and BOD concentrations.
3. Draw off the thickened, digested solids for second-stage digestion or for disposal. For quality control, monitor the drawn-off solids. The solids content will be significantly higher when primary sludges are digested.
4. If plant flexibility permits feed new waste sludge to the digester over a period of time.

It is suggested that the volume and concentration of the waste sludge added each day be somewhat uniform. At some digester installations, digested solids settling and drawoff are performed once per week, while waste sludge is added or fed daily. In this way, digester volume increases daily until the next decanting and drawoff period.

CONTINUOUS OPERATION. Continuous operation closely resembles the activated-sludge process. As in the fill-and-draw process, solids are pumped directly from the clarifiers to the aerobic digester. The digester operates at a fixed level, with the overflow sent to a solids–liquid separator. Thickened and stabilized solids are either recycled to the digestion tank or removed for further processing.

CONTINUOUS-FEED DIGESTERS. For continuous-feed digesters, the process can be improved by

- Adjusting the rate of settled return sludge to obtain the best balance between return sludge concentration and supernatant quality,
- Adjusting the settling chamber's inlet and outlet flow characteristics to reduce short-circuiting and unwanted turbulence that hinders solids concentration, and
- Modifying the weir and piping arrangements.

A lower solids concentration typically is obtained with continuous operation.

SOLID–LIQUID SEPARATION. Careful monitoring of the solid–liquid separation in the continuous- and batch-feed digesters increases the performance of an aerobic digester. The supernatant liquid should have low soluble BOD and total suspended solids (TSS) concentrations for both batch and continuous-flow operations. Table 20.19 lists characteristics of supernatant from the aerobic digestion process.

PROCESS PERFORMANCE

The performance of an aerobic digester system is measured by its efficiency while stabilizing and converting raw and partially oxidized waste sludge to a product that is suitable for subsequent processing or disposal. Performance includes the degree of solids reduction, OUR, and reduction in pathogenic organisms.

TABLE 20.19 Characteristics of supernatant from aerobic digestion systems.

Parameter[a]	Range	Typical value
pH	5.9–7.7	7.0
BOD_5, mg/L	9.0–1 700	500
Filtered BOD_5, mg/L	4.0–183	50
COD, mg/L	288.0–8 140	2 600
Suspended solids, mg/L	46.0–11 500	3 400
Kjeldahl nitrogen, mg/L	10.0–400	170
NO_3–N, mg/L	—	30
Total phosphorus, mg/L	19.0–241	100
Soluble phosphorus, mg/L	2.5–64	25

[a]BOD_5 = five-day biochemical oxygen demand; COD = chemical oxygen demand; and NO_3–N = nitrate-nitrogen.

SOLIDS REDUCTION. If an aerobic digester is operated at optimal temperature and SRT, it provides solids reduction similar to that of an anaerobic digestion system. The fraction of volatile solids contained in the feed sludge varies with the process used and the wastewater being treated. As the temperature is reduced, the SRT is increased. At temperatures lower than 10 °C (50 °F) little reduction of biodegradable solids can be expected. Figure 20.51 shows the general relationship between temperature, SRT, and solids reduction.

PATHOGEN REDUCTION. During aerobic digestion, the degree of pathogen reduction is similar to that achieved by biological reduction in that it increases as the temperature and SRT increase. Reductions of one order of magnitude are achieved at temperatures and SRT values of 35 °C (95 °F) and 15 days, or 25 °C (77 °F) and 30 days. Pathogen reduction is similar to solids reduction in that little pathogen reduction can be expected at temperatures less than 10 °C (50 °F), while significant reduction may be achieved at temperatures greater than 20 °C (68 °F) (WEF, 1995).

REACTOR LOADING. When starting an aerobic digester it is important to not overload the digester. Feed sludge should be added to the digester on a regular schedule and the aeration system equipment should be operated continuously. An aeration

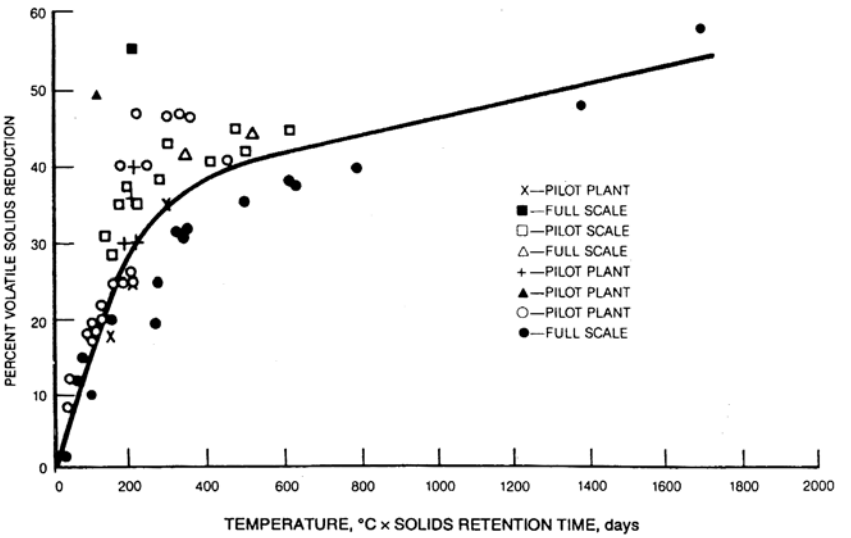


FIGURE 20.51 Volatile solids reduction as a function of digester liquid temperature and digester solids retention time.

system with adequate capacity ensures DO concentrations of 1 mg/L or more. Over-aeration or overloading of the digester may cause foaming problems. If the initial volume of sludge does not provide sufficient liquid volume to operate the aeration system effectively, additional sludge or plant influent may be fed to obtain the needed volume. The daily sludge feed can then be added on a regular schedule, preferably during as long a period as possible.

Occasionally, the VSS concentration and OUR should be determined. Sludge can be wasted after the OUR drops below the target rate of 2 mg/g VSS (as regulated in the U. S. Code of Regulations [40 CFR Part 503] rules). The volatile solids percentage reduction depends on the feed type, age, temperature, and retention time.

The startup of an aerobic digester that processes primary sludge takes a substantially longer time and more oxygen than for digestion of WAS. The degree of aerobic digestion depends on the concentration of solids in the digester and on the rate of solids feed. For routine monitoring, the total VSS may be used in place of TSS. As organic loading increases, the required SRT and total oxygen requirements increase and have a direct effect on process efficiency. For a complete-mix, continuous-flow digester, the volumetric loading rate and detention are used to indirectly reflect solids destruction.

Regular loading, rather than periodic slug doses or large inputs, improves most biological process efficiencies. Regular feeding reduces both volume and aeration equipment requirements; however, batch-type operations often are used in aerobic digesters.

Poor supernatant may result with continuous-feed conditions unless decanting occurs in a tank completely separated from the biological reactor turbulence, or aeration is terminated to allow decanting. Turbulence in the decanting chamber impairs supernatant quality and imposes an excessive solids-recycle load at the head of the treatment plant. Batch-type operations avoid the decanting problems by temporarily stopping aeration and permitting supernatant withdrawal under more quiescent conditions.

TROUBLESHOOTING

Typical performance of an aerobic digester includes the following:

1. DO concentration of at least 1 mg/L as long as minimum mixing in the digester is maintained.
2. An SRT of 10 to 15 days for WAS and 15 to 20 days for primary sludge and WAS.

3. A VSS reduction ranging from 40 to 50%. If temperatures are low (<15 °C [<59 °F]), reductions may fall to 35 or 40% unless very long detention times are provided.
4. Digester pH greater than 6.5.

If any of these parameters show unusual values, the following discussions of air diffuser clogging, low DO concentrations, nuisance odors, excessive foaming, solids deposition, low pH, and freezing and Table 20.20 can serve as troubleshooting guides.

CLOGGING OF AIR DIFFUSERS. A buildup of rags or grit on the diffusers causes diffuser clogging when the aeration system is shut off to concentrate the digested solids before supernatant decanting and solids withdrawal. Over time rags and grit in the digester may lodge on and inside the diffuser mechanisms. When aeration is resumed, the particulates clog the diffusers and eventually will reduce air discharge, causing an increase in the blower discharge pressure. Diffusers that are susceptible to this problem should be avoided.

Effective maintenance prevents or cures clogging. While elimination of diffuser clogging is difficult, equipment modification can reduce its frequency and severity.

LOW DISSOLVED OXYGEN CONCENTRATIONS. An inefficient aeration system or excessive organic loading to the digester can cause a low DO concentration. Blower, mechanical aerator, or aeration diffuser deterioration results in a loss of aeration efficiency. Routinely check and monitor the air delivery rate and pipeline pressures for potential problems. Record the position of all air valves. Investigate suspected clogging, leaks, and excess pressure. Occasionally check the power delivered to mechanical aeration shafts to determine their condition. Mechanical aerator efficiency decreases if the liquid level exceeds specified upper and lower operational limits. Consult the manufacturer's engineering data and operations and maintenance (O&M) manuals for recommended liquid level limits.

Increased organic loading can cause problems whenever the rate of oxygen required for the aerobic digestion reaction is greater than the rate at which oxygen can be transferred into the sludge liquid by the aeration system. Typically, this problem can be solved by reducing the organic loading rate and increasing the SRT. This is done by decreasing the influent waste sludge mass, the total volume added, and the amount of solids withdrawn from the digester.

Excessive solids concentrations in the digester can also cause low DO concentrations. When SS concentrations reach or exceed 3.5 to 4%, oxygen-transfer efficiencies

TABLE 20.20 Troubleshooting guide for aerobic digestion (U.S. EPA, 1978).

Indicators/ observations	Probable cause	Check or monitor	Solutions
Excessive foaming	Organic overload	Organic load	Reduce feed rate
			Increase solids in digester by decanting and recycling rate
	Excessive aeration	Dissolved oxygen	Reduce aeration rate
Low dissolved oxygen	Clogging	Decant digester, withdraw sludge, and inspect diffusers	Clean diffuser or replace with coarse-bubble diffusers or sock-type devices
	Improper liquid level	Check equipment specifications	Establish proper liquid level
	Blower malfunction	Air delivery rate, pipeline pressure, valving	Repair pipe leaks; set valves in proper position; repair blower
	Organic overload	Check organic load	Reduce feed rate
Sludge has objectionable odor	Inadequate solid retention time	Solids retention time	Reduce feed rate
	Inadequate aeration	Dissolved oxygen should exceed 1 mg/L	Increase aeration or reduce feed rate
Ice formation on mechanical aerators	Extended freezing weather	Check digester surface for ice block formation	Break and remove ice before it causes damage
pH in digester has dropped to undesirable level (less than 6.0–6.5)	Nitrification is occurring and wastewater alkalinity is low	pH of supernatant	Add sodium bicarbonate to feed sludge or lime or sodium hydroxide to digester
	In covered digester, carbon dioxide is accumulating in air and is dissolved into sludge		Vent and scrub carbon dioxide

are reduced. This reduction may cause operational problems because of low DO concentrations, depending on the capacity of the aeration system.

NUISANCE ODORS. Inadequate DO is the primary cause of odors. To correct odor problems, first increase the DO concentration by additional aeration (0.5 mg/L is a minimum DO requirement). Second, reduce the organic loading. If both of these fail,

the addition of chemicals such as potassium permanganate or hydrogen peroxide to help oxidize the odor-causing compounds in the digester may be needed. This is considered an expensive and temporary solution to the problem. Bench-scale jar tests can be used to determine the amount of chemicals needed in the digester.

EXCESSIVE FOAMING. Foaming can be caused by factors ranging from simple organic overloading to complex filamentous bacterial growth. To reduce foaming, decrease organic loading, install foam-breaking water sprays, reduce excess aeration rates, and use defoaming chemicals. To avoid dilution of the digester contents operate water sprays sparingly.

Curing filamentous bacterial growth is a difficult task that should be handled at the biological reactors. Addition of oxidants such as chlorine and hydrogen peroxide has been used both with and without beneficial results. Shocking the system with several hours of anaerobic conditions has also been tried. In most cases, limited sprays and defoaming agents control the foam until natural forces can cause a shift to a nonfilamentous type of bacteria.

SOLIDS DEPOSITION. Deposition may occur when gritty materials enter the digester and when the aeration and mixing devices do not create enough turbulence to resuspend the solids following a supernatant decanting sequence. Solids deposition can be prevented by improving operation of the grit chamber, if one exists, or by using more powerful aeration and mixing equipment. Adding fillets to tank bottoms helps reduce solids buildup.

LOW pH. In covered digesters, nitrification or accumulated carbon dioxide may cause low pH. Monitoring records of the alkalinity and nitrates in the digester supernatant or of the carbon dioxide in the air space will indicate whether the addition of lime or sodium hydroxide to the digester or venting of carbon dioxide is appropriate. Soda ash and sodium bicarbonate are also effective with less chance for overdosing.

FREEZING. Extended subfreezing weather may lead to ice formation on the digester's liquid surface and on the mechanical aeration equipment. To prevent malfunction and possible breakdown during cold temperatures, examine open digesters for ice formation. Break the ice and remove it before it damages digester appurtenances by wind action or expansion forces. Use warm air to thaw mechanical aerators affected by ice formation. In extremely cold climates it may be necessary to construct temporary covers to prevent freezing.

DATA COLLECTION AND LABORATORY CONTROL

Consistent data collection and process control through laboratory analyses are essential. Analyses for TSS, VSS and DO concentrations, and OUR of the raw and digested solids provide the minimum data for efficient operation of the aerobic digester. However, additional analyses would be warranted if operational problems arise.

MAINTENANCE MANAGEMENT PROGRAM. A planned maintenance program for the aerobic digester is similar to the maintenance program for the activated-sludge process. Key elements, including identification of maintenance tasks, scheduling, staffing, and a record system, should be plotted on trend charts to show trends in process changes over time.

MAINTENANCE TASKS. The key components that require regular attention include

- Aeration or oxygen supply system,
- Mixing and pumping equipment, and
- Instrumentation and control equipment.

Aeration and Oxygen Supply. The principal requirement for the aeration or oxygen supply system is the inspection and service of the diffuser and blower equipment. Schedule diffuser mechanism inspections at least once per year. Blowers should be maintained in accordance with manufacturer's recommendations.

Mixing and Pumping Equipment. Annually, inspect the mixing and pumping equipment for worn blades and impellers. Replace faulty components and record critical parts for inventory. Service the seals, packing, and points of lubrication as frequently as recommended by the manufacturer.

Instrumentation and Control. Use a trained service representative to maintain the instrumentation and control components. Consider using the training courses available from equipment suppliers. Contract maintenance may also be available.

RECORDS. The importance of maintaining adequate O&M records cannot be overemphasized. The purpose of recording data is to track operational information that will identify and duplicate optimum operating conditions.

Records of the volume and concentration of waste sludge fed to the digester and volume and concentration of digested solids removed from the digester should be

kept. Additional information needs to include DO concentration and pH. Keep a monthly report form. In plants where the aeration system capacity is marginally adequate in providing desirable DO concentration in the digester, record DO concentration data on a trend chart. If chemicals are added to the digester for pH or odor control, record the type and amount of chemicals added. If mechanical aerators are used, record power usage. In the case of diffused-air systems, air flow records may be of interest. If airflow meters are not available, records of power consumption may be useful. Experimenting with the aeration system often leads to significant savings in power costs.

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Appendix A

Nutrient Balance Determination and Correction Strategies

A nutrient deficiency will sometimes cause a filamentous bulking problem. The following example shows how to determine if there is a nutrient deficiency, and how to calculate the amount of nutrient that needs to be added to correct the deficiency. Once the chemical rate is determined, the chemical must be fed into the secondary influent, preferably proportional to the flow. The chemical feed equipment must be set to feed the calculated amount of nutrients over a 24-hour period.

Example A. Calculate the amount of nutrients to add to correct a nutrient deficiency.

Given:

Secondary influent biochemical oxygen demand (BOD_5)	170 mg/L
Secondary influent total Kjeldahl nitrogen (TKN)	4.5 mg/L
Secondary influent phosphorus (P)	1.0 mg/L
Secondary influent iron (Fe)	0.5 mg/L
Suggested ratio by weight, BOD_5:nitrogen (N)	100:5 = 20
Suggested ratio by weight, BOD_5:P	100:1 = 100
Suggested ratio by weight, BOD_5:Fe	100:0.5 = 200
Averge daily plant flow *Q*	28 400 m^3/d/(7.5 mg/d)
Ammonia/nitrogen atomic weight radio, NH_3:N	17:14 = 1.2
Trisodium phosphate/phosphorus atomic weight ratio, Na_3PO_4:P	164:31 = 5.3
Ferric chloride/iron atomic weight ratio, $FeCl_3$:Fe	162.5:56 = 2.9

Step 1. Calculate the amount of nutrient needed to achieve the suggested ratios.

$$\text{Nutrient needed, mg/L} = \frac{\text{Secondary influent } BOD_5\text{, mg/L}}{\text{Suggested weight ratio, } BOD_5\text{/nutrient}}$$

$$\text{Nitrogen needed, mg/L} = \frac{(BOD_5\text{, mg/L})}{(\text{Suggested } BOD_5\text{/N ratio})}$$

$$= \frac{170 \text{ mg/L}}{20} = 8.5 \text{ mg/L}$$

$$\text{Phosphorus needed, mg/L} = \frac{(BOD_5\text{, mg/L})}{(\text{Suggested } BOD_5\text{/P ratio})}$$

$$= \frac{170 \text{ mg/L}}{100} = 1.7 \text{ mg/L}$$

$$\text{Iron needed, mg/L} = \frac{(BOD_5\text{, mg/L})}{(\text{Suggested } BOD_5\text{ /Fe ratio})}$$

$$= \frac{170 \text{ mg/L}}{200} = 0.85 \text{ mg/L}$$

Step 2. Calculate the difference in the nutrients available and the nutrients needed. If the answer is zero or a negative number, there is no shortage and no nutrients need to be added.

$$\text{Nutrient shortfall, mg/L} = \text{Nutrient needed, mg/L} - \text{Nutrient available, mg/L}$$

$$\text{Nitrogen shortfall, mg/L} = (\text{N needed, mg/L} - \text{TKN available, mg/L})$$
$$= 8.5 \text{ mg/L} - 4.5 \text{ mg/L} = 4.0 \text{ mg/L}$$

$$\text{Phosphorus shortfall, mg/L} = (\text{P needed, mg/L} - \text{P available, mg/L})$$
$$= 1.7 \text{ mg/L} - 1.0 \text{ mg/L} = 0.7 \text{ mg/L}$$

$$\text{Iron shortfall, mg/L} = (\text{Fe needed, mg/L} - \text{Fe available, mg/L})$$
$$= 0.85 \text{ mg/L} - 0.50 \text{ mg/L} = 0.35 \text{ mg/L}$$

Step 3. Calculate the weight of nutrients to be added.

$$\text{Amount of nutrient required} = (\text{Nutrient shortfall, mg/L})\,(Q, \text{m}^3\text{/d or mil. gal/d})\,(\text{conversion factor})$$

In metric units:

$$\text{Nitrogen required} = (\text{N shortage, mg/L})(Q,\ \text{m}^3/\text{d})(\text{conversion factor})$$

$$= (4.0\ \text{mg/L})(28\ 400\ \text{m}^3/\text{d})\left(\frac{0.001\ \text{kg/m}^3}{\text{mg/L}}\right)$$

$$= 114\ \text{kg/d}$$

In English units:

$$\text{Nitrogen required} = (\text{N shortage, mg/L})(Q,\ \text{mil. gal/d})(\text{conversion factor})$$

$$= (4.0\ \text{mg/L})(7.5\ \text{mil. gal/d})\left(\frac{8.34\ \text{lb/mil. gal/d}}{\text{mg/L}}\right)$$

$$= 250\ \text{lb/d}$$

Similarly, phosphorus and iron required would be calculated as 20 kg/d (43.8 lb/d) and 10 kg/d (21.9 lb/d), respectively.

Step 4. Calculate the weight of the commercial chemical to be added per day to supply the needed nutrients. This makes an adjustment for the commercial chemical that is not pure and for the fact that it is not composed solely of nutrient.

$$\text{Commercial chemical to be added, kg/d (lb/d)} = \frac{(\text{Nutrient to add, lb/gal})(\text{Atomic weight ratio})(100\%)}{(\text{Concentration of chemical, \%})}$$

For anhydrous ammonia, commercial grade solution, 80% concentration

$$\text{Anhydrous ammonia} = \frac{(\text{N to add})(1.2\ \text{NH}_3/\text{N})(100\%)}{\text{NH}_3\ \text{concentration, \%}}$$

In metric units

$$\text{Anhydrous ammonia} = \frac{(114\ \text{kg/d})(1.2)(100)}{80\%} = 171\ \text{kg/d}$$

In English units

$$\text{Anhydrous ammonia} = \frac{(250\ \text{lb/d})(1.2)(100)}{80\%} = 375\ \text{lb/d}$$

For Trisodium phosphate, commercial grade solution, 75% concentration

$$\text{Trisodium phosphate, lb/d} = \frac{(\text{P to add, lb/d})\,(5.3\ \text{Na}_3\text{PO}_4/\text{P})\,(100\%)}{\text{Na}_3\text{PO}_4\ \text{concentration, \%}}$$

$$= \frac{(43.8\ \text{lb/d})\,(5.3)\,(100)}{75\%}$$

$$= 310\ \text{lb/d}$$

For ferric chloride, commercial grade solution, 39% concentration

$$\text{Ferric chloride, lb/d} = \frac{(\text{Fe to add, lb/d})\,(2.9\ \text{Fe}_3/\text{Fe})\,(100\%)}{\text{FeCl}_3\ \text{concentration, \%}}$$

$$= \frac{(21.9\ \text{lb/d})\,(2.9)\,(100)}{39\%}$$

$$= 163\ \text{lb/d}$$

Appendix B

pH Adjustment Using Caustic Soda (pH too low)

The best method for determining the amount of caustic soda (NaOH) required to raise the pH is to use a batch titration method. A solution containing a known concentration of caustic soda is added drop by drop to a mixed liquor sample. A pH meter is used to monitor the pH during the titration. The sample volume must be known and the sample must be stirred during the test. Add the caustic soda slowly until the pH stabilizes at approximately 7.2. The amount of caustic soda added during the test is proportional to the amount required to raise the pH in the treatment process.

When adding caustic soda to the process, feed it *slowly*, otherwise the microorganisms may be shocked. It is preferable to use a flow-paced feeding system.

Example B. Calculate the amount of caustic (NaOH) to add to adjust pH.

Given:

Average daily plant flow Q	28 400 m^3/d (7.5 mgd)
NaOH normality used in the titration, N	0.02 N
NaOH volume used to titrate sample pH to 7.2	6.5 mL
Equivalent weight of 1 L of 1.0 N NaOH	40 000 mg/L
Sample volume	1000 mL

Step 1. Calculate the amount of NaOH needed to raise the sample pH to 7.2.

$$\text{Caustic needed, mg/L} = \frac{(\text{NaOH used per liter of Sample, mL})(\text{Normality of NaOH Titrant})(\text{Equivalent weight of 1.0 N NaOH})}{(1000\ \text{mL/L})}$$

$$= \frac{(6.5)\,(0.02)\,(40\ 000)}{1000}$$

$$= 5.2 \text{ mg/L}$$

Step 2. Calculate the weight of pure NaOH to add.

$$\text{NaOH to add, m}^3\text{/d (lb/d)} = (Q, \text{ m}^3\text{/d or mil. gal/d})(\text{NaOH needed, mg/L})(\text{conversion factor})$$

In metric units:

$$\text{NaOH to add} = (28\ 400 \text{ m}^3\text{/d})(5.2 \text{ mg/L})\left(\frac{0.001 \text{ kg/m}^3}{\text{mg/L}}\right)$$

$$= 148 \text{ m}^3\text{/d}$$

In English units:

$$\text{NaOH to add} = (7.5 \text{ mgd})(5.2 \text{ mg/L})(8.34 \text{ lb/gal}) = 325 \text{ lb/d}$$

Step 3. Calculate the weight of commercial caustic soda solution needed to furnish the weight of pure NaOH if using a commercial grade of 25%.

$$\text{NaOH needed, m}^3\text{/d (lb/d)} = \frac{(\text{Pure NaOH needed})\,(100\%)}{\text{Solution concentration, \%}}$$

In metric units:

$$\text{NaOH needed} = \frac{(148 \text{ m}^3\text{/d})\,(100\%)}{25\%}$$

$$= 592 \text{ m}^3\text{/d}$$

In English units:

$$\text{NaOH needed} = \frac{(325 \text{ lb/d})\,(100\%)}{25\%}$$

$$= 1300 \text{ lb/d}$$

Appendix C

pH Adjustment Using Lime (pH too high)

When determining the amount of lime needed to adjust pH, obtain and weigh a small amount of the actual lime to be used (1 to 2 g) in the treatment process. While a measured sample of mixed liquor is being stirred, add small increments of the weighed (or suspension) lime until the pH is approximately 7.2. Then weigh (measure) that portion of the lime (or suspension) that was not used. The weight of the dry lime required is determined as follows.

When adding caustic soda to the process, feed it *slowly*, otherwise the microorganisms may be shocked. It is preferable to use a flow-paced feeding system.

Example C. Calculate the amount of lime to add to adjust pH.

Given:

Average daily plant flow Q	28 400 m^3/d (7.5 mgd)
Weight of lime before titration	1.0100 g
Weight of lime after titration	1.0056 g
Weight of lime used in titration	0.0044 g or 4.4 mg
Sample volume	1000 mL

Step 1. Calculate the amount of lime needed to raise the sample pH to 7.2.

$$\text{Lime needed, mg/L} = \frac{(\text{Lime used, mg})(1000\ \text{mL/L})}{(\text{Sample volume, mL})}$$

$$= \frac{(4.4\ \text{mg})(1000\ \text{mL/L})}{(1000\ \text{mL})}$$

$$= 4.4\ \text{mg/L}$$

Step 2. Calculate the weight of lime to add.

Lime to add, m^3/d (lb/d) = (Q, m^3/d or mil. gal/d) (Lime needed, mg/L) (conversion factor)

In metric units:

$$\text{Lime to add} = (28\,400\ m^3/d)(4.4\ mg/L)\left(\frac{0.001\ kg/m^3}{mg/L}\right)$$

$$= 125\ m^3/d$$

In English units:

$$\text{Lime to add} = (7.5\ mgd)(4.4\ mg/L)(8.34\ lb/gal)$$

$$= 275\ lb/d$$

Appendix D

Control of Filamentous Organisms Using Chlorine

Bulking caused by filamentous organisms may be controlled temporarily by chlorinating the return sludge or mixed liquor. Chlorination is one way to quickly control filamentous bulking, however this remedy treats only the symptom, not the cause of the problem. Furthermore, excessive chlorination may do more damage than good, because it will begin to oxidize the floc and create a disbursed floc structure that will not settle.

Chlorine has a drastic effect on all microorganisms and it must be fed at the proper dosage to avoid shocking the beneficial microorganisms. The chlorine should be fed directly to the return activated sludge at a point of excellent mixing. The chlorine dosage should be started at a low level of 2 to 3 g/kg·d (2 to 3 lb chlorine (Cl_2/d/1000 lb) mixed liquor volatile suspended solids (MLVSS). A target sludge volume index should be selected as a maximum acceptable limit. It is possible to require as much as 5 to 10 g/kg·d (5 to 10 lb/d/1000 lb) MLVSS. Once chlorine addition is started, the process should be closely monitored.

Example D. Calculate the amount of chlorine to add to control filamentous bulking.

Given:

Biological reactor MLVSS	2000 mg/L
Biological reactor volume	4.77 ML (1.26 mil. gal)
Desired chlorine dosage	2.5 g/kg·d (2.5 lb/d/1000 lb MLVSS)

Step 1. Calculate the mass of MLVSS under aeration.

MLVSS, lb = (MLVSS, mg/L)(Biological reactor volume, ML or mil. gal)
(conversion factor)

In metric units:

$$\text{MLVSS, kg} = (2000\ \text{mg/L})(4.77\ \text{ML})\left(\frac{0.001\ \text{kg/m}^3}{\text{mg/L}}\right)(0.001\ \text{m}^3/\text{L})$$

$$= 9540\ \text{kg}$$

In English units:

$$\text{MLVSS, lb} = (2000\ \text{mg/L})(1.26\ \text{mil. gal})(8.34\ \text{lb/gal})$$

$$= 21\ 020\ \text{lb}$$

Step 2. Calculate the chlorine feed rate.

In metric units:

$$\text{Chlorine feed rate, kg/d} = \left(\frac{\text{Cl}_2\ \text{dosage, g/d}}{1\ \text{kg MLVSS}}\right)(\text{MLVSS, kg})$$

$$\text{Chlorine feed rate} = \frac{(2.5\ \text{g/d})}{1\ \text{kg}}(9540\ \text{kg})$$

$$= 23\ 850\ \text{g/d}$$

$$= 23.85\ \text{kg/d}$$

In English units:

$$\text{Chlorine feed rate, lb/d} = \left(\frac{\text{Cl}_2\ \text{dosage, lb/d}}{1000\ \text{lb MLVSS}}\right)(\text{MLVSS, lb})$$

$$\text{Chlorine feed rate} = (2.5\ \text{lb/d/1000 lb MLVSS})(21\ 020\ \text{lb MLVSS})$$

$$= 52.6\ \text{lb/d}$$

Appendix E

Settling Aid Determination for Improved Mixed Liquor Suspended Solids Settling

A variety of chemicals can be used to aid activated-sludge settling. Each has advantages and disadvantages. Before selecting a chemical, first run bench (jar) tests in the lab and compare the advantages and disadvantages of each, including the cost per unit volume treated for each chemical at its optimum dosage. These bench tests will give the starting dosage. Once the ballpark dosage is set, the dosage can be fine-tuned during actual use. The key is to use the lowest dosage possible and still achieve the improved settling desired.

In some areas of low wastewater alkalinity, sufficient alum or ferric chloride cannot be added in one dose to affect a change in sludge settleability. In those cases lower the application rate so that the pH is no lower than 6.5. Over the course of several days the same results can be achieved. The lower feed rate results in an accumulation of inorganic floc over time that results in improved settling. Once a chemical feed rate in weight or volume per day is calculated, the settling aid must be fed into the mixed liquor, preferably in proportion to the flow. Set the chemical feed equipment to deliver the calculated dosage across the entire 24-hour period. Adjustments in feed rates should then be made based on actual performance in the activated-sludge system.

The following example show how to calculate the feed rates for some chemicals commonly used as settling aids. Note that these dosages are *examples only* and are not meant to be a guide for general use.

Example F. Calculate the amount of settling aid to add to improve mixed liquor settleability.

Given:

Average daily plant flow Q	28 400 m^3/d (7.5 mgd)
Return sludge flow R	7600 m^3/d (2.0 mgd)
Mixed liquor volatile suspended solids	2000 mg/L
Dosages from bench test results	
Alum: 49% at 1.332 kg/L (11.1 lb/gal)	50 mg/L (wet)
Ferric chloride: 30% at 1.296 kg/L (10.8 lb/gal)	80 mg/L (wet)
Sodium aluminate: 38% at 1.452 kg/L (12.1 lb/gal)	20 mg/L (wet)

Step 1. Calculate the mixed liquor flow rate.

Mixed liquor flow, m^3/d (mgd) = (Q, m^3/d or mgd) + (R, m^3/d or mgd)

In metric units:

$$\text{Mixed liquor flow} = 28\,400\ m^3/d + 7600\ m^3/d$$
$$= 36\,000\ m^3/d$$

In English units:

$$\text{Mixed liquor flow} = (7.5\ \text{mgd}) + (2.0\ \text{mgd})$$
$$= 9.5\ \text{mgd}$$

Step 2. Calculate the weight of settling aid needed.

Chemical needed, mass/d = (Mixed liquor flow, m^3/d or mgd) (Chemical dosage, mg/L) (conversion factor)

In metric units:

$$\text{Alum needed, lb/d} = (36\,000\ m^3/d)(50\ mg/L)\left(\frac{0.001\ kg/m^3}{mg/L}\right)$$
$$= 1800\ kg/d$$

In English units:

$$\text{Alum needed, lb/d} = (9.5\ \text{mgd})\ (50\ \text{mg/L})\ (8.34\ \text{lb/gal})$$
$$= 3960\ \text{lb/d}$$

Similarly, ferric chloride and sodium aluminate needed would be calculated as 2880 kg/d (6340 lb/d) and 720 kg/d (1590 lb/d), respectively.

Step 3. Calculate the chemical feed rate.

$$\text{Chemical feed rate} = \frac{\text{Chemical needed}}{\text{Chemical density}}$$

In metric units:

$$\text{Alum feed rate, L/d} = \frac{1800\ \text{kg/d}}{1.332\ \text{kg/L}}$$
$$= 1351\ \text{L/d}$$

In English units:

$$\text{Alum feed rate, gal/d} = \frac{3960\ \text{lb/d}}{11.1\ \text{lb/gal}}$$
$$= 357\ \text{gal/d}$$

Similarly, ferric chloride and sodium aluminate feed rates would be calculated as 2220 L/d (587 gal/d) and 496 L/d (131 gal/d), respectively.

Note. Polymer Feed Rates—To prepare polymer solutions, manufacturer's instructions should be consulted for recommended batching and feeding concentrations. For maximum effectiveness the polymer should be well-diluted and well-mixed with the mixed liquor flow.

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Appendix F

Testing Equipment for Monitoring and Process Control

This Appendix describes a wide range of testing equipment used to monitor and control the activated- sludge process. Detailed procedures for conducting these tests are in the publications cited in the list of references.

CONTROL VERSUS MONITORING. Information from monitoring tests demonstrates compliance with legal mandates (e.g., laws, the National Pollutant Discharge Elimination System permit, 40 CFR 503, etc.). Process control tests provide information that is used to control the system. A familiar example is the suspended solids (SS) analysis for mixed liquor and final effluent samples. Both are tests for solids concentration. Final effluent may be used to evaluate process performance (removals, trend analysis); however, it more importantly proves that the effluent quality meets the requirements of law. The mixed liquor concentration analysis is performed only as a check of process status, with no legal requirements to perform the test.

PROCESS CONTROL LOOP. The activated-sludge process is controlled by continuously measuring, evaluating, and adjusting operational variables, such as return sludge rates and dissolved oxygen concentrations, to satisfy the constantly changing physical, chemical, and biological demands of the system. This requires that operating personnel routinely measure process variables and make process control decisions regarding timely control adjustments. This process control loop enables the activated-sludge process to proceed in an orderly manner without changes to the process control strategy that might result in a change that yields undesirable process characteristics.

EQUIPMENT ALTERNATIVES. To perform process control and monitoring tests, various pieces of equipment can be used. Some equipment may be costly, but will provide precise information essential to successful operation of the system. Less expensive equipment may provide information that is less precise, but adequate for process control. The sophistication required, labor expended, and cost of equipment and chemicals are considerations for selecting a process control strategy and the associated equipment.

The equipment discussed in this Appendix is commercially available, and the different features of each should be considered. This section does not recommend a specific test and associated equipment to use, but rather presents the features, operational considerations, and application of various pieces of equipment and compares information obtained from different alternatives.

AMMONIA

The absence of ammonia-nitrogen in secondary effluent typically means that nitrification has occurred and ammonia-nitrogen has been converted to nitrate-nitrogen in the biological reactors. Many activated-sludge plants are required to nitrify and some to denitrify and convert nitrate-nitrogen to nitrogen gas. Normal wastewaters contain between 10 and 35 mg/L of ammonia-nitrogen. Activated-sludge plants, depending on their design and operational strategies, may nitrify partially, totally, or not at all. The degree of nitrification can be evaluated using traditional wet chemistry techniques (APHA et al., 1998). However, specific ion electrodes can be used to obtain ammonia concentrations.

AMMONIA ELECTRODES. Ammonia electrodes are approximately 13 mm (0.5 in.) in diameter and 150 mm (6 in.) in length allowing them to be used for small-volume samplers such as test tubes or biological oxygen demand (BOD) bottles. The electrode is commonly connected to a meter, such as pH or a specific ion meter. Samples and standards are adjusted to a pH greater than 11 so the ammonium ion is completely converted to free ammonia. After pH adjustment and standardization, samples can be readily measured at concentrations as low as 0.01 mg/L and as high as 17 000 mg/L ammonia.

TURBIDITY

The turbidity of a given sample indicates the presence of suspended matter and results in the scattering and absorption of light. The simplest device available for making such a device is a Secchi disk. In the early 1960s, the turbidimeter became popular for esti-

mating solids in wastewater samples. This instrument provided more precise measurements, but was not sufficiently dependable. Today, the nephelometric turbidimeter measures the scattering of light by particles at a 90-deg angle.

Many activated-sludge plants have found these different pieces of equipment useful for daily operations because conventional effluent quality tests, such as BOD or SS, are time consuming to perform and may not provide the timely results sometimes required for process control. Operators may rely on turbidity measurements to provide operational insight.

SECCHI DISK. This simple device is nothing more than a flat plate connected at the center to a cord that is customarily graduated in meters or feet. The plate is typically circular with each quadrant alternately painted black and white. The disk is lowered on the cord into the clarifier to a point where it is no longer visible to the operator. This depth is noted and recorded by the operator. The deeper into the tank the operator can see it, the clearer the water.

TURBIDIMETERS AND NEPHELOMETERS. Turbidimeters, presently used in water and wastewater plants worldwide, accurately measure light scattering. Visible light is passed through a sample of water or wastewater and scattered by particulate matter. This scattered light is received by a photocell and converted into a signal, which is an indication of the amount of light received. The meter, digital readout, or other similar device displays the quantity. The more particulate matter, the less the degree of clarity.

Turbidity standards must be used to standardize the instrument prior to sample measurement. Standards can be made fresh from formazin and turbidity-free water. This procedure can be laborious and the materials have a short shelf life. Synthetic standards are commercially available and possess a longer shelf life when properly preserved.

REFERENCE

American Public Health Association; American Water Works Association; Water Environment Federation (1998) *Standard Methods for the Examination of Water and Wastewater.* 20th Ed., Washington, D.C.

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Appendix G

Alkalinity Adjustment

Sufficient alkalinity must be present in the activated sludge system to achieve reliable nitrification. As a consequence of nitrification, alkalinity is consumed (approximately 7.14 mg/L for each milligram per liter of ammonia oxidized), and the activated-sludge system pH may be lowered excessively. Typically, system pH should range between 6.5 and 8.0. Depending on system loadings, influent alkalinity may be insufficient; consequently alkalinity (typically sodium hydroxide) must be added to replace the alkalinity that has been consumed. Typical influent alkalinity concentrations are approximately 230 mg/L. A residual alkalinity buffer of 100 mg/L (as calcium carbonate, $CaCO_3$) in the secondary effluent is desirable.

An example follows to determine if supplemental alkalinity is required. This method is based on the biology of the activated-sludge system.

Example 1. Determine if supplemental alkalinity is required.

Given:

Plant flow Q	45 000 m^3/d (12 mgd)
Biological reactor influent alkalinity	233 mg/L
Biological reactor influent total Kjeldahl nitrogen	35 mg/L
Biological reactor influent ammonia	22 mg/L
Effluent ammonia	2 mg/L
Effluent nitrate	20 mg/L

Step 1. Determine the organic nitrogen available for conversion to ammonia.

$$\begin{aligned}\text{Nitrogen available for conversion to ammonia} &= \\ \text{Influent TKN, mg/L} - \text{Influent ammonia, mg/L} &- \text{Organic nitrogen pass through} \\ &= 35\ \text{mg/L} - 22\ \text{mg/L} - 2\ \text{mg/L} \\ &= 11\ \text{mg/L}\end{aligned}$$

Step 2. Calculate the alkalinity to be added to the process, based on an alkalinity addition rate of 3.57 mg/L for each milligram per liter of ammonia to be oxidized.

$$\text{Alkalinity added} = \frac{(\text{Ammonia to be oxidized, } \cancel{\text{mg}}/\cancel{\text{L}})\,(\text{Alkalinity added, mg/L})}{(\text{Ammonia oxidized, } \cancel{\text{mg}}/\cancel{\text{L}})}$$

$$= \frac{(11\ \cancel{\text{mg}}/\cancel{\text{L}})\,(3.57\ \text{mg/L alkalinity})}{1.0\ \cancel{\text{mg}}/\cancel{\text{L}}}$$

$$= 39\ \text{mg/L alkalinity}$$

Step 3. Determine ammonia available for conversion to nitrate.

$$\begin{aligned}\text{Ammonia available} &= \text{Influent TKN, mg/L} - \text{Effluent ammonia} \\ &= 35\ \text{mg/L} - 2\ \text{mg/L} \\ &= 33\ \text{mg/L}\end{aligned}$$

Step 4. Calculate the alkalinity consumed in the process.

$$\text{Alkalinity consumed} = \frac{(\text{Ammonia available, } \cancel{\text{mg}}/\cancel{\text{L}})\,(7.14\ \text{mg/L alkalinity})}{(\text{Ammonia oxidized, } \cancel{\text{mg}}/\cancel{\text{L}})}$$

$$= \frac{(33\ \cancel{\text{mg}}/\cancel{\text{L}})\,(7.14\ \text{mg/L alkalinity})}{1.0\ \cancel{\text{mg}}/\cancel{\text{L}}}$$

$$= 236\ \text{mg/L alkalinity}$$

Step 5. Determine alkalinity added to the process from ammonia converted to nitrate gas.

$$\begin{aligned}\text{Ammonia converted} &= \text{Ammonia converted to nitrate, mg/L} - \text{Effluent } NO_3\text{, mg/L} \\ &= 33\ \text{mg/L} - 20\ \text{mg/L} \\ &= 13\ \text{mg/L}\end{aligned}$$

Step 6. Calculate alkalinity added to the process.

$$\text{Alkalinity added} = \frac{(\text{Ammonia converted, } \cancel{\text{mg}}/\cancel{\text{L}})\,(3.57 \text{ mg/L alkalinity})}{(\text{Ammonia oxidized, } \cancel{\text{mg}}/\cancel{\text{L}})}$$

$$= \frac{(13\ \cancel{\text{mg}}/\cancel{\text{L}})\,(3.57 \text{ mg/L alkalinity})}{1.0\ \cancel{\text{mg}}/\cancel{\text{L}}}$$

$$= 46 \text{ mg/L}$$

Step 7. Determine the change in alkalinity.

$$\text{Alkalinity change} = \text{Alkalinity produced} - \text{Alkalinity consumed}$$

$$= 39 \text{ mg/L} + 46 \text{ mg/L} - 236 \text{ mg/L}$$

$$= -151 \text{ mg/L}$$

Step 8. Project effluent alkalinity.

$$\text{Measured change in alkalinity} = \text{Influent alkalinity mg/L} - \text{Effluent alkalinity, mg/L}$$

$$= 233 \text{ mg/L} - 151 \text{ mg/L}$$

$$= 82 \text{ mg/L}$$

Because the calculated alkalinity is less than 100 mg/L, the feed rate for supplemental alkalinity (caustic) should be determined.

Example 2 presents a sample calculation based on the alkalinity evaluation previously presented. This approach requires that fewer calculations be performed and is based on the results of nitrification that appear in the secondary effluent.

Example 2. Determine the supplemental alkalinity requirements.

Given:

Plant flow	22 700 m^3/d (6 mgd)
Calculated effluent alkalinity	82 mg/L

Step 1. Calculate the alkalinity supplement needed to maintain a minimum effluent alkalinity of 100 mg/L.

$$\begin{aligned}\text{Alkalinity supplement} &= 100\ \text{mg/L} - \text{Effluent alkalinity, mg/L} \\ &= 100\ \text{mg/L} - 82\ \text{mg/L} \\ &= 18\ \text{mg/L}\end{aligned}$$

Step 2. Determine feed rate for addition of supplemental alkalinity using lime.

Lime addition = (Q)(alkalinity concentration, mg/L)(conversion factor)

In metric units:

$$\text{Lime addition} = (22\,700\ \text{m}^3/\text{d})\,(18\ \text{mg/L})\left(\frac{0.001\ \text{kg/m}^3}{\text{mg/L}}\right)$$

$$= 409\ \text{kg/d}$$

In English units:

$$\text{Lime addition} = (6\ \text{mgd})(18\ \text{mg/L})(8.34\ \text{lb/gal})$$

$$= 900\ \text{lb/d}$$

Appendix H

Activated-Sludge System Safety

Use the checklist that follows to develop a safety program for a treatment plant with activated-sludge facilities.

☑	Process	Area	Hazard
☐	General	All	Remove tripping hazards, clean up grease deposits, and ensure that lighting is adequate.
☐	Clarifiers and biological reactors	Open tanks, flow channels with pipe conduits, and walkways	Provide handrails and kick plates to avoid falling in open tanks or kicking tools in the tanks or lower structures.
☐	Clarifiers and biological reactors	Open tanks, flow channels with pipe conduits, and walkways	Wear safety lines and life vests when working over or around these facilities. Wear proper personal protective equipment. Falls into biological reactors may cause drowning. If possible, stop aeration while working over reactors. Because of reduced buoyancy workers may require special life jackets.
☐	Clarifiers and biological reactors	Open tanks, flow channels with pipe conduits, and walkways	Install lifelines, rings, pike poles, and jackets at each tank for rescue and to prevent drowning.

	Process	Area	Hazard
☐	Clarifiers	Clarifier drives	Follow lockout–tagout procedures before working on equipment. Use the torque indicator to verify that tension has been released before disconnecting a clarifier drive.
☐	Aeration facilities	Mechanical aerators	Keep walkway areas clean. Remove foam, algal slime, and splashed material immediately to prevent slips.
☐	Aeration facilities	Blowers	May produce high noise levels. Noise exposure should not exceed 85 db over an eight-hour period. Wear hearing protection around blowers to prevent damage to hearing.
☐	Aeration facilities	Blowers	Wear dust protection when changing or cleaning air filters. Wear proper personal protective equipment.
☐	Aeration facilities	Diffuser system	Use adequate hoists to lift air header and diffuser piping sections. Rest supports in a location that is strong and durable and will not bend or move. Wear hard hats with chin straps.
☐	Pure oxygen facilities	General	Housekeeping must be immaculate because all materials could be combustible.
☐	Pure oxygen facilities	General	Absolutely **no smoking** is allowed near oxygen-enriched areas.
☐	Pure oxygen facilities	General	Breathing pure oxygen will make an individual giddy and can result in burnt lungs. Wear proper personal protective equipment.
☐	Pure oxygen facilities	General	Ozone is heavier than air and will settle in pits and subsurface depressions. Purge these areas to make them safe.
☐	Pure oxygen facilities	General	A minimum of 6 to 10 air changes are required in ventilated areas. Purge all unventilated areas before entering.
☐	Pure oxygen facilities	Liquid oxygen	Severe freeze burns can occur on contact with the body because of extremely low temperature, –183 °C (–300 °F). Wear proper personal protective equipment.

	Process	Area	Hazard
☐	Pure oxygen facilities	Liquid oxygen	Repair all oxygen-related equipment in accordance with the manufacturer's guidelines using approved parts and replacement equipment to prevent introducing an incompatible material.
☐	Pure oxygen facilities	Liquid oxygen	Oxygen can be trapped in the weave of fabric; be aware of this hazard and deal with it accordingly for contaminated clothing. Wear proper personal protective equipment before working with the system. If clothing is saturated with oxygen, remove the clothing under a running shower. A fire hazard will continue to exist until the liquid oxygen has dissipated, which may take 30 minutes or longer.

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Appendix I

Preventive Maintenance Schedule (Typical)

The following checklist is an example of a preventive maintenance program for activated-sludge facilities. In developing a site-specific schedule consult the service manuals that were provided with each piece of equipment.

Activated-sludge system preventive maintenance (typical)	Daily	Weekly	Monthly	Quarterly	Biannual	Annual	Comments
Aeration blower							
Maintain proper motor lubricant level		W					
Lubricate motor roller bearings							1.5 months
Check for abnormal noises and vibration				Q			
Check that air filters are in place and not clogged				Q			
Check motor bearing rise temperature				Q			
Check motor for voltage and frequency variations				Q			
Check that all covers are in place and secure				Q			
Rotate blower operation				Q			
Lubricate motor ball bearings				Q			
Check that electrical connections are tight				Q			
Check wiring integrity				Q			
Lubricate motor sleeve bearing					B		or 2000 hours
Inspect and clean rotor ends, windings, and blades					B		
Check that electrical connections are tight and corrosion is absent					B		
Change blower bearing oil						A	
Relubricate after checking flexible couplings							As needed

(*continued*)

Activated-sludge system preventive maintenance (typical)	Daily	Weekly	Monthly	Quarterly	Biannual	Annual	Comments
Oxygen dissolution system							
Lubricate motor					B		
Change gear drive oil					B		
Lubricate flex coupling						A	or 2500 hours
Inspect gear tooth pattern wear, shaft and bearing end play alignment, bolting, and seal condition						A	
Fine bubble diffusers							
Check biological reactor surface pattern	D						
Check air mains for leaks	D						
Check and record operating pressure and airflow	D						
Purge water moisture from distribution piping			W				
Bump diffuser system			W				
Drain biological reactor						A	
Remove excess solids that may accumulate						A	
Clean diffusers						A	
Check that retaining rings are in place and tight						A	
Check that fixed and expansion joint retaining rings are tight						A	
Secondary clarifier							
Remove trash and debris	D						
Test torque-control line switches		W					
Test torque overload alarm		W					
Verify torque scale pointer moves		W					
Check drive unit for accumulated condensation		W					
Check drive oil level and quality		W					
Check drive overload response controls						A	
Inspect entire mechanism above and below water line						A	
Inspect and tighten all nuts and bolts							Regular interval
Inspect lubrication for torque-overload protection device, per manufacturer's instructions							e.g., 18 months or 500 cycles

(*continued*)

Activated-sludge system preventive maintenance (typical)	Daily	Weekly	Monthly	Quarterly	Biannual	Annual	Comments
Return activated sludge pumps (centrifugal)							
Lubricate pump bearings				Q			or 2000 hours
Lubricate motor bearings						A	
Waste activated sludge pumps (centrifugal)							
Lubricate pump bearings				Q			or 2000 hours
Lubricate motor bearings						A	

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Chapter 21

Trickling Filters, Rotating Biological Contactors, and Combined Processes

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INTRODUCTION

Tricking filters, biotowers, and rotating biological contactors (RBCs) are generally known as *fixed-film treatment processes*. Of these three processes, the trickling filter process predates biotowers, RBCs, and combined fixed-film and suspended growth (FF/SG) processes.

In fact, trickling filters predate most of the treatment methods considered in other chapters of this manual, and they are still a viable process. New types of filter media are now used; therefore, rock media systems are labeled *trickling filters*, and plastic media systems are labeled *biotowers*. Trickling filters are being incorporated into wastewater facilities using new methods or processes, and many rock filters are being refurbished for continued use. This chapter helps both operators and engineers grasp the operations and maintenance requirements of trickling filters as used in existing and new systems.

Although their performance has been good, RBC equipment operation has been plagued by failures. This chapter discusses many of the changes that occurred in both design and operation. It includes discussions of predicting operating problems or plant overload and emphasizes methods of upgrading or improving RBC operations.

Combined processes [i.e., trickling filters, biotowers, or RBCs (fixed-film) coupled with suspended-growth (activated sludge) processes] now number several hundred in the United States. Combined FF/SG processes are designed to take advantage of the strengths and minimize the weaknesses of each process. In many cases, the practice is used to reduce construction costs by avoiding the need for additional tankage. In some industrial or high-strength-waste applications, the FF/SG processes have helped eliminate shock loads to the activated sludge process. The coupling of biological processes has solved many problems, but also produced new control criteria or concerns. This chapter addresses operations and maintenance concerns associated with the coupling or combining of biological processes.

Fixed-film biological processes remove dissolved organics and finely divided organic solids from wastewater. Removal occurs primarily by converting soluble and colloidal material into a biological film that develops on the filter media. Raw domestic and industrial wastewater typically contains settleable solids, floatable materials, and other debris. Failure to remove these solids before the wastewater enters the fixed-film reactors can interfere with their oxygen-transfer capabilities, plug the filter media, result in high solids yield, or create other problems. Therefore, both fixed-film and combined-growth processes are typically preceded by screenings and the grit removal process. Primary treatment processes should be used to reduce the fixed-film process load.

The fixed-film or biological media removes soluble biochemical oxygen demand (BOD) and produces biological solids. Most often, the process removes carbonaceous BOD; however, sometimes the fixed-film systems can be loaded so slow-growing, nitrogen-converting autotrophic bacteria (nitrifiers) can compete with the more rapid-growing heterotrophic bacteria used for carbonaceous BOD removal; therefore, the fixed-film process can be used to nitrify the wastewater.

In combined FF/SG processes, the second-stage process may remove varying amounts of soluble BOD (SBOD), depending largely on the loading and performance of the first-stage process. Combined processes are given different names, depending on which stage removes the most SBOD and at which point biological solids are introduced to the treatment scheme.

To ensure that treatment is successful, the following principles must be considered in both the design and operation of fixed-film and combined processes.

CONCEPTS. Removal of organic materials through the use of fixed and combined reactors is accomplished by means of a biological film on the fixed-film media. This film—a viscous, jellylike slime—typically is composed of a large and diverse population of living organisms (e.g., bacteria, protozoa, algae, fungi, worms, and even insect larvae). Most of the mass of this population is aerobic organisms. An *aerobic organism* requires oxygen to function properly.

As the slime layer thickens, the adsorbed organic matter is metabolized before it can reach the microorganisms near the media face. As a result, the microorganisms near the media face enter into an endogenous phase of growth and lose their ability to cling to the media surface (Metcalf and Eddy, 1979). This allows the flowing wastewater to scour the slime from the filter media—a process is known as *sloughing*—and a new slime growth begins. The sloughing process continues at various stages throughout the filter. However, sloughing can be encouraged either by increased hydraulic loading, supplemental aeration, temperature changes, other operator-induced changes, or environmental conditions.

The removal of soluble organic material is a relatively rapid process. Good removal of soluble organics can typically be achieved at low to moderate loading of the fixed-film reactors. However, the stabilization or breakdown of biological solids generated in removing the soluble organics is a longer process. The time required for completion of this process will vary, depending on the type of filter media being used, rate of organic loading to the fixed-film process, hydraulic shear, temperature, and other factors (Water Pollution Control Federation, 1988).

LOAD VARIATIONS. Fixed-film reactors (trickling filters or RBCs) vary in their ability to absorb either seasonal or shock industrial wastewater loads. For either process, extremes may cause a bleed-through of BOD or even severe sloughing or biological kill. Recycled filter effluent is often used to dilute incoming raw waste and add oxygen to the trickling filters, biotowers, or first stages of the RBCs. Using recycle techniques, treatment of wastewater with 5-day BOD (BOD_5) concentrations greater than

10 000 mg/L is possible. This occurs especially in the treatment of food processing waste, for which trickling filters are often used.

pH AND ALKALINITY. Bacteria associated with fixed-film reactors typically thrive in a pH range between 5.5 and 9.0; the best pH range is between 6.8 and 7.2. Often, treatment problems result from rapid changes in pH values rather than from extreme long-term average values.

Although low pH may result from the discharge of industrial wastes or poorly buffered natural waters, a drop in pH may also occur in the treated wastewater if the fixed-film or combined reactors are lightly loaded or when temperatures are moderate. This indicates that nitrification is occurring. Nitrification oxidizes ammonia, resulting in the loss of alkalinity and a corresponding pH drop.

TOXICITY. Both fixed-film and combined-growth processes are typically less susceptible to toxicity or shock loads than suspended-growth (activated sludge) systems. However, complex organic substances, heavy metals, pesticides, inorganic solids, and even surges of disinfectants (e.g., chlorine) could either greatly reduce the performance of, or cause a biological kill within, both fixed-film and combined processes. The toxicity causes either poor treatment performance or massive sloughing. Source control through industrial waste management is necessary if industrial discharges are causing the toxicity problem.

NUTRIENTS. Wastewater that is primarily from domestic sources typically has more than sufficient nutrients to ensure that bacterial growth is not inhibited because of the lack of essential nutrients. However, some industrial wastes (especially food processing) lack sufficient nutrients to promote normal bacterial growth. Mixtures of domestic and industrial waste can also be nutrient deficient when the industrial portion dominates the municipal plant's organic load.

The most commonly deficient nutrients are nitrogen (N) and phosphorus (P). To be available for bacterial growth, nitrogen must be in the form of soluble ammonia, and phosphorus must occur in the orthophosphate form. Empirical ratios based on the amounts of nutrients needed for producing biological cells suggest that for each 45 kg (100 lb) of BOD_5, 2.3 kg (5 lb) of nitrogen and 0.5 kg (1 lb) of phosphorus must be available for proper cell growth. In equation form, this ratio is 90 BOD_5:4.6 N:1 P (100 BOD_5:5 N:1 P).

TEMPERATURE. Biological activity (hence BOD removal) in all treatment systems declines as temperatures decrease. However, fixed-film bacteria appear to be more sensitive to the temperature drop than the bacteria in suspended-growth (activated

sludge) systems. For example, a drop in temperature from 26 to 20 °C (78 to 68 °F) in a suspended-growth system will typically halve the coefficient of removal. The same temperature drop in a fixed-film reactor could decrease the removal rate coefficient by two-thirds or more. As a result of reduced efficiency during winter months, several literature sources indicate that filters should be sized 25% larger in the northern United States than in southern areas. Attempting to conserve heat in the wastewater as it proceeds through treatment may sometimes reduce the adverse effects of cold temperatures. Following are some ideas on how this can be accomplished:

- Removing a unit from service,
- Covering the fixed-film process,
- Reducing recirculation,
- Using forced rather than natural ventilation,
- Reducing the settling tank's hydraulic retention time,
- Operating in parallel rather than in series,
- Adjusting orifice and splash plates to reduce spray,
- Constructing windbreaks to reduce wind effects,
- Intermittently dosing the filter,
- Opening dump gates or removing splash plates from distributor arms, and
- Covering open sumps and transfer structures.

DISSOLVED OXYGEN. Dissolved oxygen is needed to sustain the aerobic microorganisms in the fixed-film process. As water flows over the fixed-film media, oxygen transfers to the water. When water is recycled in the fixed-film process, the presence of a high concentration of dissolved oxygen in the fixed-film underflow or treated effluent does not necessarily mean that this same concentration is available in the RBC's first stage, the trickling filter's interior, or the biotower's various levels. Oxygen deficiencies with trickling filter and biotower media have been less troublesome than those with RBC media.

Biotowers with high-rate (plastic or redwood) media are frequently designed for BOD_5 loadings between 320 and 480 kg BOD_5/100 m^3·d (200 and 300 lb BOD_5/1000 cu ft/day) before concerns are raised about low dissolved oxygen in the filter underflow. However, some biotowers are designed for loadings less than 240 kg BOD_5/100 m^3·d (150 lb BOD_5/1000 cu ft/day) to prevent odor problems. Loadings with rock filter media are often maintained at less than 90 kg BOD_5/100 m^3·d (50 lb BOD_5/1000 cu ft/day) to ensure adequate dissolved oxygen and low odor potential. A survey of highly loaded trickling filters or biotowers indicates that odors result less frequently from high organic loading or low dissolved oxygen in the filter underflow than from constituents in

the wastewater (e.g., high industrial loading). Some odors always emanate from trickling filters and biotowers; the proximity and sensitivity of nearby residents will often determine whether the odor is a nuisance.

Dissolved oxygen can be a limiting factor in RBC performance, if improperly designed. Organic loadings to RBCs should be limited to 2.9 to 3.9 kg $BOD_5/100\ m^2 \cdot d$ (6.0 to 8.0 lb BOD_5/1000 sq ft/day) or 1.2 to 2.0 kg $SBOD_5/100\ m^2 \cdot d$ (2.5 to 4.0 lb $SBOD_5$/1000 sq ft/day) for the first-stage units in service. First-stage units are typically loaded at three to four times the recommended BOD_5 load of the total units in service.

To reduce the oxygen limitations of RBC facilities, a number of plants have been upgraded by preceding or combining preaeration, trickling filter, activated sludge, or solids contact with RBC reactors. Alternatively, supplemental aeration has been added to the RBC units in some facilities. These approaches to RBC upgrading are discussed in the Combined Processes section of this chapter.

MICROORGANISMS. The treatment of wastewater by fixed-film processes produces a biological (zoogleal) slime that coats the surface of the media. When fixed-film reactors are used for BOD removal, the microbial population consists of various species of heterotrophic bacteria with smaller populations of protozoa and fungi. If these reactors are used for nitrification, autotrophic nitrifying microorganisms predominate, with smaller numbers of heterotrophic bacteria.

Under conditions of low dissolved oxygen, nutrient deficiencies, or low pH values, organisms that either remove BOD slowly or exhibit poor settling characteristics can dominate the fixed-film reactor. These organisms are predominately filamentous bacteria and sometimes fungi and are a nuisance.

Eliminating filamentous bacteria typically involves identifying the source of the nuisance and eliminating the condition that allows them to dominate the system. In addition, the recycle of suspended-growth bacteria over the fixed-film reactor has often reduced the presence of filamentous bacteria. This mode resembles the selector activated sludge process described in Chapter 20. This approach for fixed-film reactors is discussed in more detail in the Combined Processes section of this chapter.

TRICKLING FILTERS AND BIOTOWERS

Trickling filters attempt to duplicate the natural purification process that occurs when polluted wastewater enters a receiving stream and trickles over a rock bed or rocky river bottom. In the natural purification process, bacteria in the rock bed remove the soluble organic pollutants and purify the water. For more than 100 years (since the late 1880s), trickling filters have been considered a principal method of

wastewater purification. The principle of using a rock bed for purification was applied in filter design, with the rock beds typically ranging from 0.9 to 2.4 m (3 to 8 ft) deep. After declining use in the late 1960s and early 1970s, trickling filters regained popularity in the late 1970s and early 1980s, primarily because of new media types. The new high-rate media were typically preferred over rock media because they offer more surface area for biological growth and improved treatment efficiency. The advent of high-rate media minimized many of the rock media problems (e.g., plugging, uncontrolled sloughing, odors, and filter flies). Consequently, almost all trickling filters constructed in the late 1980s use high-rate media (Water Pollution Control Federation, 1988); they are called *biotowers*.

This section focuses on the operation and maintenance of both types of trickling filters. Their operations and maintenance needs may vary greatly, depending on the type of filter media used and how the filter was designed (Albertson and Eckenfelder, 1984).

ALTERNATIVES. There are four basic categories of filter design, based on the organic loading of the trickling filter/biotower. In the first three categories—low-, intermediate-, and high-rate filters—the filter removes all or essentially all of the BOD applied (Table 21.1). In the fourth category (the roughing filter), the filter is typically combined with another biological treatment step (typically activated sludge, RBC, or another filter), where a substantial amount of BOD removal occurs.

The categories of trickling filters/biotowers are typically based on BOD_5 loading to the filter divided by the volume of filter media, calculated as follows:

$$\text{Organic } (BOD_5) \text{ load} = \frac{BOD_5 \text{ applied, lb/d}}{\text{Volume of media, 1000 cu ft}} \tag{21.1}$$

Where

BOD_5 applied = kg primary effluent BOD_5/d;
= (primary effluent BOD_5, mg/L)(flow, ML/d) and

Volume of media $= \dfrac{\text{horizontal (plan) area, } m^2 \times \text{media depth, m}}{100}$

Or (in U.S. customary units)

BOD_5 applied = lb primary effluent BOD_5/d;
= (primary effluent BOD_5, mg/L)(flow, mgd)
(8.34 lb/gal); and

Volume of media $= \dfrac{\text{horizontal (plan) area, sq ft} \times \text{media depth, ft}}{1000}$

TABLE 21.1 Trickling filter categories.

	Trickling filter categories			
Operating characteristics	**Low**	**Intermediate**	**High**	**Roughing**
Organic loading, lb BOD/d/1000 cu ft/day	<25	25–40	40–100	100–300
Filter media[a]	Rock or high rate	Rock or high rate	Rock or high rate	High rate
Nitrification[b]	Yes	Partial	Unlikely	No
Combined process required[c]				
—For secondary treatment	No	Unlikely	Likely	Yes
—For tertiary treatment	Yes	Yes	Yes	Yes
Type typically used[d]	TF/SC	TF/SC	TF/SC	TF/AS
	ABF	ABF	TF/RBC	BF/AS
			2-stage filters	RF/AS 2-stage filters

[a]High rate = plastic or redwood.
[b]At 26 °C (78 °F) and without a second-stage or combined process.
[c]Indicates if combined or dual process is typically used.
[d]TF/SC = trickling filter–solids contact; TF/AS = trickling filter–activated sludge; ABF = activated biofilter; TF/RBC = trickling filter–rotating biological contactor; BF/AS = biofilter–activated sludge; and RF/AS = roughing filter–activated sludge.

Although filters/biotowers are typically not classified by hydraulic loading, the hydraulic or wetting rate is a useful loading parameter and is calculated as follows:

$$\text{Hydraulic load wetting rate} = \frac{\text{Total flow (including recycle), pumped, gal/min}}{\text{Horizontal (plan) area, sq ft}} \qquad (21.2)$$

Where

Total flow = incoming + filter recycle flow;
= sum of filter pump capacity, gal/min; and

Horizontal plan area = $\frac{3.14\,(\text{diameter}^2)}{4}$, for circular unit
= length × width, for rectangular unit.

Example 21.1. Calculate the organic and hydraulic loadings of a filter.

Given:

Q (Flow)	= 5 mgd,
Primary effluent BOD_5	= 120 mg/L,
Filter diameter	= 110 ft,
Media depth	= 8 ft,
Number of filters	= 1, and
Total filter pumping capacity	= 7000 gal/min.

Solution:

$$\text{Horizontal plan area} = \frac{3.14\ (110)^2}{4}$$

$$= 9499 \text{ sq ft}$$

$$\text{Filter volume} = \frac{(9499 \text{ sq ft})(8 \text{ ft})}{1000}$$

$$= 76(1000 \text{ cu ft})$$

$$BOD_5 \text{ applied} = (120 \text{ mg/L})(5 \text{ mgd})(8.34)$$

$$5004 \text{ lb } BOD_5/\text{d}$$

$$\text{Organic load filter} = \frac{5400 \text{ lb } BOD_5/\text{d}}{76\ (1000 \text{ cu ft})}$$

$$= 65.8 \text{ lb } BOD_5/\text{d}/1000 \text{ cu ft}$$

$$\text{Hydraulic load} = \frac{70000 \text{ gal/min}}{9499 \text{ sq ft})}$$

$$= 0.74 \text{ gpm/sq ft}$$

Organic loading, typically expressed as total BOD_5 in the primary effluent, is often referred to as *total organic loading* (TOL). Another common way to evaluate BOD loading depends on the amount of soluble filter/biotower BOD. This loading is referred to as the *soluble organic loading* (SOL).

Low-Rate Filters/Biotowers. Low-rate filters/biotowers typically include rock trickling filter media. At loadings of less than 40 kg $BOD_5/100\ m^3 \cdot d$ (25 lb $BOD_5/d/1000$ cu ft), fewer problems from filter flies, odors, or media plugging (ponding) are expected than with filters operating at higher loading rates.

Low-rate trickling filters with rock media range in depth from 0.9 to 2.4 m (3 to 8 ft). Most low-rate filters are circular with rotary distributors. However, a number of

rectangular rock filters remain in operation. With rock media, low-rate filters are typically not hydraulically limited; application rates ranging from 0.01 to 0.04 $L/m^2 \cdot s$ (0.02 to 0.06 gpm/sq ft) are common. Both circular and rectangular filters are sometimes equipped with dosing siphons or periodic pumping to provide a high wetting rate for short intervals between rest periods.

With high-rate plastic filter media, a minimum wetting rate (accomplished via recirculation or dosing) is typically maintained to prevent the media from drying out and to ensure good contact. A rate of 0.4 $L/m^2 \cdot s$ (0.7 gpm/sq ft) is typically considered good practice. Potential loss in BOD removal performance should be evaluated at lower rates.

Sloughed solids from a low-rate filter are typically well-digested, so these filters yield less solids than higher rate filters. Solids yields of 0.5 kg total suspended solids (TSS)/kg (0.5 lb TSS/lb) secondary influent BOD_5 are not uncommon, especially with rock media.

To provide tertiary treatment or polished effluent, combined processes [e.g., trickling filter/solids contact (TF/SC) or activated biofilter (ABF)] may be used. Combined processes are typically not required to achieve effluent of conventional secondary treatment quality. Secondary quality effluent is readily attainable if the low-rate trickling filter design incorporates filter media with bioflocculation capabilities or good secondary clarification (Harrison et al., 1984). For more information, see the Combined Processes section of this chapter.

Intermediate-Rate Filters. Intermediate filters may be loaded up to 64 kg BOD_5/100 $m^3 \cdot d$ (40 lb BOD_5/d/1000 cu ft). Recirculation of trickling filter/biotower effluent is typically practiced to ensure good distribution and thorough blending of filter and secondary effluents to prevent bleed-through or short-circuiting of BOD with the treated effluent.

Biological solids that slough from an intermediate trickling filter are not as well-digested as those from a low-rate unit. Yields ranging from 0.6 to 0.8 kg TSS/kg (0.6 to 0.8 lb TSS/lb BOD_5) are common, depending on the filter media type.

Nitrifying bacteria have difficulty competing with heterotrophic bacteria, and ammonia removal via nitrification is typically incomplete. However, carbonaceous BOD removal is nearly complete. Therefore, with good clarification following the filter, use of a combined process to achieve secondary treatment is almost never necessary. Both the TF/SC and ABF processes can be used to improve effluent quality, as described in the Combined Processes section of this chapter.

High-Rate Filters. The maximum organic removal of most filter media ranges from 48 to 96 kg $SBOD_5$/100 $m^3 \cdot d$ (30 to 60 lb $SBOD_5$/d/1000 cu ft), depending on tem-

perature, wastewater characteristics, and other conditions. High-rate filters, typically loaded at their maximum organic loading capabilities, receive total BOD_5 loadings ranging from 64 to 160 kg $BOD_5/100\ m^3 \cdot d$ (40 to 100 lb $BOD_5/d/1000$ cu ft). Achieving secondary effluent quality with high-rate filters reliably without a second-stage process is less predictable than with low- or intermediate-rate filters. Therefore, high-rate trickling filters are typically used with combined processes (Table 21.1).

With the recirculation typically used with high-rate filters, hydraulic loading rates typically range from 0.3 to 0.4 $L/m^2 \cdot s$ (0.5 to 0.7 gpm/sq ft), depending on the type of filter media used.

Roughing Filters. Roughing filters are typically designed to allow a substantial amount of SBOD to bleed through the trickling filter. An RBC or second, smaller trickling filter follows the first-stage filter to complete the BOD oxidation. The second stage of treatment is typically 30 to 50% of the size required without a roughing filter. An activated sludge process that follows a roughing filter typically has to assimilate the sloughed solids and remaining BOD; therefore, a significant load has not been reduced.

Roughing filters typically have a design load ranging from 160 to 480 kg $BOD_5/100\ m^3 \cdot d$ (100 to 300 lb BOD_5/day/1000 cu ft). A further description of the process modes follows in the Combined Processes section of this chapter.

DESCRIPTION OF PROCESS. Regardless of the type of trickling filter/biotower used, the pollutant-removal mechanisms remain the same. Microorganisms cover a filter consisting of rock (river or crushed aggregate), plastic, or redwood media. The wastewater enters the filter medium at a controlled rate (trickled), causing intimate contact between waste, the air, microorganisms, and other organisms.

The term *filter* is misleading, because it suggests physical separation of the solids from the liquid via straining action. This does not occur, even with closely packed rock media, and certainly not with the more open high-rate media used in biotowers. Instead, treatment occurs when the microorganisms absorb and use dissolved organics for their growth and reproduction as the wastewater cascades randomly through the voids (spaces between the media).

The complex population of microorganisms is predominately aerobic. It absorbs oxygen from air circulating through the media. Circulation can be enhanced by a forced ventilation system consisting of a series of fans and an air-distribution system. However, most trickling filters/biotowers rely solely on natural ventilation to supply the oxygen necessary for aerobic treatment.

High-rate biotower media offer more surface area than rock media for microbial attachment per cubic meter (cubic foot) of media. Also, biotowers have more void

space than rock media, allowing sloughed solids to exit the biotower and improving air circulation.

The ability to control the unit process will vary greatly, depending on the facilities and equipment provided by the design engineer. Also, the operating strategy used for process control may result in significant changes in the process' character and its ability to remove pollutants. These issues are considered in the following two sections.

DESCRIPTION OF EQUIPMENT. The structure, distribution, and support system used with the media are collectively named either a *trickling filter* or a *biotower*. The term *trickling filter* typically applies to filters that use rock media and are relatively shallow [1.2 to 3.0 m (4 to 10 ft) deep]; processes that use plastic or redwood media with depths greater than 3 m (10 ft) are typically referred to as *biological towers* or *biotowers*. A similar term, *biofilter*, sometimes refers to filter towers in which biological solids from an activated sludge system are recycled over the media.

The following six basic components are common to all trickling filter and biotower systems:

- Distribution system,
- Filter media,
- Underdrain system,
- Containment structure,
- Filter pump station or dosing siphon, and
- Secondary clarifiers.

These basic components are illustrated in Figure 21.1. The purpose of these parts is described in Table 21.2. A more detailed description of the basic components follows.

Distribution Systems. The two basic types of distribution systems are fixed-nozzle and rotary distributors. Fixed-nozzle distributors were frequently used during the early to mid-1900s, but their use on new trickling filters is limited. Fixed-nozzle distributors consist of a piping system, often supported slightly above the top of the trickling filter media, that feeds wastewater and recycled wastewater from a pumping station or siphon box through spray nozzles. A number of advancements in fixed-nozzle design include springs, balls, or other mechanisms to evenly distribute wastewater at various flows. Even with these improvements, obtaining even distribution with a fixed-nozzle distribution system is more difficult than with rotary distribution systems. Fixed-distributor systems have also declined in use because of difficult access to the nozzles for cleaning raising safety concerns. Rotary distributors consist of a center well (typi-

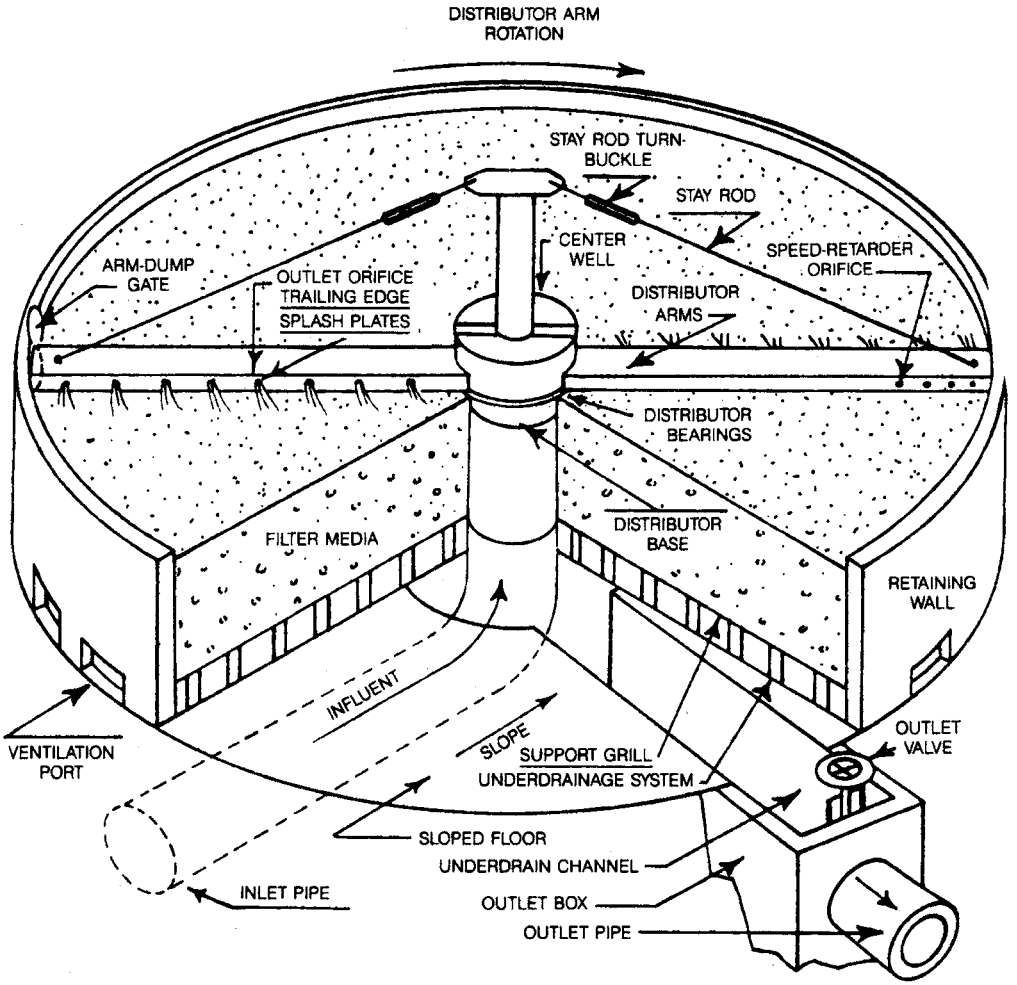


FIGURE 21.1 Trickling filter parts. (Copyrighted material from *Operation of Wastewater Treatment Plants*, Volume 1, 6th Edition, Chapter 6, "Trickling Filters"; reproduced by permission of the Office of Water Programs, California State University, Sacramento.)

cally metal) mounted on a distributor base or pier. The distributor typically has two or more arms that carry the pumped or siphoned wastewater to varying sized orifices for distribution over the media surface. The thrust of the water spray drives the filter arms forward. Speed-retardant back-spray orifices are often used to adjust the distributor's rotational speed, while maintaining the desired flowrate to the filter.

Recently, some rotary distributors have been equipped with motorized drive units to precisely control the wastewater flow distribution speed. Distributors may be set up

TABLE 21.2 Parts of a trickling filter (California State, 1988).

Part	Purpose
Inlet pipe	Conveys wastewater to trickling filter
Distributor base	Supports rotating distributor arms
Distributor bearings	Allows distributor arms to rotate
Distributor arm	Conveys wastewater to outlet orifices located along the arms
Outlet orifice	Controls flow to filter media; adjustable to provide even distribution of wastewater to each square metre (square foot) of filter media
Speed-retarder orifice	Regulates speed of distributor arms
Splash plate	Distributes flow from orifices evenly over filter media
Arm dump gate	Drains distributor arm and controls filter flies along filter retaining wall; also used for flushing distributor arm to remove accumulated debris that might block outlet orifices
Filter media	Provides a large surface area on which the biological slime grows
Support grill	Keeps filter media in place and out of underdrainage system
Underdrain system	Collects treated wastewater from under filter media and conveys it to the underdrain channel; also permits air flow through media.
Underdrain channel	Drains filter effluent to the outlet box
Outlet box	Collects filter effluent before it flows to the next process
Outlet valve	Regulates flow of filter effluent from outlet box into outlet pipe; closed when filter is to be flooded
Outlet pipe	Conveys filter effluent to next treatment process
Retaining wall	Holds filter media in place
Ventilation port	Allows air to flow through the media
Stay rod	Supports distributor arm
Turnbuckle on stay rod	Permits adjusting and leveling of distributor arm to produce an even distribution of wastewater over the media
Center well	Provides for higher water head to maintain equal flow to distributor arms; typically a head of 45 to 60 cm (18 to 24 in.) is maintained on the orifices
Splitter box	Divides flow to the trickling filters for recirculation or to the secondary clarifiers
Recirculation pump	Returns or recirculates flow to the trickling filters

to be mechanically driven at all times or just when stalled. These operating provisions are aimed at selecting a distributor speed to increase biomass sloughing. Decreasing distributor speed may prevent plugging, decreased performance, and odors, particularly in heavily loaded filters. Adding motorized drives also can increase the performance of an exiting tricking filter or biotower.

The distributor support bearings are either at the top of the mast or at the bottom of the turntable. Both types of bearings are widely used.

Another newer method of more precisely controlling the wastewater flow distribution to the trickling filter is a system of pneumatically controlled gates to open and close the orifices on both sides of the distributor arms. As flow to the trickling filter varies, the speed is maintained by automatically adjusting the gates over the orifices.

Filter Media. Of the many types of media materials used to support biological growth, the most common types are shown in Figure 21.2. Media are typically classified as either high-rate (high surface area and void ratio) or standard rock media.

Filter media types made of plastic sheets include vertical, 60-degree crossflow, and 45-degree crossflow. Random media are open-webbed plastic shapes. For carbonaceous BOD removal, their surface area typically ranges from 89 to 105 m^2/m^3 (27 to 32 sq ft/cu ft) of media, and their void percentage is between 92 and 97% (open-space percentage of unit volume). Filter media for nitrification (post-BOD removal) are available, with surface areas in excess of 131 m^2/m^3 (40 sq ft/cu ft). Based on numerous studies to compare trickling filter media, the present consensus is that cross-flow media may offer better flow distribution than other media, especially at low organic loads. Compared with 60-degree cross-flow media, vertical media provide nearly equal distribution and may better avoid plugging, especially at higher organic loadings.

Rock media may consist of either graded material from natural river beds or crushed stone. Most rock media provide approximately 149 m^2/m^3 (15 sq ft/cu ft) of surface area and less than 40% void space.

A significant difference between rock media and plastic media is that most loose stone aggregates have a dry weight of approximately 1282 kg/m^3 (80 lb/cu ft) compared with a density of 32 to 48 kg/m^3 (2 to 3 lb/cu ft) for plastic media. Additional provisions required for plastic media include UV protective additives on the exposed top layer of plastic media filters; thicker plastic walls for media packs installed in the lower sections of the filter, where loads increase; and, under certain conditions, a means for shielding the top layer from the effects of the distributor's hydraulic force.

Underdrain System. The underdrain system supporting rock media typically consists of precast blocks laid over the entire sloping filter floor. Underdrain and support

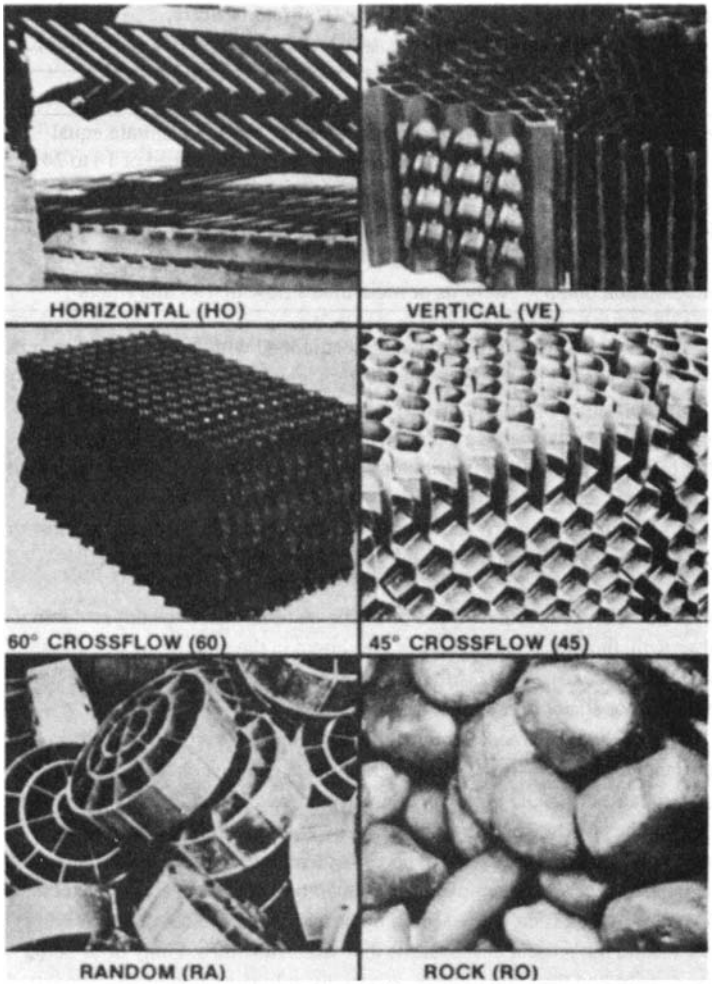


FIGURE 21.2 Trickling filter media (Harrison and Daigger, 1987).

systems for high-rate media typically consist of a network of concrete piers and support stringers placed with their centers 0.3 to 0.6 m (1 to 2 ft) apart. Redwood or pressure-treated wood is also used as underdrain material.

Underdrains for plastic or high-rate filter media are typically 0.3 to 0.6 m (1 to 2 ft) deep to allow air movement to the interior of the filter. Floors typically slope downward to a collection trough that carries wastewater to an outlet structure. The collection trough also serves as an air conduit to the interior of the trickling filter. Ac-

cess to the filter underdrain system should be available at the outlet box to allow periodic inspection. The confined space entry procedures described in Chapter 5 govern the inspection.

Containment Structure. The housing for rock media typically consists of poured-in-place concrete. Filter towers are lightweight containment structures consisting of precast concrete, fiberglass panels, or other materials. These structures are used with high-rate media that are self-supporting (exert no wall pressure).

Ventilation ports, typically located at the base of the filter tower, are designed to prevent the filter tower from being stained by the heavy splash of distributed wastewater cascading to the filter floor. Closed louvers, if available, allow the vents to be closed during cold weather. The filter structure may include low-pressure fans and air ducts (typically fiberglass) to distribute air in the filter underdrain.

The wall of the containment structure often extends 1.2 to 1.5 m (4 to 5 ft) above the top of the filter media. This prevents spray from staining the sides of the filter tower, reduces wind effects that may reduce wastewater temperatures or stall distributors, and provides a structural base for domed covers.

Filter Pump Station. As an integral part of the trickling filter or biotower system, the pumping station typically lifts the primary effluent and the recirculated filter effluent, if any, to the top of the media. Sometimes a siphon dosing tank or gravity flow feeds the distributor. The filter/biotower feed pumps most typically used are vertical-turbine units mounted above a wet well. Submersible pumps and dry-pit centrifugal pumps may also be used in the filter pump station.

The trickling filter/biotower is typically elevated so the hydraulic grade line allows gravity flow to the secondary clarifier or other downstream treatment units. If recirculation is used, the downstream treatment unit or clarifier typically controls the water level in the pumping station wet well, so a control valve is not necessary to modulate the amount of underflow returning to the pumps.

Secondary Clarifier. In the past, clarifier design often received insufficient attention. Although wastewater treatment professionals typically recognize the need for improved clarifier design criteria associated with suspended-growth or activated sludge plants, this need also exists with the design and operation of secondary clarifiers used in the fixed-film trickling filter/biotower process.

Performance of the trickling filter/biotower process is typically not limited by SBOD removal, but by the secondary clarifier's ability to separate suspended solids from treated wastewater. This is especially true for low-, intermediate-, and high-rate

processes that remove most of the SBOD. Therefore, effluent quality depends largely on the particulate BOD associated with solids remaining in the clarifier effluent.

With the trickling filter/biotower process, past practices have resulted in secondary clarifiers with high hydraulic overflow rates and shallow sidewater depths [2.4 to 3.0 m (8 to 10 ft)]. Corresponding suspended-growth systems were often designed with clarifiers having much lower hydraulic overflow rates and sidewater depths of 3.0 to 3.7 m (10 to 12 ft). As trickling filter/biotower plants are now required to achieve secondary or even higher treatment levels, the clarifier sidewater depth must be larger to provide a greater separation zone for solids removal. Likewise, reduced overflow rates may be needed to achieve the required effluent quality (Tekippe and Bender, 1987).

PROCESS CONTROL. Many operating problems may be avoided by changing one or more of the following process control variables: flow patterns, distribution rates, and clarifier operation.

Flow Patterns. Although operators do not control the arrangement of the major treatment units, opportunities may exist to take units offline, operate in stages (parallel or series filters), or recycle settled biological solids over high-rate filter media. For example, staging or operating filters in series sometimes increases the overall system's BOD removal because of increased efficiency in the higher-loaded first stage. If both rock and high-rate filters are available, operators should consider operating the rock filter in the first stage to achieve a high reduction in produced biological solids. Then, the second-stage filter would be operated in a polishing mode, taking advantage of the high-rate filter media's bioflocculation capabilities.

With little or no modification, many existing trickling filters/biotowers with high-rate media may incorporate small amounts of biological solids recycle over the filter media to enhance the flocculation of particulate solids. Recycled solids may be returned to the filter underflow of the rock filter media, as is done in trickling filter and solids combined processes.

Distribution Rates. As a principal process control measure, operators can control the rates at which wastewater and filter effluent are distributed to the filter media. Recirculation can serve several purposes, as follows:

- Reduce the strength of the wastewater being applied to the filter;
- Increase the hydraulic load to reduce flies, snails, or other nuisances;
- Maintain distributor movement during low flows;

- Produce hydraulic shear to encourage solids sloughing and prevent ponding;
- Dilute toxic wastes, if present;
- Reseed the filter's microbial population;
- Provide uniform flow distribution; and
- Prevent filters from drying out.

The most common recirculation patterns used for trickling filters/biotowers are shown in Figure 21.3. If odors emanate from the primary clarifier or headworks, recycling filter effluent to either location may help control them. When the recirculated water passes through either the primary or secondary clarifier, operators need to prevent excessive hydraulic loading of the clarifier.

A typical control strategy for highly loaded or roughing filters is to frequently (once per week) maintain the maximum pumping rate possible for a 2- to 3-hour period. This encourages sloughing, so solids buildup is less likely, and uncontrolled sloughing is minimized.

Another approach is to slow the distributor arm using back-spray nozzles, so the media receives a greater instantaneous flush. When a trickling filter/biotower accumulates excess solids, aerobic surface area decreases, which, in turn, reduces oxygen transfer. Because oxygen does not penetrate more than 1 to 1.5 mm of film thickness, there is no benefit with more than 0.76 mm (0.03 in.) biomass on the media (Albertson, 1989).

A German process parameter that has been considered in the United States is *Spulkraft flushing intensity* (SK), which is defined by the following equation:

$$\mathrm{SK} = \frac{(q + r)(1000\ \mathrm{mm/m})}{(a)(n)(60\ \mathrm{min/h})} \tag{21.3}$$

Where

SK	= flushing intensity, mm/pass of arm;
$q + r$	= total hydraulic rate, $m^3/m^2 \cdot h$;
a	= number of distributor arms;
n	= rotational speed, rev/min; and
1.0 $m^3/m^2 \cdot h$	= 0.41 gpm/sq ft.

Some recommended SK values for design and flushing flowrates are given in Table 21.3.

Compared with the activated sludge treatment process, trickling filters can use 30 to 50% less energy if the pumping rate is optimized. Thoughtful consideration needs to be given to balancing the need to maintain a minimum wetting rate versus the potential energy savings of lower recirculation rates.

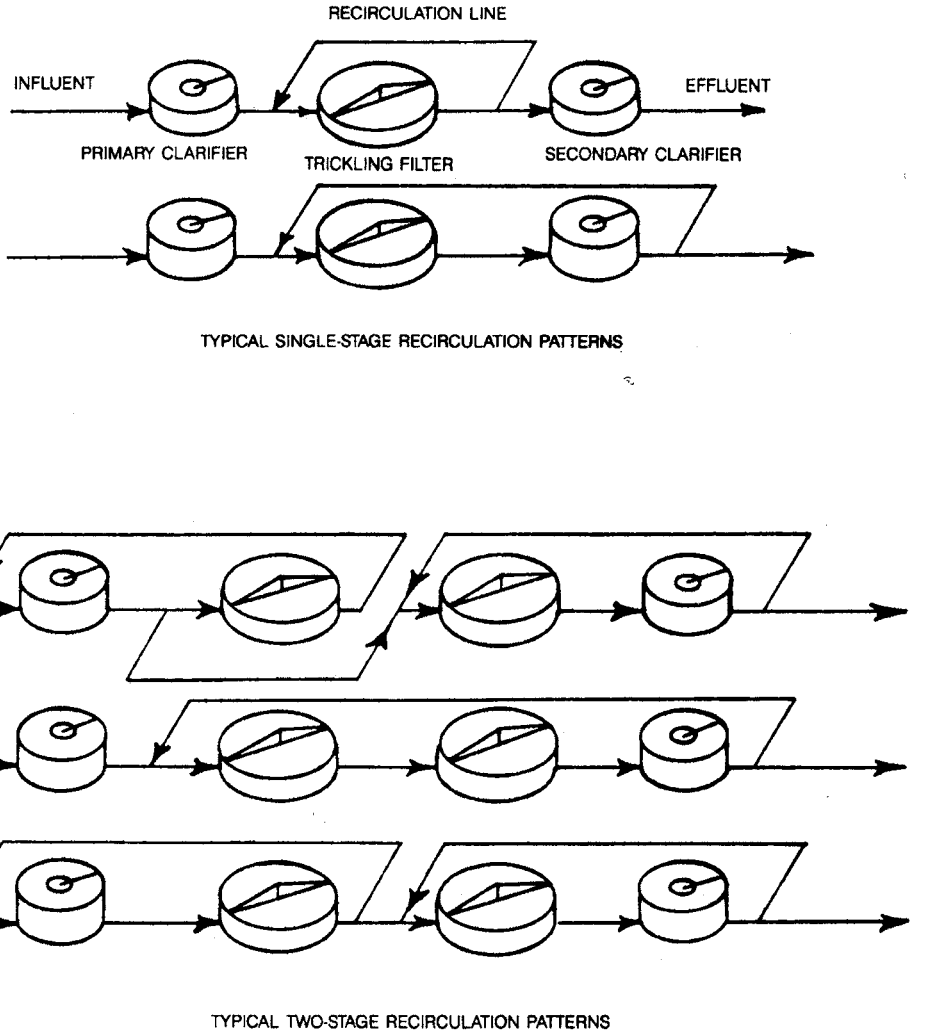


FIGURE 21.3 Recirculation patterns for trickling filters.

Clarifier Operation. The manner in which secondary clarifiers are operated can significantly affect trickling filter performance. Although clarifier operation with fixed-film reactors is not as critical as that with suspended-growth systems, operators must still pay close attention to final settling.

Sludge must be removed quickly from the final settling tank before gasification occurs or denitrification causes solids to rise. Use of the secondary clarifier as a principal means of thickening (rather than simply for solids settling) may not produce the best

effluent quality, especially during summer months, when denitrification is likely to occur. The sludge blanket depth in the secondary clarifier should be limited to 0.3 to 0.6 m (1 to 2 ft). Continuous pumping or intermittent pumping with automatic timer control are used to accomplish solids wasting.

TROUBLESHOOTING. Even though the trickling filter/biotower process is considered one of the most trouble-free means of secondary treatment, the potential for operating problems exists (Table 21.4). The source of mechanical problems is often obvious. However, less obvious causes of problems may stem from operations, design overload, influent characteristics, and other non-equipment-related items.

Good records and data associated with the trickling filter are essential in locating, identifying, and applying the proper corrective measure to solve problems. Tracking SBOD, suspended solids, pH, temperature, and other parameters may be necessary to recognize trends that result in adverse trickling filter/biotower effects.

Common operating problems may result from increased growth, changes in wastewater characteristics, improper design, or equipment failures. Regardless of the source, these problems eventually become categorized into either operation or maintenance areas. In summary, the problems addressed in Table 21.4 are as follows:

Operations:

- Increase in secondary clarifier effluent suspended solids,
- Increase in secondary clarifier effluent BOD,
- Objectionable odors from filter,
- Ponding on filter media,
- Filter flies, and
- Icing.

TABLE 21.3 Design and flushing Spulkraft (SK) values for distributors (revised, higher SK values reflect new, post-publication data) (Albertson, 1989).

BOD_5 loading (lb/d/cu ft[a])	Design SK (mm/pass)	Flushing SK (mm/pass)
<25	25–75	100
50	50–150	150
75	75–225	225
100	100–300	300
150	150–450	450
200	200–600	600

[a]BOD = biochemical oxygen demand; lb/d/cu ft × 16.02 = $kg/m^3 \cdot d$.

TABLE 21.4 Troubleshooting guide for trickling filters.

Problem/possible cause	Corrective action
Operations	
Increase in secondary clarifier effluent suspended solids	
Clarifier hydraulically overloaded	Check clarifier surface overflow rate; if possible, reduce flow to clarifier to less than 35 $m^3/m^2 \cdot d$ (900 gal/d/sq ft) by reducing recirculation or putting another clarifier into service
	Expand plant
Denitrification in clarifier	Increase clarifier sludge withdrawal rate
	Increase loading on trickling filter to prevent nitrification; skim floating sludge from entire surface of clarifier or use water sprays to release nitrogen gas from sludge so sludge will resettle
Excessive sloughings from biofilter because of changes in wastewater	Increase clarifier sludge withdrawal rate
	Check wastewater for toxic materials, changes in pH, temperature, BOD, or other constituents
	Identify and eliminate source of wastewater causing the upset
	Enforce sewer-use ordinance
Equipment malfunction in secondary clarifier	Check for broken sludge-collection equipment and repair or replace broken equipment
Short-circuiting of flow through secondary clarifier	Level effluent weirs
	Install clarifier center pier exit, baffles, effluent weir baffles, or other baffles to prevent short-circuiting
Increase in secondary clarifier effluent biochemical oxygen demand (BOD)	
Increase in effluent suspended solids	See corrective actions for "Increase in secondary clarifier effluent suspended solids"
Excessive organic loads on filter	Calculate loading
	Reduce loading by putting more biofilters in service
	Increase BOD removal in primary settling tanks by using all tanks available and minimizing storage in primary sludge tanks
	Eliminate high-strength sidestreams in plant
	Expand plant
Undesirable biological growth on media	Perform microscopic examination of biological growth
	Chlorinate filter to kill off undesirable growth

TABLE 21.4 Troubleshooting guide for trickling filters (*continued*).

Problem/possible cause	Corrective action
Objectionable odors from filter	
Excessive organic load causing anaerobic decomposition in filter	Calculate loading
	Reduce loading by putting more biofilters in service
	Increase BOD removal in primary settling tanks by using all tanks available and minimizing storage or primary sludge in tanks
	Encourage aerobic conditions in treatment units ahead of the biofilter by adding chemical oxidants (e.g., chlorine, potassium permanganate, or hydrogen peroxide) or by preaerating, recycling plant effluent, or increasing air to aerated grit chambers
	Enforce industrial waste ordinance, if industry is source of excess load
	Scrub biofilter offgases
	Replace rock media with plastic media
	Expand plant
Insufficient ventilation	Increase hydraulic loading to wash out excess biological growth
	Remove debris from filter effluent channels and underdrains
	Remove debris from top of filter media
	Unclog vent pipes
	Reduce hydraulic loading if underdrains are flooded
	Install fans to induce draft through filter
	Check for filter plugging caused by breakdown of media
Ponding on filter media	
Excessive biological growth	Reduce organic loading
	Slow down distributor to increase 5K value
	Increase hydraulic loading to increase sloughing
	Flush filter surface with high-pressure stream of water
	Chlorinate filter influent for several hours; maintain 1 to 2 mg/L residual chlorine on the filter
	Flood filter for 24 hours
	Shut down filter until media dries out
	Enforce industrial waste ordinance if industry is source of excess load

TABLE 21.4 Troubleshooting guide for trickling filters (*continued*).

Problem/possible cause	Corrective action
Poor media	Replace media
Poor housekeeping	Remove debris from filter surface, vent pipes, underdrains, and effluent channels
Filter flies (psychoda)	
Insufficient wetting of filter media (a continually wet environment is not conducive to filter fly breeding and a high wetting rate will wash fly eggs from the filter)	Increase hydraulic loading
	Unplug spray orifices or nozzles
	Use orifice opening at end of rotating distributor arms to spray filter walls
Filter environment nodule conducive to filter fly breeding	Flood filter for several hours each week during fly season
	Chlorinate the filter for several hours each week during fly season; maintain a 1- to 2-mg/L chlorine residual on the filter
Poor housekeeping	Keep area surrounding filter mowed; remove weeds and shrubs
Icing	
Low wastewater temperature	Decrease recirculation
	Remove ice from orifices, nozzles, and distributor arms with a high-pressure stream of water
	Reduce number of filters in service, provided effluent limits can still be met
	Reduce retention time in pretreatment and primary treatment units
	Construct windbreak or covers.
Maintenance	
Rotating distributor slows down or stops	
Insufficient flow to turn distributor	Increase hydraulic loading
	Close reversing jets
Clogged arms or orifices	Flush out arms by opening end plates; flush out orifices; remove solids from influent wastewater
Clogged distributor arm vent pipe	Remove material from vent pipe by rodding or flushing
	Remove solids from influent wastewater
Bad main bearing	Replace bearing
Distributor arms not level	Adjust guy wires at tie rods

TABLE 21.4 Troubleshooting guide for trickling filters (*continued*).

Problem/possible cause	Corrective action
Distributor rods hitting media	Level media
	Remove some media
Dirt in main bearing lube oil	
Worn bearing dust seal	Replace seal
Worn turntable seal or seal plate	Replace seal; inspect seal plate and replace if worn
Condensate not drained regularly or oil level too low	Check oil level, drain condensate, and refill if needed
Water leaking from distributor base	
Worn turntable seal	Replace seal
Leaking expansion joint between distributor and influent piping	Repair or replace expansion joint
Broken top media	
Foreign material	Flush out with a high-pressure stream of clean water
	Rod out with wire or hook
	Disassemble and clean
Secondary clarifier sludge collector stopped	
Torque overload setting exceeded	Reduce sludge blanket; withdraw excess sludge
	Check if skimmer portion of collector hung up on scum trough; free and repair or adjust skimmer
	Drain tank and remove foreign objects
Loss of power	Reset drive unit circuit breaker if tripped (after cause for trip is identified and corrected)
	Reset drive unit, motor control center, or plant main circuit breakers as necessary when power is restored to plant after interruption
	Check drive motor for excessive current draw; if current excessive, determine reason
	Check drive motor overload relays; replace if bad or undersized
Failure of drive unit	Check drive chains and shear pins; replace as necessary and use proper size shear pin, or damage will occur
	Check and replace worn gears, couplings, speed reducers, or bearings as needed; lubricate and provide preventive maintenance for units as per manufacturer's instruction
Recirculation pumps delivering insufficient flow	
Excessive head	Open closed or throttled valves
	Unplug distributor arms, headers, and laterals

TABLE 21.4 Troubleshooting guide for trickling filters (*continued*).

Problem/possible cause	Corrective action
	Unplug distributor nozzles and orifices
	Unplug distributor vent lines
Pump malfunction	Adjust or replace packing or mechanical seals
	Adjust impeller to casing clearance
	Replace wear rings if worn excessively
	Replace or resurface worn shaft sleeves
	Check impeller for wear and entangled solids; remove debris; replace impeller if necessary
	Check pump casing for air lock
	Release trapped air
	Lubricate bearings as per manufacturer's instructions
	Replace worn bearings
Pump drive motor failure	Lubricate bearings as per manufacturer's instructions
	Replace worn bearings
	Keep motor as clean and dry as possible
	Pump and motor misalignment; check vibration and alignment
	Redesign as needed
	Burned windings; rewind or replace motor
	Check drive motor for excessive current draw; if current draw is excessive, determine reason
	Check drive motor overload relays; replace if bad or undersized
	Reset drive motor, motor control centers, or plant main circuit breakers after cause for trip is identified and corrected, or when power is restored after interruption

Maintenance:

- Rotating distributor slowing down or stopping,
- Dirt in main bearing lube oil,
- Water leaking from distributor base,
- Nozzle or orifices plugged,
- Top media broken,
- Secondary clarifier sludge collector stopped, and
- Recirculation pumps delivering insufficient flow.

PLANNED MAINTENANCE. Planned maintenance will vary from plant to plant, depending on unique design features and equipment installed. Although this chapter cannot address all of these items, a summary of the most common and important maintenance tasks follows.

Table 21.5 is a guide to planned maintenance for the following:

- Rotary distributors,
- Fixed-nozzle distributors,
- Filter media,
- Underdrains,
- Media containment structure,
- Filter pumps,
- Secondary clarifiers, and
- Appurtenant equipment.

The information provided in Table 21.5 is not equipment- or plant-specific. Therefore, both the manufacturer's literature and engineer's operating instructions should be consulted and followed. The frequency of maintenance procedures depends on site-specific conditions. However, until operating experience is gained, frequent plant inspections and maintenance should continue. Maintenance schedules should consider the increased performance of trickling filters in warm weather months, which may reduce the effect of removing process units from service.

DISTRIBUTOR BEARINGS. Distributor bearings typically ride on removable races (tracks) in a bath of oil (Figure 21.4). The oil, typically specified by the manufacturer, is selected to prevent oxidation and corrosion and to minimize friction. Because the oil level and condition are crucial to the life of the equipment, they need regular checking in accordance with the manufacturer's recommendations (typically weekly). A common procedure is to check the oil by draining approximately 0.6 L (1 pt) into a clean container. If the oil is clean and free of water, it is returned to the unit. If the oil is dirty, it is drained and refilled with a mixture of approximately one part oil and three parts solvent (e.g., kerosene). Then, the distributor is operated for a few minutes, the mixture is drained, and the distributor is filled with clean oil.

If water is found in the oil, then either the seal fluid is low or the gasket in the mechanical seals requires replacement.

SAFETY. Work on distributors may proceed only after the arms have been stopped and locked in place, and the distributor pump's or control valve's electrical switch has

TABLE 21.5 Planned maintainance for trickling filters.

Rotary distributors

- Observe the distributor daily. Make sure the rotation is smooth and that spray nozzles are not plugged.
- Lubricate the main support bearings and any guide or stabilizing bearings according to the manufacturer's instructions. Change lubricant periodically, typically twice a year. If the bearings are oil-lubricated, check the oil level, drain condensate weekly, and add oil as needed.
- Time the rotational speed of the distributor at one or more flow rates. Record and file the results for future comparison. A change in speed at the same flow rate indicates bearing trouble.
- Flush distributor arms monthly by opening end shear gates or blind flanges to remove debris. Drain the arms if idle during cold weather to prevent damage via freezing.
- Clean orifices weekly with a high-pressure stream of water or with a hooked piece of wire.
- Keep distributor arm vent pipes free of ice, grease, and solids. Clean in the same manner as the distributor arm orifices. Air pockets will form if the vents are plugged. Air pockets will cause uneven hydraulic loading in the filter, and nonuniform load and excessive wear of the distributor support bearing.
- Make sure distributor arms are level. To maintain level, the vertical guy wire should be taken up during the summer and let out during the winter by adjusting the guy wire tie rods. Maintain arms in the correct horizontal orientation by adjusting horizontal tie rods.
- Periodically check distributor seal and, if applicable, the influent pipe to distributor expansion joint for leaks. Replace as necessary. When replacing, check seal plates for wear and replace if wear is excessive. Some seals should be kept submerged even if the filter is idle or their life will be severely shortened.
- Remove ice from distributor arms. Ice buildup causes nonuniform loads and reduces main bearing life.
- Paint the distributor as needed to guard against corrosion. Cover bearings when sandblasting to protect against contamination. Check oil by draining a little oil through a nylon stocking after sandblasting. Ground the distributor arms to protect bearings if welding on distributor and lock out the drive mechanism at the main electrical panel. Adjust secondary arm overflow weirs and pan test wastewater distribution on filter as needed.

Fixed nozzle distributors

- Observe spray pattern daily. Unplug block nozzles manually or by increasing hydraulic loading. Flush headers and laterals monthly by opening end plates. Adjust nozzle spring tension as needed.

Filter media

- Observe condition of filter media surface daily. Remove leaves, large solids and plastics, grease balls, broken wood lath or plastic media, and other debris. If ponding is evident, find and eliminate the cause. Keep vent pipes open, and remove accumulated debris. Store extra plastic media out of sunlight to prevent damage via ultraviolet rays. Observe media for settling. After they are installed, media settle because of their own weight

TABLE 21.5 Planned maintainance for trickling filters (*continued*).

and the weight of the biofilm and water attached to its surface. Settling should be uniform and should stabilize after a few weeks. Total settling is typically less than 0.3 m (1 ft) for random plastic media, less for plastic sheet media, and nearly zero for rock. If settling is nonuniform or excessive, remove some of the media for inspection.

- Observe media for hydraulic erosion, particularly in regions where reversing jets hit the media.

Underdrains

- Flush out periodically if possible. Remove debris from the effluent channels.

Media containment structure

- Maintain spray against inside wall of filter to prevent filter fly infestation and to prevent ice buildup in winter.
- Practice good housekeeping. Keep fiberglass, concrete, or steel outside walls clean and painted, if applicable. Keep grass around structures cut, and remove weeds and tall shrubs to help prevent filter fly and other insect infestations. Remember, using insecticides around treatment units may have adverse effects on water quality or the biological treatment units.

Filter pumps

- Check packing or mechanical seals for leakage daily. Adjust or replace as needed. Lubricate pump and motor bearings as per manufacturer's instructions. Keep pump motor as clean and dry as possible. Periodically check shaft sleeves, wearing rings, and impellers for wear; repair or replace as needed. Perform speed reducer, coupling, and other appurtenant equipment maintenance according to manufacturer's instructions.

Secondary clarifier

- Lubricate drive motor bearings, speed-reducing gear, drive chains, work and spur gears, and the main support bearing for the solids-collection equipment according to the manufacturer's instructions. Flush scum troughs and grease wells daily. Maintain solids-withdrawal equipment. Clean effluent wells and baffles at least weekly. Paint or otherwise protect equipment from corrosion as needed.

Appurtenant equipment

- Maintain piping, valves, forced draft blowers, and other appurtenant equipment according to the manufacturer's instructions.

been disengaged and locked out on the electrical panel. The filter medium should not be walked on, because it will be slippery. Plastic grating is often placed as a permanent walking surface to provide safe access to the distributor.

Covered trickling filters have special safety considerations, because they are considered confined spaces. The possibility exists for the atmosphere under the dome to

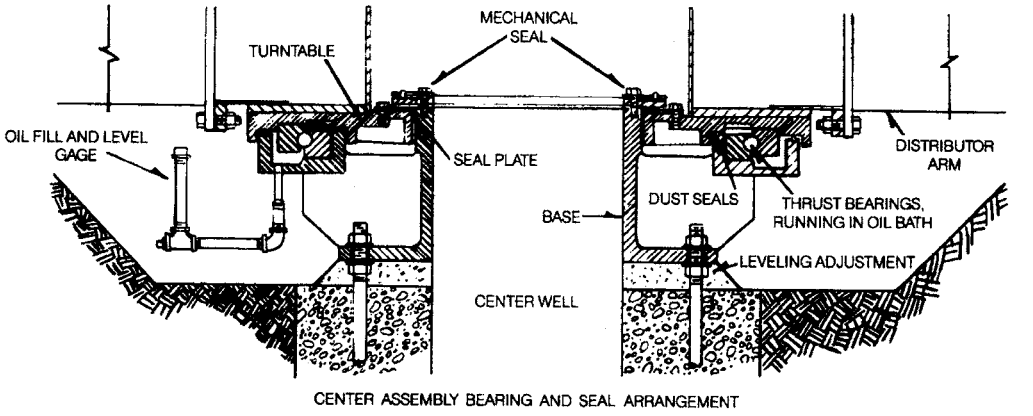


FIGURE 21.4 Trickling filter bearing (Copyrighted material from *Operation of Wastewater Treatment Plants*, Volume 1, 6th Edition, Chapter 6, "Trickling Filters"; reproduced with the permission of the Office of Water Programs, California State University, Sacramento).

contain little oxygen or much hydrogen sulfide or ammonia. Maintenance in these areas must include proper confined space entry procedures. Chapter 5 discusses other safety considerations.

ROTATING BIOLOGICAL CONTACTORS

A rotating biological contactor's filter media consist of plastic discs mounted on a long, horizontal, rotating shaft (Figure 21.5). A biological slime similar to that of the trickling filter/biotower grows on the media. However, rather than being stationary, the filter media rotate into the settled wastewater and then emerge into the atmosphere, where the microorganisms receive oxygen that helps them consume organic materials in the wastewater.

Rotating biological contactors have been extensively used at hundreds of locations in the United States to treat municipal and industrial wastewater. It is estimated that more than 600 RBC plants are now used for industrial and municipal wastewater treatment. Most of the plants are designed and used for BOD_5 removal and a few for both BOD_5 and nitrogen removal.

When RBCs were initially introduced for wastewater treatment during the late 1970s and early 1980s, mechanical problems and organic overloading occurred frequently. By the mid-1980s, both equipment manufacturers and consulting engineers had developed standards that minimized most of the problems, but some systems are

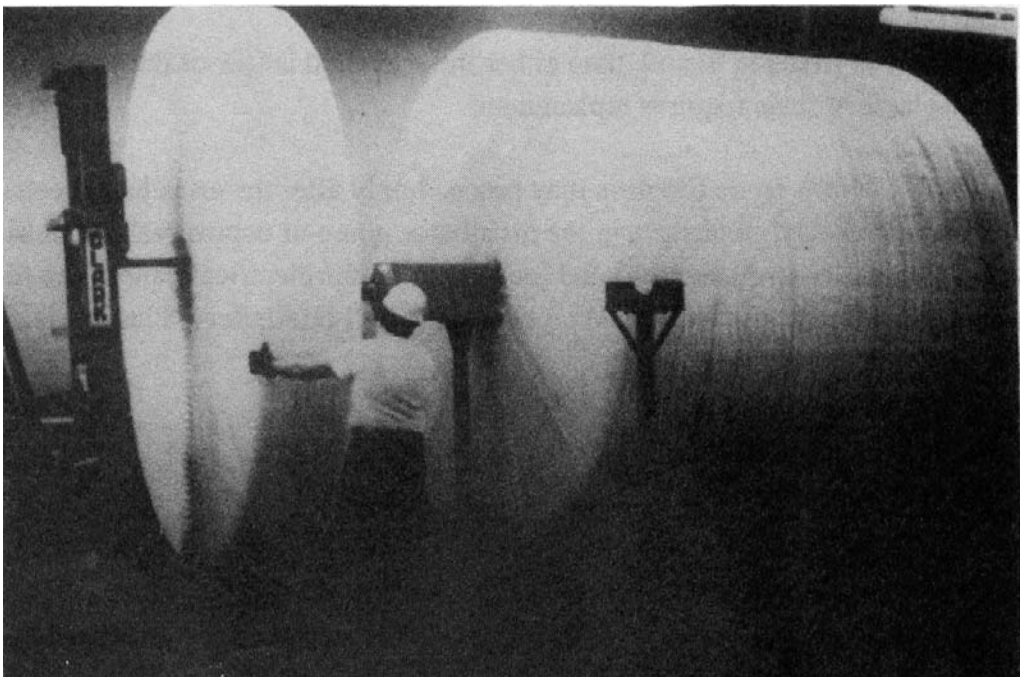


FIGURE 21.5 Rotating biological contactor shaft and media.

still mechanically unsound. This section discusses the use of RBCs principally for carbonaceous BOD_5 removal and ammonia nitrification.

ALTERNATIVES. The flow pattern for RBC treatment of wastewater resembles that for most other biological systems, because good preliminary and primary treatment are essential to remove solids that would otherwise interfere with RBC performance (Figure 21.6).

A secondary clarifier must be provided to remove sloughed solids from the treated wastewater. Solids that settle in the secondary clarifier can either be recycled to the primary clarifier for cosettling or pumped directly to a solids-handling system (Figure 21.6).

The term *shaft* typically is used to describe both the metal support and the filter media discs. The discs are made of high-density circular plastic sheets, typically 3.6 m (12 ft) in diameter (although larger sizes are available from some manufacturers). The sheets, bonded and assembled onto the horizontal shafts, are typically 7.6 m (25 ft) long. Each shaft typically provides approximately 9300 m^2 (100 000 sq ft) of surface area for micro-

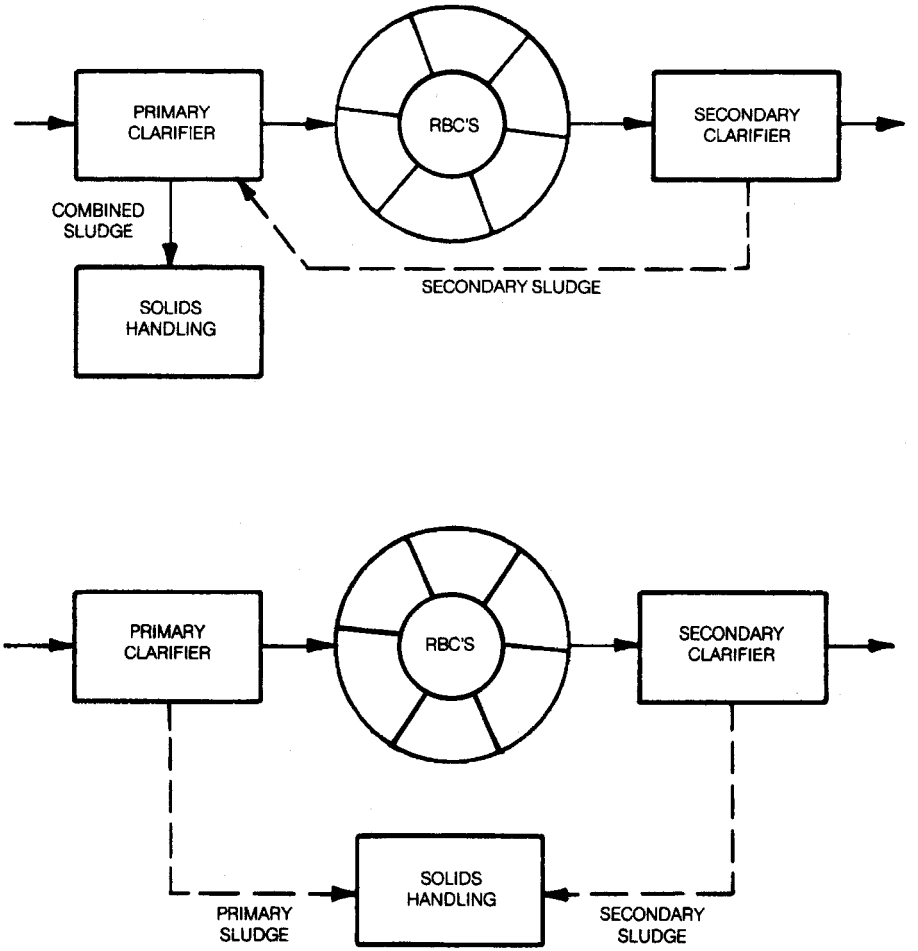


FIGURE 21.6 Rotating biological contactor process flow schematic.

organism attachment. Lower density media are typically used for carbonaceous BOD_5 removal, and higher density media are typically used for ammonia nitrification.

Alternative selection associated with RBCs consists primarily of the number and arrangement of shafts (Figure 21.7) that support the RBC discs (Zickefoose, 1984). A common arrangement includes a separate shaft for each stage, especially when the flow is perpendicular to the shafts, as shown in plan A of Figure 21.7. A single shaft can be divided into two or more stages by adding a baffle at one or more sections along the flow pattern (plan B of Figure 21.7). This arrangement typically applies when the wastewater flow pattern parallels the shaft. A stage may also be eliminated by removing

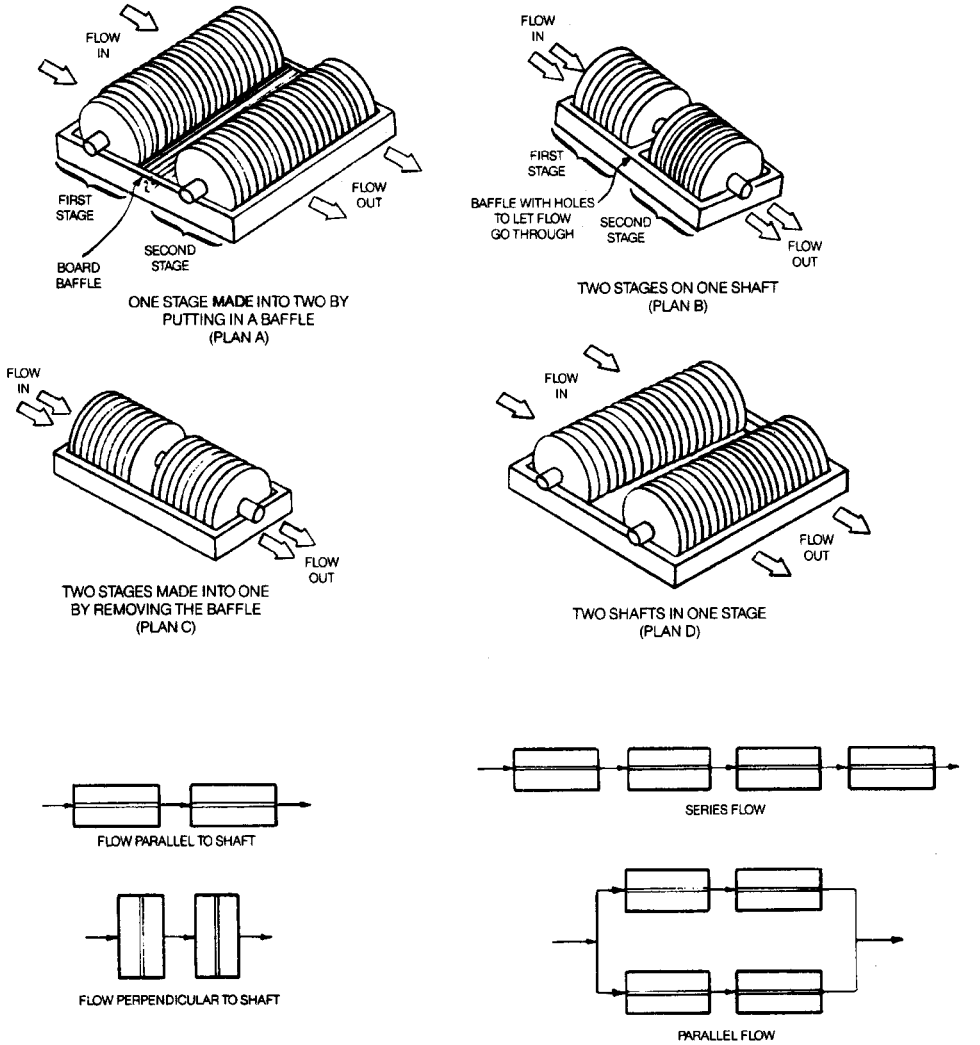


FIGURE 21.7 Stage arrangements and flow patterns for rotating biological contactors.

a baffle, as shown in plan C of Figure 21.7. The baffles may be constructed of either perforated concrete or slotted boards. To reduce the organic loading of a stage, baffles are often removable. This allows two or more shafts to operate in a single stage, as illustrated in plan D of Figure 21.7. Staging is often used to improve effluent quality. Four or more stages, combined with lower organic loading, are typically used to obtain a nitrified or well-treated effluent.

Staging is sometimes used to overcome oxygen-transfer problems in the first shafts (first stages) of an RBC facility. Often, baffles are removed on the first several stages of multistage facilities to distribute loading among several shafts. This method, among others, has been used to reduce the organic loading and overcome oxygen-transfer difficulties in heavily loaded RBC reactors.

A train (several parallel series of stages) is also typically used to reduce loadings on the first RBC stages. Baffles may also be removed between shafts to increase the surface area available in the first stage. Figure 21.7 illustrates the use of both trains and stages in either parallel or series flow modes. Good designs will include a number of gates and baffles to provide for system flexibility. This allows operators to vary the flow pattern to accommodate facility-specific load and effluent quality criteria.

Designers should consider including one or more of the following to ensure that the process will have adequate operating flexibility:

- Supplemental aeration to increase dissolved oxygen levels in the first and second stages;
- A means for removing excess biofilm growth (e.g., supplemental aeration, rotational speed control, and reversal);
- Multiple treatment trains;
- Removable baffles between all stages;
- Variable rotational speeds in the first and second stages;
- Load cells for first- and second-stage shafts;
- Alternate flow distribution systems (e.g., step feeding); and
- Recirculation of secondary clarifier effluent.

A significant number of RBCs have encountered oxygen limitations or overloads in the first stages. In other cases, the RBCs have simply reached their design loads. Regardless of the reason, RBC upgrades are typically accomplished by adding more RBCs or by constructing the following:

- New processes in parallel (i.e., side-by-side) with existing RBCs (e.g., activated sludge processes, trickling filters, or aerated lagoons); and
- New processes in series (i.e., preceding or following existing RBCs), such as activated sludge processes, trickling filters, aerated lagoons, preaeration processes, or solids contact processes.

DESCRIPTION OF PROCESS. Rotating biological contactor systems consist of plastic media, typically a series of vertical discs, mounted on a horizontal shaft that

slowly rotates, turning the media into and out of a tank of wastewater. Rotating biological contactor shafts are rotated by either a mechanical or a compressed air drive so the media on up to 40% of its diameter are immersed in the wastewater. The wastewater being treated flows through the contactor by simple displacement and gravity. Bacteria and other microorganisms that are naturally present in the wastewater adhere and grow on the surface of the rotating media. The biological film sloughs off whenever the biomass growth becomes too thick and heavy for the media to support. The sloughed biofilm and other suspended solids are carried away in the wastewater and removed in the secondary clarifier.

The biological slime on the first stages is typically 0.15 to 0.33 cm (0.06 to 0.13 in.) thick. A healthy biomass on the first stage tends to be light brown, while the biomass on later stages tends to have a gold or reddish sheen. Lightly loaded units may be nearly devoid of visible biomass. A white or gray biomass indicates domination by filamentous (*Beggiatoa*, *Thiothrix*, or *Lepothrix*) bacteria—an unhealthy sign.

Like the trickling filter process, many of the process choices are fixed during design, and RBC operators have limited opportunities to make changes. The design choices discussed in the following section will help both operators and designers better understand the RBC process.

Loadings for RBCs are typically based on BOD_5 loading to the RBC units divided by the media's surface area. Organic loading is typically calculated for all units online or simply for the first stages, where an oxygen limitation may exist. The organic load may be based on either the soluble or total BOD.

$$\text{Organic } (BOD_5) \text{ load} = \frac{BOD_5 \text{ applied, lb/d}}{\text{Area of media, 1000 sq ft}} \tag{21.4}$$

Where

BOD_5 applied = kg of primary effluent BOD_5/d;
= (primary effluent BOD_5, mg/L)(flow, ML/d); and

Media surface area, 100 m^3 $= \dfrac{\text{Surface per shaft, } m^2 \times \text{number of shafts}}{100}$

Or (in U.S. customary units)

BOD_5 applied = lb of primary effluent BOD_5/d;
= (primary effluent BOD_5, mg/L)(flow, mgd)
(8.34 lb/gal); and

Media surface area, 1000 sq ft $= \dfrac{\text{Surface per shaft, sq ft} \times \text{number of shafts}}{1000}$

Although RBCs are typically not classified by hydraulic loading, the hydraulic load is a useful operating parameter and is calculated as follows:

$$\text{Hydraulic load, gpd/sq ft} = \frac{\text{Total flow into plant, gpd}}{\text{Surface area per shaft, sq ft} \times \text{number}} \qquad (21.5)$$

Example 21.2. Calculate the organic and hydraulic loads of an RBC system.

Given:

Q	= 3 mgd,
Primary effluent BOD_5 (TOL)	= 120 mg/L,
Primary effluent soluble BOD_5 (SOL)	= 80 mg/L, and
Total number of RBC shafts	= 8 at 100 000 sq ft/shaft. Four of the eight shafts are in the first stage (four trains of two shafts each).

Solution:

Total system	= 100 000 sq ft × 8 shafts
Surface area	= 800 000 sq ft
First stage	= 100 000 sq ft × 4 shafts
Surface area	= 400 000 sq ft
TOL	= (120 mg/L)(3 mgd)(8.34)
	= 3002 lb BOD_5/d
SOL	= (80 mg/L)(3 mgd)(8.34)
	= 2002 lb $SBOD_5$/d
System TOL	$= \frac{3002 \text{ lb } BOD_5/d}{800 \text{ units}^a}$
	= 3.75 lb BOD_5/d/1000 sq ft
System SOL[b]	$= \frac{2002 \text{ lb } SBOD_5/d}{800 \text{ units}}$
	= 2.5 lb $SBOD_5$/d/1000 sq ft
First-stage TOL	$= \frac{3002 \text{ lb } SBOD_5/d}{400 \text{ units}}$
	= 7.5 lb $SBOD_5$/d/1000 sq ft

$$\text{First-stage SOL}^{b} = \frac{2002 \text{ lb } BOD_5/d}{400 \text{ units}}$$
$$= 5.0 \text{ lb } SBOD_5/d/1000 \text{ sq ft}$$

$$\text{System hydraulic load} = \frac{(3 \text{ mgd})(1 \times 10^6 \text{ gpd/mgd})}{800\,000 \text{ sq ft}}$$
$$= 3.75 \text{ gpd/sq ft}$$

(Notes: [a]Each unit is equal to 1000 sq ft. [b]For system SOL and first-stage SOL, organic loading exceeds the acceptable limits often used to gauge the ability to operate without problems. System upgrading may be required to improve performance or prevent adverse effects.

DESCRIPTION OF EQUIPMENT. Rotating biological contactor systems typically include the following six equipment items (many also include instrumentation):

- Tankage,
- Baffles,
- Filter media,
- Cover,
- Drive assembly, and
- Inlet and outlet piping.

Figures 21.8 and 21.9 illustrate various equipment components that are typically used in the RBC process. The names for individual equipment components may differ slightly, depending on the manufacturer. The purpose of each part is described in Table 21.6 and discussed further in the following sections.

Tankage. Containment structures or tanks for RBC equipment may consist of metal tanks for small pilot plants or single-shaft units. However, multishaft units almost always include tankage made of concrete basins (Figure 21.8). The tank volume typically provides approximately 1 hour of hydraulic contact time; this typically corresponds to 4.9 L tank volume/m^2 (0.12 gal/sq ft) of standard-density filter media.

Baffles. Internal baffling or weir structures separate the stages of the RBC reactors. Baffling along one shaft is accomplished by removing a section of discs and replacing it with a stationary bulkhead (Figure 21.9). Baffling used to separate multiple shafts may be made of either concrete or wood. Removable baffles are often used to allow process changes after the facility is constructed.

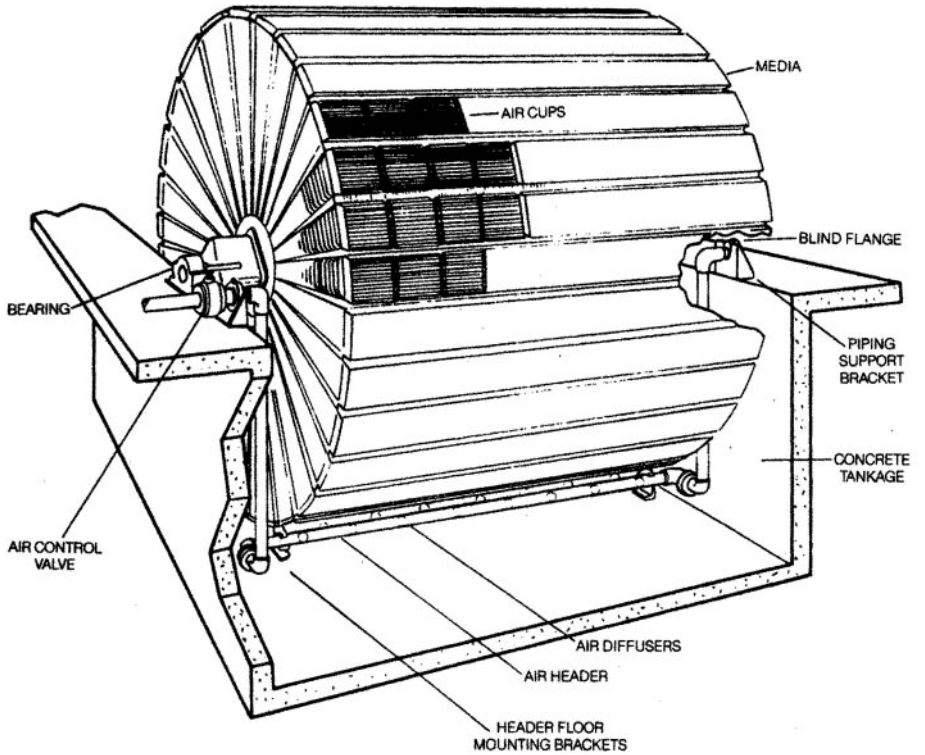


FIGURE 21.8 Air-driven rotating biological contactor.

Filter Media. The media used for RBCs is composed of high-density polyethylene. Manufacturers vary the thickness and shape of the material to conform to their own standards. Similar variations occur in the shapes and sizes of the shafts and structural frames used to support individual discs.

Two broad categories of RBC media exist: standard-density media (Figure 21.10) and high-density media (closer disc spacing). Standard-density media have approximately

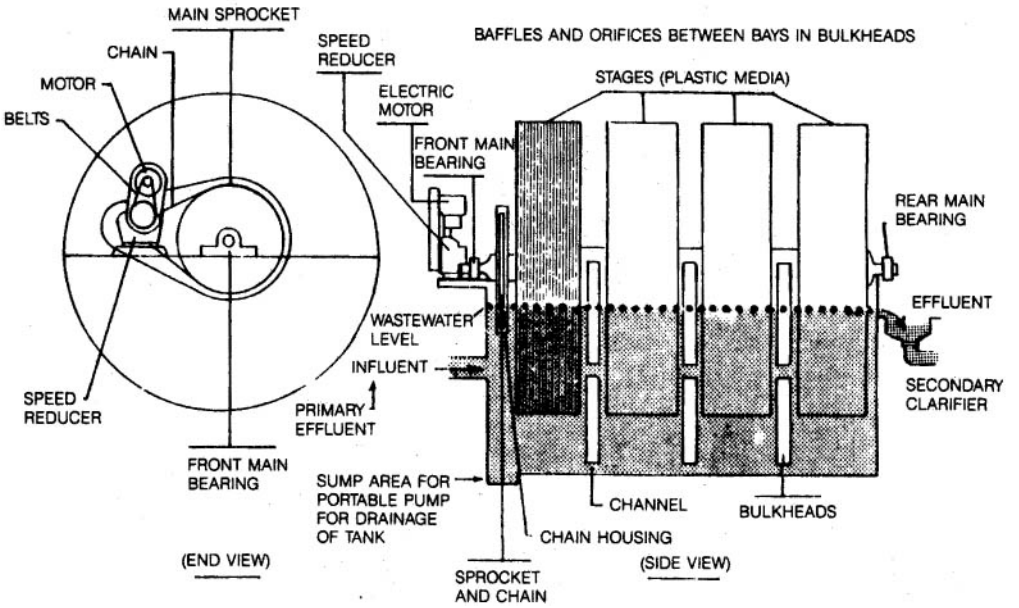


FIGURE 21.9 Mechanically driven rotating biological contactor.

9300 m^2 (100 000 sq ft) of surface area/shaft. High-density media are typically used in the later or nitrification stages of RBCs and may have between 11 200 and 16 700 m^2 (120 000 and 180 000 sq ft) of surface area/shaft (Gross et al., 1984).

Covers. Covers or enclosures are used with RBCs to:

- Protect biological slimes from freezing;
- Prevent rain from washing off slime growth;
- Prevent media exposure to sunlight, which results in algae growth;
- Protect the media from UV rays, which can weaken them; and
- Provide protection from the elements.

Covers are often made of fiberglass or other reinforced resin plastics. Another approach involves housing a number of shafts in a building. In either case, the RBC enclosure must have ventilation, humidity and condensation control, and heat loss provisions.

Rotating Biological Contactor Drives. The discs can be rotated by either mechanical or air drive units. Both types of drives have bearings to support the RBC shafts. Every

TABLE 21.6 Parts of a rotating biological contactor.

Part	Purpose
Concrete or steel tank divided into bays (sections) by baffles (bulkheads)	Tank: holds the wastewater and allows it to come in contact with the organisms on the discs
	Bays and baffles: prevent short-circuiting of wastewater
Orifice or weir in baffle	Controls flow from one stage to the next or from one bay to the next
Rotating media	Provides support for organisms; rotation provides food (from wastewater being treated) and air for organisms
Cover over contactor	Protects organisms from severe fluctuations in the weather, especially freezing; also helps contain odors
Drive assembly	Rotates the media
Influent lines with valves	Influent lines: transport wastewater to the RBC*
	Influent valves: regulate influent to RBC and isolate RBC for maintenance
Effluent lines with valves	Effluent lines: convey treated wastewater from the RBC to the secondary clarifier
	Effluent valves: regulate effluent from the RBC and isolate the RBC for maintenance
Underdrains	Allow for removal of solids that may settle out in the tank

*Rotating biological contactor.

RBC shaft has at least one bearing designed to accommodate thermal expansion as the shaft heats and cools; most shafts have one expansion and one non-expansion bearing.

Mechanical-drive RBCs use a chain and sprocket assembly (Figure 21.9) to rotate the shaft. The motors, typically rated at 3730 to 5590 W (5 to 7.5 hp)/shaft, may be equipped to allow changing shims or sprocket sizes and installation of an electronic speed controller to vary rotational speed.

Air-driven RBC units have a blower and air diffuser at the bottom of each RBC shaft (Figure 21.8; California State University, 1988). Air cups pinned to the edge of the plastic disc trap air bubbles released from the air header. As the air bubbles rise, they cause the RBC shaft to rotate.

The advantages of air-driven units are that less torque is applied to the shaft, the biomass tends to be thinner (sheared by the air), and the wastewater may contain slightly more dissolved oxygen. In some cases, diffused air has been used in mechanical-drive RBCs to reduce solids accumulation at the tank bottom and mini-

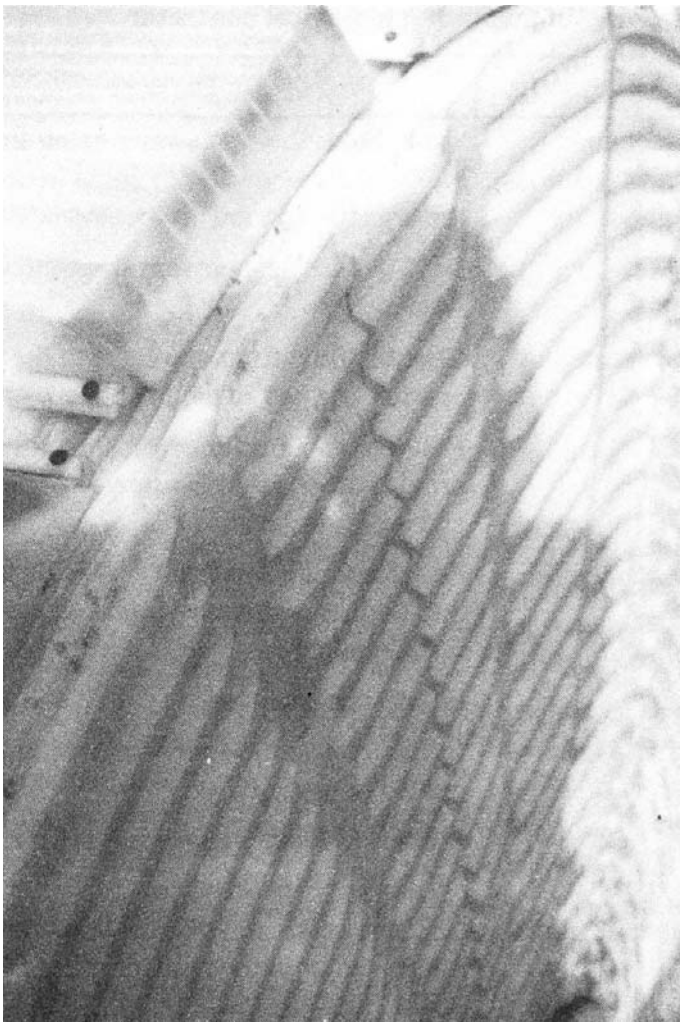


FIGURE 21.10 Standard-density rotating biological contactor media.

mize localized anaerobic conditions. The air for RBCs is typically not captured for reuse because of its low pressure [17.2 to 20.7 kPa (2.5 to 3 psi)].

Positive-displacement or centrifugal blowers may be used; however, centrifugal blowers are easier to control by adjusting the throttle on the blower suction valve. Positive-displacement blowers must be equipped with a variable-speed drive or con-

tinuously vented to the atmosphere. A major problem with air-drive units has been loping or unbalanced rotation. In extreme cases, rotation has stopped, and mechanical rotation, cleaning, or the use of high air rates has been necessary to re-establish rotation. Other disadvantages of air-drive units are higher power use and the need to balance and adjust the air flow to the diffusers.

Influent and Effluent Lines and Valves. The piping and valves associated with the RBC process typically do not affect performance significantly. If channels are used to transfer water, the hydraulic velocities should be adequate to maintain solids in suspension. Another approach is to aerate the channels to prevent solids deposition.

Because the flow velocities are typically low, the flow can typically be distributed via weirs, slide gates, or other conventional structures. A flow-splitting structure is best for distributing wastewater to a number of trains.

Instrumentation. Electronic or hydraulic load cells are useful to periodically measure total shaft weight. Some shafts have a load cell device installed under the shaft support bearing on the idle end of the shaft. Such a cell has a hand-operated hydraulic pump to lift the bearing from its base and generate a hydraulic pressure that can be converted to shaft weight. Load cell information is used to judge the condition of biological growth and the weight of the biomass. Electronic speed indicators and remotely activated air valves have been provided at air-drive installations to facilitate maintenance and adjustment of rotational speed.

PROCESS CONTROL. The most important element of process control is daily shaft inspection by a trained operator. Principal observations typically include the biomass condition in each stage and the dissolved oxygen levels exiting the individual stages.

Observations about the first-stage biomass are typically the most critical. A healthy first-stage biomass is uniformly brown and distributed in a thin, even layer. A heavy, shaggy biomass in the first stage indicates an organic overload, which can be caused by an insufficient number of RBCs, industrial waste, or the effect of sidestreams (e.g., digester supernatant).

A U.S. Environmental Protection Agency (U.S. EPA) study (Chesner and Iannone, 1968) reported difficulties with the initial stages of RBC systems indicated by heavy biofilm growth, the presence of nuisance organisms (e.g., *Beggiatoa*), and a reduction in BOD_5 removal rates. These problems have been attributed to excessive organic loading rates that result in low dissolved oxygen levels, which subsequently lead to *Beggiatoa* growth and deteriorating process efficiency. *Beggiatoa*—whitish autotrophic sulfur bacteria—use hydrogen sulfide and sulfur as energy sources in the presence of oxygen.

Beggiatoa organisms compete with heterotrophic organisms for oxygen and space on RBC media surfaces. Their predominance can increase the biomass concentration on the media, while substantially reducing BOD_5 removal per unit area. The study suggested that, whenever the first stage load exceeded 20 to 40 $g/m^2 \cdot d$ (6 to 8 lb $BOD_5/d/1000$ sq ft), the media surface was associated with *Beggiatoa* or sulfide-oxidizing organisms. This loading should correspond approximately to an $SBOD_5$ loading in the range of 12 to 20 $g/m^2 \cdot d$ (2.5 to 4.0 $lb/d/1000$ sq ft).

If white or gray splotches develop on the disc surfaces, then *Beggiatoa* or *Thiothrix* bacteria are developing in large numbers and are a nuisance. Both *Thiothrix* and *Beggiatoa* are filamentous-type organisms that reduce the RBC's removal rate capability and cause poor settling sludge in the secondary clarifier. These organisms typically develop in the presence of high concentrations of hydrogen sulfide (H_2S). Sulfides may result from the following:

- Low oxygen levels caused by an extreme overload of the first stage,
- Septic wastes,
- Industrial discharges,
- Anaerobic deposits on the bottom of the RBC tank, or
- Reduced dissolved oxygen levels during warm-weather operations.

A second indicator closely observed in RBC operation is the dissolved oxygen concentration throughout various stages. High organic loading may result in low dissolved oxygen levels. For carbonaceous BOD_5 removal, a minimum dissolved oxygen level ranging from 0.5 to 1.0 mg/L is needed at the end of the first stage, and at least 2 to 3 mg/L is needed at the end of the last stage of the RBC unit.

Depending on the biomass and dissolved oxygen observations, operators may need to make process-control changes to the following:

- Other processes,
- Stages and trains,
- Supplemental aeration,
- Step feeding or an enlarged first stage,
- Recirculation,
- Rotational speed, or
- Secondary clarifier.

Other Processes. Rotating biological contactors depend, to a great extent, on the preceding treatment steps to effectively reduce the solids or BOD levels in high-strength

influent streams that could otherwise result in interference or overload. For example, efficient grit removal and screening are essential to prevent solids buildup under the discs. Good primary treatment is required to reduce the organic and hydrogen sulfide loadings to the RBC units. Although all RBCs need periodic cleanout or flushing, the need for frequent cleaning indicates that either preliminary or primary treatment units need improvement.

Sidestreams (e.g., supernatants from anaerobic or aerobic digesters and filtrate or concentrate from dewatering processes, drying beds, or lagoons) may significantly affect both the BOD and ammonia levels entering the RBCs. Therefore, these recycle streams demand careful monitoring and control to avoid adverse effects on RBC operations (U.S. EPA, 1984).

Staging and Trains. The number of trains and stages is a principal process-control variable affecting RBC performance. The number of stages is typically increased to improve RBC performance (this assumes no overloading of the first stages). A minimum of two to three stages is typically necessary to reliably achieve secondary effluent quality when treating domestic wastewater. Three to four stages are needed to achieve effluent BOD_5 concentrations of less than 20 mg/L.

Any changes in the number of stages should follow consideration of organic loading. Placing additional trains online may be necessary to reduce the organic load. Typically acceptable loading limits are 1.5 to 2.0 kg $BOD_5/100\ m^2 \cdot d$ (3 to 4 lb $BOD_5/d/1000$ sq ft) for the overall shaft loading and 2.0 to 2.9 kg $BOD/100\ m^2 \cdot d$ (4 to 6 lb $BOD_5/d/1000$ sq ft) for the first stage. The RBC system is typically designed and analyzed on an $SBOD_5$ basis. On this basis, acceptable loads are approximately 50% of those for total BOD_5. Pre-aeration before the first stage merits consideration to reduce the possibility of oxygen deficiencies.

The number of stages and trains may be adjusted to provide proper hydraulic retention time, typically considered less significant than organic loading. Hydraulic retention time depends directly on the available liquid volume in the RBC tank and the wastewater flow. Research has indicated that retention as low as 4.9 L of tank volume/m^2 of media (0.12 gal/sq ft) does not reduce RBC efficiency (however, lower values lack such tests). Hydraulic loadings for carbonaceous BOD removal are typically maintained in the range 0.4 to 0.12 $m^3/m^2 \cdot d$ (1.0 to 3.0 gpd/sq ft), while nitrification loading is typically 0.04 to 0.10 $m^3/m^2 \cdot d$ (1.0 to 2.5 gpd/sq ft) or even less than 0.04 $m^3/m^2 \cdot d$ (1.0 gpd/sq ft).

Supplemental Aeration. The importance of dissolved oxygen in aerobic wastewater treatment is well-known. An inadequate dissolved oxygen concentration may be a major cause of process failure. In the RBC system, supplemental aeration should be used

whenever the BOD_5 loadings to the first stage are high or when dissolved oxygen concentrations in the incoming wastewater are low (Surrampalli and Baumann, 1989). The reported benefits of supplemental aeration include the following:

- Elimination of *Beggiatoa* growth,
- Thinner biofilms on the media,
- Increased dissolved oxygen levels,
- Higher $SBOD_5$ removal rates,
- Higher ammonia-nitrogen removal rates, and
- Enhanced shaft and media life.

The increased removal rates with supplemental aeration are attributed to higher dissolved oxygen concentrations and thinner, *Beggiatoa*-free biomass growth that enhances mass diffusion of substrate and oxygen into the inner layers of the active biomass.

Step Feeding or Enlarged First Stage. It is desirable to operate RBC plants with an enlarged first stage, particularly when the first stage is organically overloaded (Surampalli and Baumann, 1993). Step feeding, or *step aeration*, as it is called when applied to activated sludge processes, is used extensively in activated sludge plants to improve the oxygen demand situation at the head end of treatment systems that would otherwise be organically overloaded. To avoid a high oxygen demand at the beginning of an activated sludge aeration tank, the incoming wastewater is distributed along the aeration tank at several locations to result in a more even oxygen demand throughout the tank. Similarly, an enlarged first stage can be used effectively to avoid overload and to attenuate variations in wastewater characteristics, thereby eliminating oxygen-limiting conditions and the development of nuisance organisms. Fortunately, an enlarged first stage can be created simply by removing the baffle between the first and second stages of RBC systems.

Recirculation. Recirculating RBC-treated effluent (either before or after the secondary clarifier) does not significantly improve the treatment efficiency. Nonetheless, under certain conditions (e.g., during startup or when high industrial wastes are present), recirculation may avoid overloading and thus lead to more reliable RBC performance. Recirculation may also be advantageous where large hydraulic fluctuations occur (e.g., flow changes from industrial parks or schools). Recirculation via holding or thickening tanks should be avoided, however, because the sludge could produce high sulfide concentrations in the recycle flow that would stimulate the growth of nuisance microorganisms.

Rotational Speed. The equipment manufacturer's recommendations should govern the selection of rotational speed for the RBC discs. Typical rotational speeds range from 1.0 to 1.6 rpm.

While less energy is required to rotate RBCs at slower speeds, the slower speeds will also reduce the oxygen-transfer capability. Some facilities have observed increased efficiency by rotating countercurrent to influent flow (when perpendicular to the shaft), while others have found no change, regardless of the direction of rotation.

Secondary Clarifier. Clarifier operation with the RBC process resembles that already described for trickling filters. Use of the secondary clarifier as a principal means of thickening should be avoided to minimize denitrification or solids carryover with the treated effluent.

Sloughing of the discs may result from toxic loads, temperature changes, or normal hydraulic shear action. Daily monitoring the clarifier sludge blanket and accounting for the amount of solids pumped [in kilograms per day (pounds per day)] will help operators identify potential solids buildup or other problems.

Nitrification. Rotating biological contactors are also used to nitrify secondary effluent. Secondary treatment systems used ahead of separate-stage RBC nitrification include a variety of activated sludge and attached-growth systems. Separate-stage RBC nitrification is typically used as an add-on step to existing secondary biological systems that are required to meet ammonia-nitrogen (NH_3-N) effluent limits.

Major variables influencing ammonia nitrification in an RBC system include influent organic nitrogen and ammonia-nitrogen concentrations, dissolved oxygen concentrations, wastewater temperature, pH, alkalinity, and influent flow and load variability. Staged or plug-flow configurations promote development of nitrifying organisms. Thus, appropriate staging is necessary for nitrification to take place in RBC systems. The growth of nitrifiers depends on the $SBOD_5$ concentration present in the stage's wastewater. Typically, nitrification is observed when the $SBOD_5$ concentration in the stage's wastewaters is reduced to 15 mg/L, and maximum nitrification is observed when $SBOD_5$ declines to 10 mg/L or less.

Wastewater temperature is the major variable controlling full-scale RBC nitrification below 13°C (55°F), becoming increasingly documented when temperatures of 4°C (40°F) are approached. Wastewater temperatures higher than 13°C (55°F) do not result in higher nitrification rates in full-scale units, because the oxygen-transfer rate, rather than the biological growth rate, controls the reaction at these temperatures.

Nitrification is more sensitive to dissolved oxygen concentration than heterotrophic carbonaceous removal systems. A minimum desired dissolved oxygen level of 2 mg/L

is often quoted. High effluent dissolved oxygen concentrations combined with low levels of $SBOD_5$ can lead to deterioration of nitrification rates via the proliferation of higher life forms that ingest nitrifying microorganisms. To discourage selective predation of nitrifying bacteria, it is suggested that dissolved oxygen concentrations of no more than 3.5 mg/L and $SBOD_5$ concentrations of 6 to 8 mg/L be maintained in the polishing stages of RBC nitrification trains.

Nitrification is an acid-producing biochemical reaction. Approximately 7.1 mg of calcium carbonate alkalinity is theoretically consumed per milligram of ammonia-nitrogen oxidized. Depending on initial alkalinity and unoxidized nitrogen concentrations, the nitrification process could reduce wastewater alkalinity until the pH drops to 6.5 and even to 6.0 or less. Increased nitrification is observed when the pH is between 7.0 and 8.5, with nitrification efficiency falling off dramatically as the pH decreases from 7.0 to 6.0.

TROUBLESHOOTING. When properly designed and operated, RBCs can provide trouble-free secondary treatment. However, some RBC plants constructed during the late 1970s and early 1980s required significant troubleshooting or plant modifications to achieve the desired treatment level without operating problems.

Troubleshooting operational problems begins with obtaining good records and data associated with the RBC process. Tracking total and soluble BOD_5, suspended solids, organic nitrogen, ammonia-nitrogen, pH, alkalinity, dissolved oxygen, and other parameters is necessary to recognize trends that may have an adverse effect on the RBC system. The sampling frequency may have to be increased to ensure representative data.

Equipment failures (e.g., broken shafts or failed filter media) were common occurrences on many of the early RBC installations. Most of these problems were resolved through equipment warranty or performance specifications. Many of the problems associated with the early designs have been mitigated by using more conservative design practices, improving equipment design and manufacturing practices, shaft weighing devices, and using supplemental aeration to improve biomass uniformity. Table 21.7 is a troubleshooting guide for other problems associated with the design, operation, and maintenance of RBCs.

PLANNED MAINTENANCE. Like any treatment process, the RBC system demands routine attention, or operations and maintenance problems will occur. Chain drives, belts, sprockets, rotating shafts, and other moving parts need inspection and maintenance according to the manufacturers' instructions or with guidance from the

TABLE 21.7 Troubleshooting guide for rotating biological contactors (RBCs).

Indicators/observations	Probable cause	Check or monitor	Solutions
Decreased treatment efficiency	Organic overload	Check peak organic loads; if less than twice the daily average, should not be the cause	Improve pretreatment or expand plant
	Hydraulic equalization	Check peak hydraulic loads; if less than twice the daily average, should not be the cause	Flow equalization; eliminate source of excessive flow; balance flows between reactors
	pH too high or too low	Desired range is 6.5 to 8.5 for secondary treatment, 8 to 8.5 for nitrification	Eliminate source of undesirable pH or add an acid or base to adjust pH; when nitrifying, maintain alkalinity at seven times the influent ammonia concentrations
	Low wastewater temperatures	Temperature less than 15 °C (59 °F) will reduce efficiency	If available, place more treatment units in service
	Snails in nitrification units	Evaluate nitrification rate	Periodically remove unit from service and add caustic to clean media
Excessive sloughing of biomass from discs	Toxic materials in influent	Determine material and its source	Eliminate toxic material if possible; if not, use flow equalization to reduce variations in concentration so biomass can acclimate
	Excessive pH variations	pH below 5 or above 10 can cause sloughing	Eliminate source of pH variations or maintain control of influent pH
Development of white biomass over most of disc area	Septic influent or high hydrogen sulfide concentrations	Influent odor	Pre-aerate wastewater or add sodium nitrate, hydrogen peroxide, or ferrous sulfate; supplemental aeration may also help, especially in the first stages
	First stage is organically overloaded	Organic loading on first stage	Adjust baffles between first and second stages to increase fraction of total surface area in first stage
Solids accumulating in reactors	Inadequate pretreatment	Determine if solids are grit or organic	Remove solids from reactors and provide better grit removal or primary settling

TABLE 21.7 Troubleshooting guide for rotating biological contactors (RBCs) (*continued*).

Indicators/observations	Probable cause	Check or monitor	Solutions
Shaft bearings running hot or failing	Inadequate maintenance	Maintenance schedules and practices	Lubricate bearings as per manufacturer's instructions
Motors running hot	Inadequate maintenance	Oil level in speed reducer and chain drive	Lubricate as per manufacturer's instructions
	Improper chain drive alignment	Alignment	Align properly
Snail growth	Wastewater environmental conditions prone to snail growth	Biomass growth or snail accumulation in tanks	Periodic chemical cleaning Periodically increase RBC speed
	Low organic loading	Low organic load	Rearrange loading to RBC units to increase organic load

design engineer. Although these requirements will vary among plants, the RBC maintenance guide given in Table 21.8 provides many of the typically required maintenance procedures for RBCs.

Routine maintenance should include the inspection of shafts and replacement of broken air cups or media that might otherwise jam or interfere with shaft rotation. Housekeeping should include the removal of grease balls via a net device. The manufacturer may provide advice on making field repairs to media that become separated. Unbonded surfaces may sometimes be repaired by melting the plastic with a heated metal rod or other manufacturer-recommended product.

Mechanical Drive Systems. Shaft bearings should be inaudible above the splashing. A screwdriver or metal rod can be used to transmit bearing noise to the operator's ear. Vibration meters can also sense noise (vibrations). Drive motors, which need daily inspection, typically should run cool enough to touch with a bare hand [less than 60 °C (140 °F)]. If motor amperage readings are recorded, they should be taken and logged at least semiannually. During daily observations of the belt drive, a squealing noise is the first indication that a problem has occurred. Because belts are often sold as a set, the whole set should be replaced with identical belts from the same manufacturer.

Air-Drive Systems. Air-drive systems require more careful monitoring and attention than mechanical drive units, because shaft speed and balance must be maintained via

TABLE 21.8 Rotating biological contactor maintenance guide.

Interval	Procedure
Daily	Check for hot shaft and bearings. Replace bearings if temperature exceeds 93 °C (200 °F).
Daily	Listen for unusual noises in shaft and bearing. Identify cause of noise and correct if necessary.
Weekly	Grease the mainshaft bearings and drive bearings. Use manufacturer's recommended lubricants. Add grease slowly while shaft rotates. When grease begins to ooze from the housing, the bearings contain the correct amount of grease. Add six full strokes where bearings cannot be seen.
4 weeks	Inspect all chain drives.
4 weeks	Inspect main shaft bearings and drive bearings.
4 weeks	Apply a generous coating of general-purpose grease to main shaft sub ends, main shaft bearings, and end collars.
3 months	Change oil in chain casing. Use manufacturer's recommended lubricants. Be sure oil level is at or above the mark on the dipstick.
3 months	Inspect belt drive.
6 months	Change oil in speed reducer. Use manufacturer's recommended lubricants.
6 months	Clean magnetic drain plug in speed reducer.
6 months	Purge the grease in the double-sealed shaft seals of the speed reducer by removing the plug located 180° from the grease fitting on both the input and output seals' cages. Pump grease into the seal cages and then replace the plug. Use manufacturer's recommended grease.
12 months	Grease motor bearings. Use manufacturer's recommended grease and recommendations for lubrication. To grease motor bearings, stop motor and remove drain plugs. Inject new grease with pressure gun until all old grease has been forced out of the bearing through the grease drain. Run motor until all excess grease has been expelled. This may require up to several hours' running time for some motors. Replace drain plugs.

indirect air lift. Shaft speed should be checked daily and compared with manufacturer recommendations. Shaft balance also requires periodic checks to ensure that excess biomass has not built up on one side of the discs. This check involves timing quarter turns of the RBC shaft. If the shaft becomes badly out of balance, correcting the problem requires stopping or isolating the shaft, draining the tank, or otherwise chemically stripping the biomass.

Periodically increasing the air capacity to 150% of the normal volume may help control biomass growth. Purging often strips excess biomass that would otherwise

cause imbalance. Daily monitoring of blower oil pressure will help indicate the possible presence of clogged diffusers or other interferences.

COMBINED PROCESSES

Treatment is typically thought of as occurring in sequential major steps—preliminary, primary, secondary, and tertiary. However, the major secondary treatment step sometimes combines use of fixed-film reactors (e.g., trickling filters and RBCs) in series or in conjunction with other forms of biological treatment (e.g., activated sludge). These combined processes are often referred to by a number of terms, such as *step systems*, *two-stage*, *series*, *dual*, *coupled*, or *combined processes*. This section covers the operation and maintenance of what, for lack of a better term, will be called *combined processes*—the coupling of fixed-film and suspended growth processes.

In the mid- to late 1970s, filter media improvements included the development of high-rate media (Figure 21.2), as described earlier in this chapter. The first applications of high-rate media were in roughing filters used primarily by industry to accommodate high loadings (Harrison and Daigger, 1987). The new media allowed trickling filters to be organically loaded 10 to 15 times higher than rock media loadings without odor or plugging problems. It soon became evident that biological treatment could often be accomplished with a combination of highly loaded trickling filters followed by activated sludge. Advantages and disadvantages of the parent trickling filter and activated sludge processes are given in Table 21.9. Combining the processes has often coupled the simplicity, shock resistance, and low maintenance of the trickling filter with the improved effluent quality or increased nitrification of the second-stage activated sludge or contact basin. Figure 21.11 compares the reliability of combined, activated sludge, and trickling filter processes in achieving good effluent quality.

ALTERNATIVES. Numerous combinations of processes are possible, depending on the trickling filter and activated sludge processes used, the loading of individual units, and the point at which sludge or other recycled streams are reintroduced to the main flow stream. The most common combined processes (and their typical acronym) are listed in Table 21.10.

Process schematics for each combined process are illustrated in Figure 21.12. Table 21.11 presents loading criteria typically considered appropriate for both the component processes and the combined process. These criteria are not absolute values, because site-specific conditions may cause the loading balance to vary. A brief description of each combined process follows.

TABLE 21.9 Advantages and disadvantages of trickling filter and activated sludge processes.

Advantages	Disadvantages
Trickling filter systems	
Simplicity	Higher initial cost
Thick secondary sludge	More land area required
Low operating costs	Odor problems
Shock resistance	Temperature sensitivity
Low maintenance	Poor response to operational changes
Little power required	
Activated sludge systems	
Increased operational flexibility	Complexity
Lowest initial cost	Greater sludge volume
Less land area required	Sensitive to shock loads
Reduced odor	High power requirements
Nitrification control	Greater operating costs

Activated Biofilter. The activated biofilter process (Figure 21.12) uses a lightly loaded trickling filter with high-rate media. Biological or activated solids are recycled from the bottom of the secondary clarifier and returned to the trickling filter (hence, the term *activated biofilter* or *biological filter*). Many consider that recycled solids improve settleability, similar to that in a selector-activated-sludge process. An initial high food-to-microorganism (F:M) ratio and high dissolved oxygen concentration are sometimes attributed to the ABF process' ability to improve the settling characteristics of secondary solids.

While performing well at low organic loads, the ABF process proved to be unable to consistently achieve good effluent quality as organic loads approach 1.6 kg $BOD_5/m^3 \cdot d$ (100 lb $BOD_5/d/1000$ cu ft). The ABF process without short-term aeration also proved to be susceptible to poor performance in cold climates. To overcome these problems, the ABF tower was later modified to include a relatively small aeration basin, described in the Biofilter Activated Sludge section of this chapter (Harrison, 1980).

Trickling Filter–Solids Contact. The trickling filter–solids contact process (Figure 21.12) typically uses a moderately to highly loaded trickling filter, followed by a small contact channel only 8 to 17% of the size typically required by a traditional activated sludge process. By combining the trickling filter with the contact channel, the filter size is typically reduced to 50% or less of that required by a traditional trickling filter process (Harrison and Timpany, 1988).

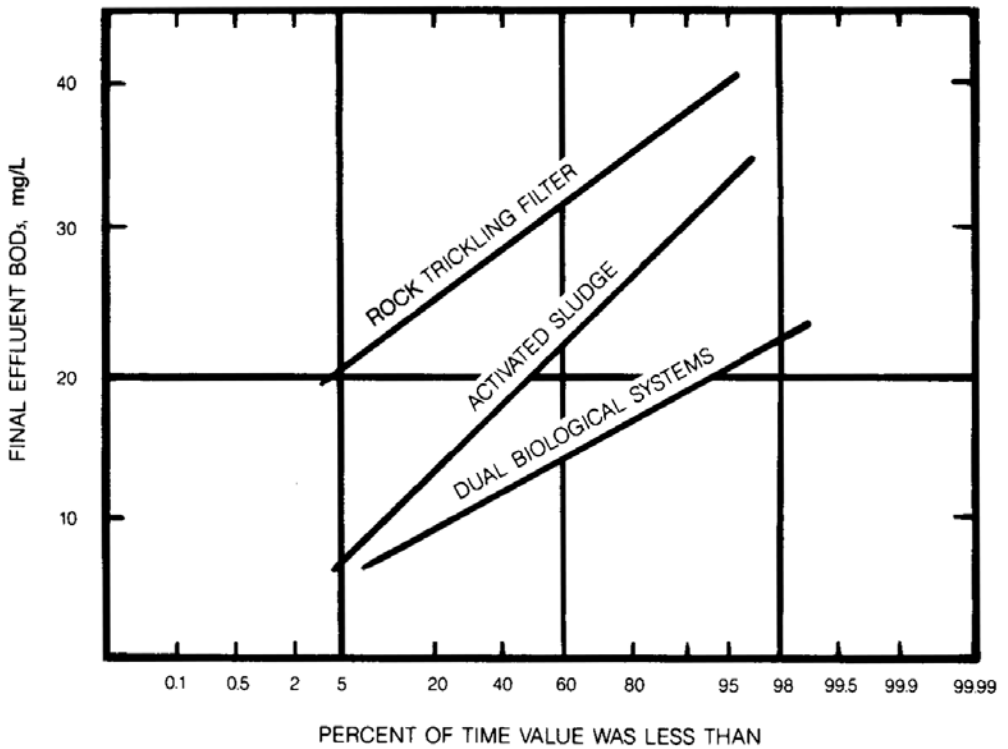


FIGURE 21.11 Comparison of the effluent quality provided by rock trickling filters, activated sludge, and dual treatment systems.

The trickling filter–solids contact process results in low power requirements because the trickling filter removes most of the SBOD. Other benefits include the ability to easily upgrade existing rock trickling filters by polishing their effluent when return activated sludge (RAS) is used as a bioflocculating agent (Timpany and Harrison, 1989).

TABLE 21.10 Names and acronyms for combined processes (Harrison et al., 1984).

Name	Acronym
Activated biofilter	ABF
Trickling filter–solids contact	TF/SC
Roughing filter–activated sludge	RF/AS
Biofilter–activated sludge	BF/AS
Trickling filter–activated sludge	TF/AS

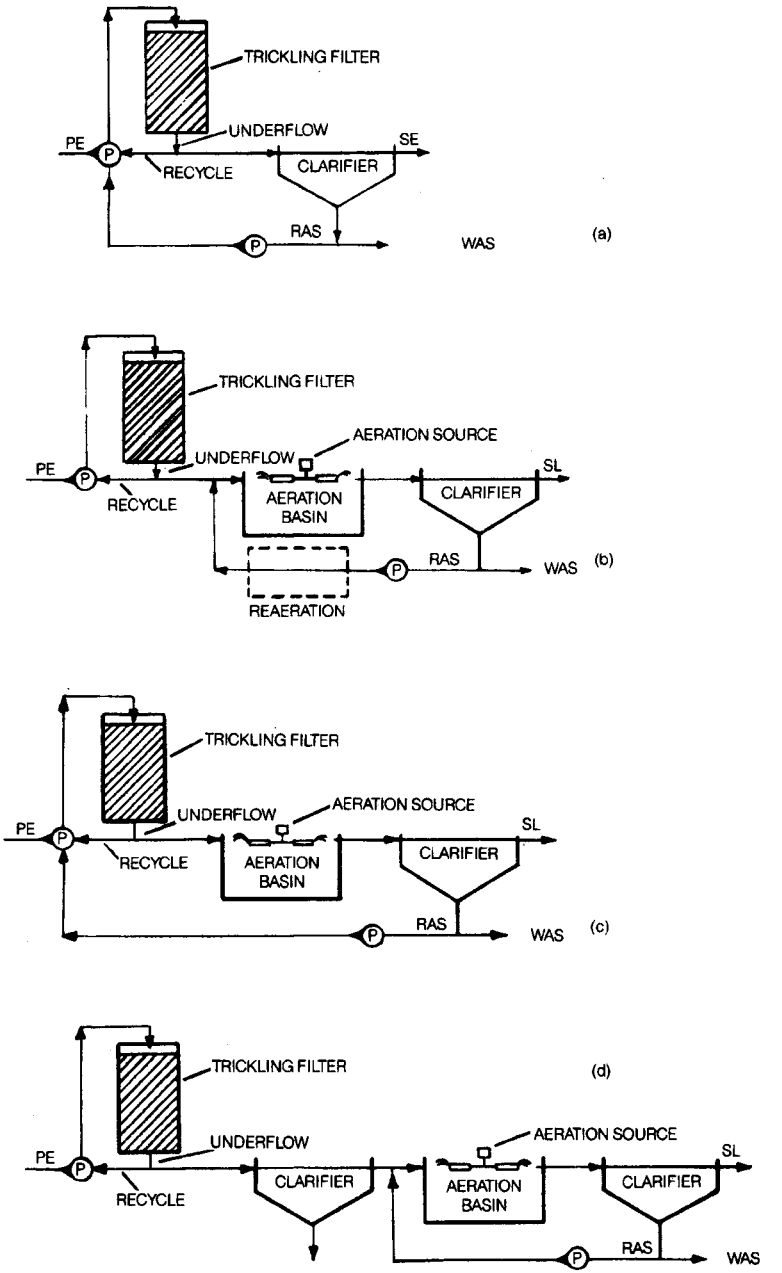


FIGURE 21.12 Combined system process schematics: (a) activated biofilter (ABF), (b) trickling filter–solids contact (TF/SC) and roughing filter–activated sludge (RF/AS), (c) biofilter–activated sludge (BF/AS), and (d) trickling filter–activated sludge (TF/AS).

TABLE 21.11 General design criteria for combined processes.

Item	Appropriate design criteria	
	Range	**Typically used**
Component processes		
Activated sludge		
F:M ratio[a]	0.2–0.4	0.3
MLSS[b]	1500–4000	2500
Retention time	4.0–8.0	6.0
Mean cell residence time[c]	5–15	10
RAS	6200–12000	8000
Basin oxygen[d]		
Totally available	0.8–1.8	1.6
Typically on	0.6–1.4	1.0
Trickling filter		
Media type	Rock or high rate	High rate
BOD loading[e]	5–40	20
Hydraulic loading[f]	0.02–1.0	0.8
Combined processes		
ABF		
Media type	High rate	High rate
BOD loading	10–75	30
Hydraulic loading	0.8–5.0	2.0
Filter MLSS	1500–3000	2000
TF/SC		
Media type	Rock or high rate	High rate
BOD loading	20–75	40
Hydraulic loading	0.1–2.0	1.0
Channel MLSS	1500–3000	2000
Hydraulic residence time[g]	0.5–2.0	1.0
Mean cell residence time	0.5–2.0	1.0
RAS	6000–12000	8000
Minimum channel mixing		
Diffused air (sq ft/mil. gal)	2000–4000	3000
Mechanical (hp/mil. gal)	60–130	100

TABLE 21.11 General design criteria for combined processes (*continued*).

Item	Appropriate design criteria	
	Range	**Typically used**
RF/AS, TF/AS, and BF/AS		
Media type	High rate	High rate
BOD loading	100–300	150
Hydraulic loading	0.8–5.0	2.0
Basin MLSS	1500–4000	2500
Basin retention time	0.5–4.0	2.0
Mean cell residence time	1.0–7.0	3.0
F:M ratio	0.5–1.2	0.9
Basin oxygen		
Total available	0.6–1.2	0.9
Typically on	0.3–0.9	0.6

[a]F:M ratio = lb primary effluent BOD/d/lb MLVSS (lb/lb × 1 000 = g/kg).
[b]MLSS = mg/L.
[c]Mean cell residence time (MCRT) = days (aeration basin only).
[d]Basin oxygen = lb O_2/lb primary effluent BOD.
[e]Biochemical oxygen demand (BOD) loading = lb BOD/d/1000 cu ft for trickling filter (lb/d/1000 cu ft × 1.602×10^{-2} = kg/m^3·d).
[f]Hydraulic loading = gpm/sq ft for trickling filter [gpm/sq ft × (6.791×10^{-4}) = m/m·s].
[g]Hydraulic residence time = hours based on influent Q only (no RAS).

Roughing Filter–Activated Sludge. A common method of upgrading existing activated sludge plants is to install a roughing filter ahead of the activated sludge process (Figure 21.12). This process is also used in situations where a plant receives a waste high in SBOD. The roughing filter is typically one-fifth to one-eighth the size required if treatment were accomplished with the trickling filter process alone. Hydraulic retention time in the aeration basin is typically 30 to 50% of that required with activated sludge alone.

Both the TF/SC and roughing filter–activated sludge (RF/AS) process have the same process schematic (Figure 21.12), but the RF/AS uses a much smaller trickling filter than the TF/SC, so the former depends more on aeration to provide oxygen, remove BOD, and digest solids. This differs from the TF/SC process, where the trickling filter provides almost all wastewater treatment, and the contact channel only enhances solids flocculation and effluent clarity. Differences in capital costs, often influenced by the availability of existing units, often determine the choice between the TF/SC or RF/AS process.

Biofilter–Activated Sludge. The biofilter–activated sludge (BF/AS) process (Figure 21.12) resembles the RF/AS process, except that its return activated sludge is recycled over the trickling filter in a way similar to the ABF process. Incorporating RAS recycle over the trickling filter sometimes reduces sludge bulking from filamentous bacteria, especially when treating difficult food processing wastes. However, there is no evidence that sludge recycle improves the trickling filter's oxygen-transfer capability (Harrison, 1980).

Recent evidence indicates that adding aerated RAS can help reduce odors from trickling filters. It is believed that, by providing a bacteria population to the filter influent, sulfides are metabolized and therefore not released as odorous compounds (Joyce et al., 1995).

Trickling Filter–Activated Sludge. The trickling filter–activated sludge (TF/AS) process (Figure 21.12) is loaded in a manner similar to that of either the RF/AS or BF/AS. However, the TF/AS process includes an intermediate clarifier between the trickling filter and the aeration basin. The intermediate clarifier removes sloughed solids from the trickling filter underflow before it enters the aeration basin.

A major benefit of using the TF/AS mode is that solids generated from carbonaceous BOD removal can be separated from the second-stage treatment. This two-stage approach is often best where nitrogen oxidation (nitrification) is required, and the second stage of the process is designed to be dominated by nitrifying microorganisms. Another advantage of intermediate clarification is the reduced effects of trickling filter sloughing on the activated sludge portion of the process. However, researchers have not shown clear evidence of reduced oxygen requirements or improved settleability in intermediate clarification. Therefore, most high-rate or roughing filters in combined processes are designed as RF/AS or BF/AS to eliminate the cost of intermediate clarification, unless nitrification is required.

DESCRIPTION OF PROCESSES. Combined processes consist of a two-stage or two-step method of removing pollutants. The first-stage filter (fixed-film) supplies 30 to 50% of the oxygen requirements for total biological treatment with RF/AS, BF/AS, or TF/AS. Essentially all of the oxygen for biological reactions is supplied in the filter with either the TF/SC or ABF processes.

Biological solids are produced from the use of soluble organic material as food matter. These biological solids attach to the fixed-film filter media until hydraulic shear, excessive growth, or other conditions induce sloughing of the biomass. The type of filter media used, hydraulic loading rate to the filter, and the organic loading all result in variations in sloughing frequencies and in the characteristics and mass of the sloughed solids.

Biological activity in the aeration basin after the fixed-film reactor allows additional contact time for suspended-growth bacteria to synthesize any remaining SBOD. In addition, the bacteria undergo endogenous respiration (aerobic digestion of cell matter). Basins with longer contact times (1 to 3 hours) provide greater opportunities for stabilization of biological solids and removal of additional SBOD than do smaller basins (e.g., contact channels). A reaeration basin (Figure 21.12) provides another method of allowing time for solids digestion. Because solids from the clarifier underflow to be reaerated are much thicker than the aeration basin mixed-liquor solids, less volume is required to digest solids in a reaeration basin than in an aeration basin.

The mixture of digested biological solids and treated effluent undergoes separation in the final clarifier. A mixed liquor from combined processes, similar to that of activated sludge (although perhaps less susceptible to upset), requires good separation of treated effluent and solids to achieve high effluent quality.

DESCRIPTION OF EQUIPMENT. The basic combined processes (Figure 21.12) use several common reactors and equipment items, regardless of the type of process mode. Common equipment items are listed below (Figure 21.13).

- Trickling or biotower (fixed-film reactor),
- Filter pumping station,
- Contact channel or aeration basin (suspended-growth reactor), and
- Clarifier (intermediate or final).

Trickling Filter or Biotower. The trickling filter structure for rock media can be incorporated into any combined process. However, many combined processes are loaded at rates that typically favor the use of high-rate synthetic filter media, which are less susceptible to plugging, odors, or other problems. This is particularly true if treatment of high-strength wastes is the reason for combining processes. Accordingly, most combined systems use biotowers rather than the trickling filter structures associated with rock media.

Filter Pumping Station. The filter pumping stations used with combined systems are similar to those described in the Trickling Filters and Biotowers section of this chapter.

Contact Channel or Aeration Basin. The suspended-growth reactor may consist of a relatively large aeration basin, contact channel, or re-aeration structure. If an aeration basin is used, it is smaller than the aeration basin in an activated sludge

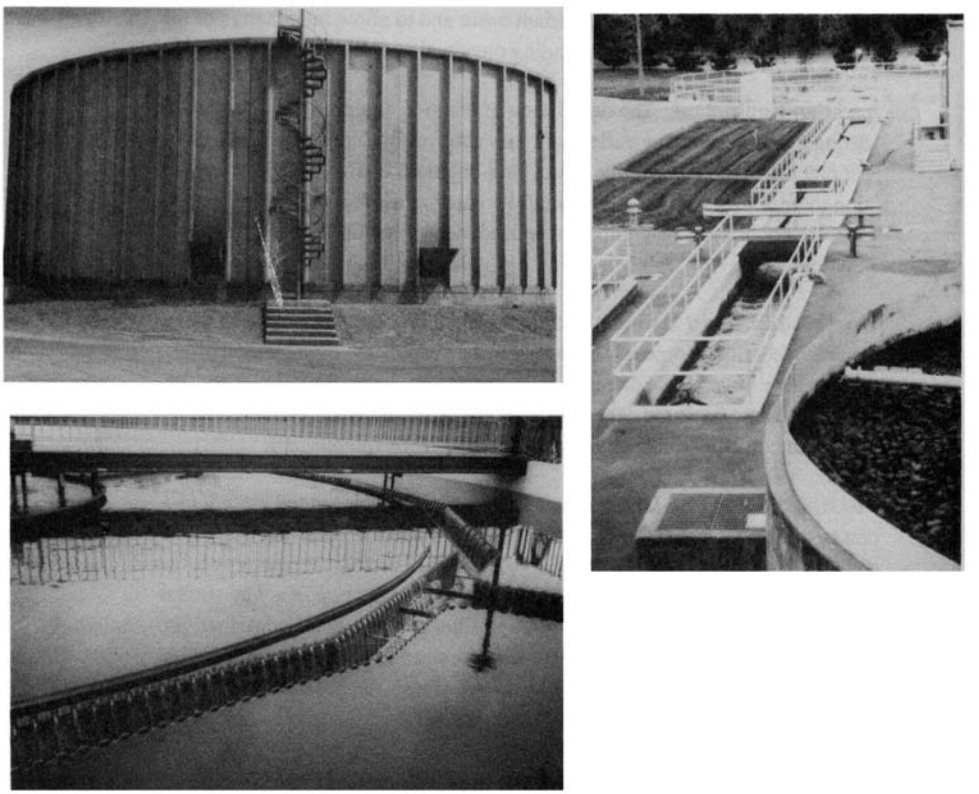


FIGURE 21.13 Combined system components: biotower (top), contact channel (bottom), and clarifier (right).

process, but its features are similar (see Chapter 20). Contact channels resemble aeration basins, except that most contact channels have a length-to-width ratio of approximately 5:1 for plug flow. Water depth is not as critical in a solids contact unit, because oxygen transfer is typically not limiting. Re-aeration basins are typically designed with sizes similar to those of the contact channel to provide a redundant basin and allow interchange of the contact and reaeration units, depending on actual operating needs.

Aeration Equipment. The description of aeration equipment in Chapter 20 adequately represents the variety of types used in combined processes. Current practices tend to favor the use of fine-bubble diffusion or low-energy aeration to minimize floc shear, es-

pecially preceding the secondary clarifier. A wide variety of aeration equipment is used, depending on the specific situation.

Clarifier. The final clarifier for combined processes is similar to that of the activated sludge process. Although some proponents of combined processes claim more stable or better settling sludge results, the consensus indicates no basis for departing from the types of clarification equipment used for a corresponding activated sludge plant (see Chapter 20).

PROCESS CONTROL. Combining fixed-film and suspended-growth processes greatly increases the operator's ability to make process-control changes. By varying the arrangement or number of biological reactors online, combined systems can often be broadly modified to operate similar to either an activated sludge process or a trickling filter. If the combined process has an unequal balance in treatment unit sizes (i.e., constructed with large trickling filters and small basins or vice versa), the possibility of making broad process changes is reduced.

Process Changes. Combined processes can often be designed or modified to operate in several modes (Figure 21.12). Often, only minor piping and valve position changes are required to provide the opportunity to make complete process mode changes. For example, combined plants are typically designed to operate in either the RF/AS or BF/AS modes. Likewise, an existing activated sludge plant upgraded with a roughing filter ahead of the aeration basin is often designed to operate as a BF/AS, RF/AS, TF/SC, or as only an activated sludge process.

Biotower. Process control for the biotower is similar to that already described in the Trickling Filters and Biotowers section of this chapter. However, operating a combined system allows operators to bypass or flow split, as necessary, a certain portion of the primary effluent direct to the downstream activated sludge or contact channel. Combined process modes also provide a mixed liquor that can be recycled over many types of filter media (except rock or high-density media), should the biofilter mode be needed to minimize filamentous growth or other problems.

Contact Channel or Aeration Basin. The three methods typically used to control the amount of mixed liquor in the suspended-growth basin or channel are constant mixed liquor, F:M ratio, and solids retention time (SRT). Calculations for these three parameters are presented in Chapter 20, and the Appendix contains sample calculations. However, the biomass associated with a trickling filter is not included in either the F:M ratio or SRT calculations (i.e., only the aeration basin solids are used to calculate the biomass). Also, the food (F) is based on the primary effluent (ignoring removal via the

trickling filter), because filter underflow entering the suspended-growth system contains sloughed solids similar to those of RAS returning to an aeration basin. The filter underflow food would impart an internal BOD load if included in the calculations. Some operators also find it helpful to determine the SBOD loading to the aeration basin as a control parameter.

Operators of activated sludge processes directly following trickling filters may experience swings in mixed liquor concentrations from sloughing. This may make tight control via the constant mixed-liquor method difficult. Some plants experience higher RAS concentrations from the final clarifiers following sloughing periods. In plants that waste sludge from the clarifier underflow (as opposed to the aeration basin), this will tend to return the mixed-liquor concentration to acceptable levels.

Typical SRT values for plants operating with activated sludge alone are typically not applicable to combined processes. As mentioned above, the portion of the residence time in the trickling filter is not accounted for in the SRT calculation. The SRTs for activated sludge can often be significantly lower than textbook values, when the process is proceeded by an attached growth process.

Clarification. Process control of the secondary clarifier for combined processes resembles that presented in Chapter 17 for activated sludge). Field experiences have shown that nitrification can be more difficult to control with combined processes than with either component process. To minimize the effects of denitrification, many operators maintain less than 0.2 m (0.5 ft) of sludge in the secondary clarifier and operate at relatively high RAS rates to prevent rising solids or other problems from denitrification.

The clarity or turbidity of combined process effluent is often less than that from either component process. This is especially true when the combined process is operated at relatively high loads. Changing process modes or increasing the SRT may be necessary to improve effluent clarity.

TROUBLESHOOTING. Combined systems historically have had fewer operating problems than either activated sludge or trickling filter processes. However, trouble-free operation demands good operator control and initial plant design. Table 21.12 presents a troubleshooting guide that, with Tables 21.3 and 21.7, will enable the operator to identify common problems and develop solutions. Steps must be taken to correct these problems, or plant efficiency and performance will be adversely affected.

PLANNED MAINTENANCE. In general, combined processes offer greater flexibility for maintenance of individual treatment units. These coupled processes tend to

TABLE 21.12 General troubleshooting guide for combined processes.

Problem	Effect/observation[a]
Uncontrolled sloughing	Large variations in MLSS concentration Poor effluent quality
Too many units on line	High energy use Inability to obtain good bacterial reduction without excessive chlorine use Rising sludge
Poor primary clarification	Plugging Standing water Odors Reduced efficiency Filter flies
Hydraulic overload	High effluent TSS
Nitrification	High effluent TSS High chlorine demand Low pH
Nutrient shortage	Filamentous bacteria Rising sludge Pass through of soluble BOD
Organic overload	Pass through of soluble BOD Odors Low DO Poor effluent quality
Snails	Snail cases settle in basins and transfer structures
Heavy industrial load	Shock organic loads Nutrient deficiency Low pH Sludge contamination Odor problems Corrosion problems
Cold weather	Loss in removal efficiency Icing problems Loss of nitrification
Organic underload	High energy use Nitrification

[a]MLSS = mixed liquor suspended solids; TSS = total suspended solids; BOD = biochemical oxygen demand; and DO = dissolved oxygen.

be more forgiving when a single treatment unit is removed from service, particularly during warm weather, when biological activity is higher. The maintenance of combined systems is similar to that of the component processes discussed in the Trickling Filters and Biotowers section of this chapter and in Chapter 20. These portions of the manual and Chapter 5 discuss safety considerations.

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Chapter 22

Biological Nutrient Removal Processes

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OVERVIEW OF BIOLOGICAL NUTRIENT REMOVAL

Treatment plants typically remove nutrients (e.g., nitrogen and phosphorus) from wastewater because of environmental, public health, or economic concerns. In the environment, nutrients stimulate the growth of algae in surface water. Researchers have found that 0.005 mg/L (5 μg/L) of soluble orthophosphate will limit algae growth (WEF, 2001). Other studies have shown that more than 0.05 mg/L of inorganic forms of nitrogen (ammonia-nitrogen and nitrate-nitrogen) may enhance algae growth.

Molecular or free (un-ionized) ammonia can be toxic to certain species of fish. More than 0.2 mg/L of un-ionized ammonia may cause acute toxicity, so it is often controlled via such factors as water pH, temperature, and ammonium ion concentration.

Public health concerns relate to drinking water that contains nitrogen. Regulators typically prefer that drinking water sources contain less than 10 mg/L of nitrate-nitrogen.

Nutrient removal may also reduce a treatment plant's overall operating costs. When aerobic biological treatment processes must nitrify wastewater, denitrifying the effluent (converting nitrate-nitrogen to atmospheric nitrogen) can recover lost oxygen and alkalinity, thereby saving aeration energy. Denitrification also can reduce or eliminate the need for chemicals to maintain an optimum pH for biological treatment. If phosphorus removal is required, biological phosphorus removal (BPR) may reduce chemical needs and eliminate the associated sludge. Finally, biological nutrient removal (BNR) may produce a sludge with better settling properties than the sludge produced via conventional treatment.

Several nutrient removal methods are available (Figure 22.1). One effective method is source control (e.g., reducing the phosphorus used in soap products, especially detergents). Some agencies have eliminated more than 50% of the phosphorus in raw wastewater via good source control. [For more information on source-control programs, see *Developing Source Control Programs for Commercial and Industrial Wastewater* (WEF, 1996).]

Natural systems (e.g., wetlands, overland flow, or facultative lagoons) may also be used to control nutrients. For more information on nutrient removal via natural or land-based systems, see *Natural Systems for Wastewater Treatment* (WEF, 2001).

Nutrients also can be controlled via chemical and biological processes. For more information on chemical–physical BNR systems, see *Biological and Chemical Systems for Nutrient Removal* (WEF, 1998a). For information on aerobic fixed-film processes [e.g., trickling filters and rotating biological contactors (RBCs)], see *Aerobic Fixed-Growth Reactors* (WEF, 2000).

This chapter focuses on suspended-growth BNR processes. Limited information on fixed-film nutrient removal processes is also presented. Most involve specialized

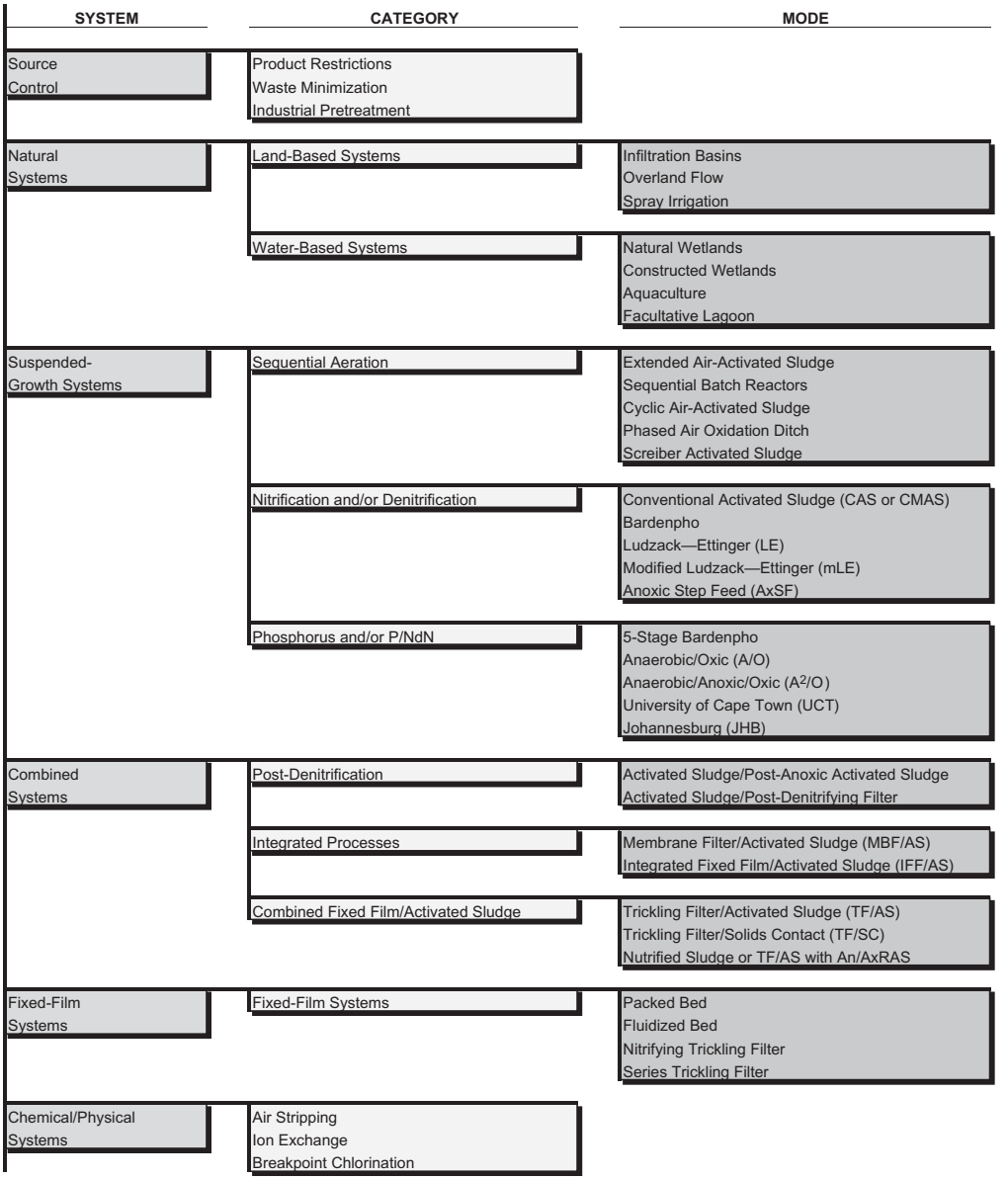


FIGURE 22.1 Nutrient removal alternatives.

reactors with zones, cells, or baffles designed to promote the growth of the bacteria that remove nutrients and the production of a good settling sludge.

Wastewater characteristics also affect both the ability to remove nutrients and the rate of removal (Table 22.1; WEF, 2005). For example, if the influent's inert (non-biodegradable), solids change, operators may need to lengthen the solids retention time (SRT) or mean cell residence time (MCRT) to maintain nitrification. If the wastewater has a high biochemical oxygen demand (BOD) but the oxygen use rate is low, then denitrifying or phosphorus-removing organisms may not be able to compete with other organisms in metabolizing organic material.

Both BNR and BPR depend on sufficient amounts of readily biodegradable organic substrate [chemical oxygen demand (COD) or BOD]. Wastewater treatment professionals have determined that 8.6 mg of COD is needed to remove 1 mg of nitrate-nitrogen from wastewater, but only 0.7 to 1.9 mg of a more readily biodegradable

TABLE 22.1 Biochemistry of BNR processes.

Biological Nitrogen Control Reactions	
1. Biochemical Nutrients Removed by	• 5.0 mg N removed per 100 mg BOD removed • 1 mg P per 100 mg BOD removed • For conventional aerobic process—2.3 mg P/100 mg TSS and 12.2 mg N/100 mg TSS • For biological phosphorous process—3 to 5 mg P/100 mg TSS
2. Biochemical Nitrogen Oxidation (Nitrification)	• 4.57 mg oxygen required per mg nitrogen oxidized • 7.14 mg $CaCO_3$ alkalinity depleted per mg nitrogen oxidized • 0.06 to 0.2 mg net volatile suspended solids formed per mg nitrogen oxidized

3. Biochemical Oxidized Nitrogen Removal (Denitrification)	• 2.86 mg oxygen released per mg oxidized nitrogen removed
	• Carbon source
	  • 1.91 mg methanol per mg oxidized nitrogen removed
	  • 0.7 mg methanol per mg dissolved oxygen removed
	  • 8.6 mg COD per mg oxidized nitrogen removed
	• 3.57 mg $CaCO_3$ alkalinity recovered (added to system) per mg oxidized nitrogen removed
	• 0.5 mg VSS per mg COD (or BOD_5) removed

4. Chlorine Demand due to Nitrite-Nitrogen (Associated with Incomplete Nitrification or Denitrification)	• 5 mg chlorine per mg nitrite-nitrogen, yielding nitrate-nitrogen

substrate (e.g., methanol) is needed. Experiments have indicated that 50 mg of COD is consumed per 1 mg of phosphorus removed from municipal wastewater (Randall, 1992).

Because of the need for sufficient biodegradable organic substrate, numerous treatment plants in cold climates (where BOD constituents break down slowly) enhance or condition wastewater by fermenting sludge or managing recycle streams to ferment byproducts (this is called *primary sludge fermentation*). Primary sludge fermentation typically is done on-site and may eliminate the need for methanol or other commercial, flammable substances. It probably will be unnecessary during warm weather, when natural fermentation in the collection system produces enough volatile fatty acid (VFA) for nutrient removal processes.

As you may have noted, many acronyms are used to describe nutrient-removal processes—so many, in fact, that BNR is often called "the alphabet soup" process (Table 22.2).

BIOLOGICAL SELECTORS. There are dozens of ways to modify or enhance conventional activated sludge or fixed-film systems to remove nutrients, improve sludge settling, and recover oxygen or alkalinity. Most methods used to enhance biological treatment involve specialized reactors or zones called *selectors*.

Growth Zones. Most wastewater treatment professionals are familiar with aerobic or oxic activated sludge processes [Figure 22.2(a)], in which biological growth is managed by controlling the oxygen concentration and recycling flows, such as return activated sludge (RAS) and mixed-liquor recycle (MLR), to the reactor [Figure 22.2(b)]. The wastewater's oxygen concentration is kept near or above 2.0 mg/L, because nitrification declines when dissolved oxygen concentrations drop below 0.5 mg/L. Also, the oxidation–reduction potential (ORP) is kept near or above +100 mV.

To create an anoxic zone, a baffle or partial wall is installed in the reactor, and the aerators in that area are shut off. Little dissolved oxygen is present (less than 0.5 mg/L) in this zone, but chemically bound oxygen (in nitrite and nitrate) may be present in RAS or MLR flow. Also, ORPs should be between −100 and −200 mV (for rapid denitrification).

Anaerobic zones contain neither dissolved oxygen nor chemically bound oxygen and have ORPs below −300 mV [Figure 22.2(c)]. They typically are created by sending MLR to denitrification selector cells rather than to the head of the anaerobic zone, which would increase chemically bound oxygen levels too much. Sometimes a supplemental source of carbon is necessary to ensure that dissolved and chemically bound oxygen are rapidly removed.

TABLE 22.2 Nutrient removal acronyms and terminology.

Acronyms and Terms	
μ_{max}	Maximum growth rate
2	Secondary
A/O	Anaerobic/oxic process
A^2/O	Anaerobic/anoxic/oxic process
An	Anaerobic
Ax	Anoxic
AxSF	Anoxic step feed
BioP	Biological phosphorus
BNR	Biological nutrient removal
BOD	Biochemical oxygen demand
BOD_{2INF}	Biochemical oxygen demand in the secondary influent
BPR	Biological phosphorus removal
CAS	Conventional activated sludge
CBOD	Carbonaceous BOD
CO_2	Carbon dioxide
COD	Biodegradable organic substrate
dN	Denitrification
DO	Dissolved oxygen
EBPR	Enhanced biological phosphorus removal
EFF	Effluent
F	Food expressed as mass of BOD/d
F/M	Food-to-microorganism ratio—with M as mass of TSS
F/M_V	Food-to-microorganism ratio—with M as mass of VSS
HLR	Hydraulic loading rate
HRT	Hydraulic residence time
IFAS	Integrated fixed-film activated sludge
INF	Influent
$iTSS_{2INF}$	Inert TSS in the secondary influent
JHB	Johannesburg process
LE	Ludzack–Ettinger
M	Mass of TSS in the aeration basin
MBR	Membrane bioreactor
MCRT	Mean cell residence time (sometimes referred to as SRT or solids retention time)

TABLE 22.2 Nutrient removal acronyms and terminology (*continued*).

	Acronyms and Terms
ML	Mixed liquor
mLE	Modified Ludzack–Ettinger
MLR	Mixed-liquor recycle, also called internal recycle
MLR_{Ax}	Mixed-liquor recycle from the anoxic zone
MLR_{Ox}	Mixed-liquor recycle from the oxic zone
MLSS	Mixed-liquor suspended solids
MLVSS	Mixed-liquor volatile suspended solids
Mr	Mixed-liquor recycle ratio
M_V	Mass of VSS in the aeration basin
N	Nitrogen or nitrification
N_2	Nitrogen gas
NH_4-N	Ammonia nitrogen
NO_2-N	Nitrite-nitrogen
NO_3-N	Nitrate-nitrogen
NO_X	Nitrite and nitrate
NO_{X2EFF}	Nitrate in the secondary effluent
O_2	Molecular oxygen
ON	Organic nitrogen
ORP	Oxidation–reduction potential
Ox	Oxic
P	Phosphorus or produced or particulate
P_{NO_x}	Produced nitrate
P_x	Produced solids
Q or Q_{INF}	Influent flow
Q_{RAS}	Return activated sludge flow
Q_{WAS}	Waste activated sludge flow
R or RAS	Return activated sludge
RBBOD	Readily biodegradable BOD
Rr	Return activated sludge ratio
SBOD	Soluble BOD
SBR	Sequencing batch reactor
SDNR	Specific dentrification rate
SLR	Solids loading rate
SP	Soluble phosphorus

TABLE 22.2 Nutrient-removal acronyms and terminology (*continued*).

Acronyms and Terms	
SRT	Solids retention time
SVI	Sludge volume index
TKN	Total Kjeldahl nitrogen
TOD	Total oxygen demand
TP	Total phosphorus
TSS	Total suspended solids
TSS_{2EFF}	Total suspended solids in the secondary effluent
TSS_{WAS}	Total suspended solids in the waste activated sludge
UCT	University of Cape Town process
V	Volume of reactor
VSS	Volatile suspended solids
WAS	Waste activated sludge
Xr	Anoxic recycle ratio
Y	Solids yield
Aerobic (oxic) process	Biological treatment that is done in the presence of elemental (O_2) oxygen.
Anaerobic process	Biological treatment that is done with no elemental or combined (NO_2 or NO_3) oxygen.
Anoxic process	Biological treatment that is done with no elemental oxygen but has combined (NO_2 or NO_3) oxygen present.
Attached-growth process	Biological treatment that is done with microorganisms attached or fixed to media such as rocks and plastic (also referred to as fixed-film processes).
Biological nutrient removal	The term applies to removing nutrients (usually nitrogen and phosphorus) by using microorganisms.
Biological phosphorus removal	The term applies to removing phosphorus by encouraging high-uptake of phosphorus by bacteria, followed by wasting the bacteria and the phosphorus contained in their biomass.
Carbonaceous BOD removal	Biological conversion of carbonaceous organic matter to cell tissue and various gaseous end products.
Combined process	Suspended-growth and fixed-growth processes that work in combination with each other.
Denitrification	The biological process by which nitrate is reduced to nitrogen gas.
Facultative processes	Biological processes that can function either with or without oxygen being present.

TABLE 22.2 Nutrient removal acronyms and terminology (*continued*).

	Acronyms and Terms
Fixed-film process	See "attached-growth processes".
nitrification	A two-step biological process in which ammonia is converted to nitrite (NO_2) and then (step-2) nitrite is biologically converted to nitrate (NO_3).
Readily biodegradable BOD	BOD that is rapidly degraded, often consisting of simple organic compounds or volatile fatty acids.
Soluble BOD	BOD on a filtered sample, usually where a sample is vacuumed through a 0.45-μm filter.
Suspended growth processes	A biological process in which the bacteria responsible for treatment are suspended within a liquid.
Substrate	The term used to denote organic matter or other nutrients used by bacteria during their growth.
Volatile fatty acids (VFA)	General term used to describe easily digestible organic compounds such as acetate and other anaerobic fermentation products.

Selector Size and Equipment. Updating a treatment plant for filament control, ammonia removal, denitrification, or BPR involves several changes (Figure 22.3). For example, converting from conventional wastewater treatment to BNR may involve changing gates, baffles, mixers, and recycle pumps; improving aeration equipment and foam control; and adding clarification, RAS pumping, and instrumentation and controls. Also, many BNR facilities operate at long MCRTs, so more aeration basin volume may be required to maintain the necessary residence time to sustain nitrifying bacteria.

The size and number of selector zones needed for BNR depends on wastewater characteristics, treatment goals, and other factors. Typically, 20 to 30% of the total basin volume will be dedicated to anoxic or anaerobic zones. Plants with stringent nutrient limits may dedicate as much as 50% of the total basin volume to anoxic or anaerobic zones. Bench or pilot testing may be needed to confirm selector sizing and design criteria. [For details on sizing selectors, see the "Integrated Biological Processes for Nutrient Control" chapter in *Design of Municipal Wastewater Treatment Plants* (WEF, 1998b) or the 4th edition of *Wastewater Engineering* (Metcalf and Eddy, Inc., 2003).]

The wastewater conveyance methods also may need to be changed. Wastewater is often conveyed via pumping or air-entraining devices (e.g., screw pumps, flow-

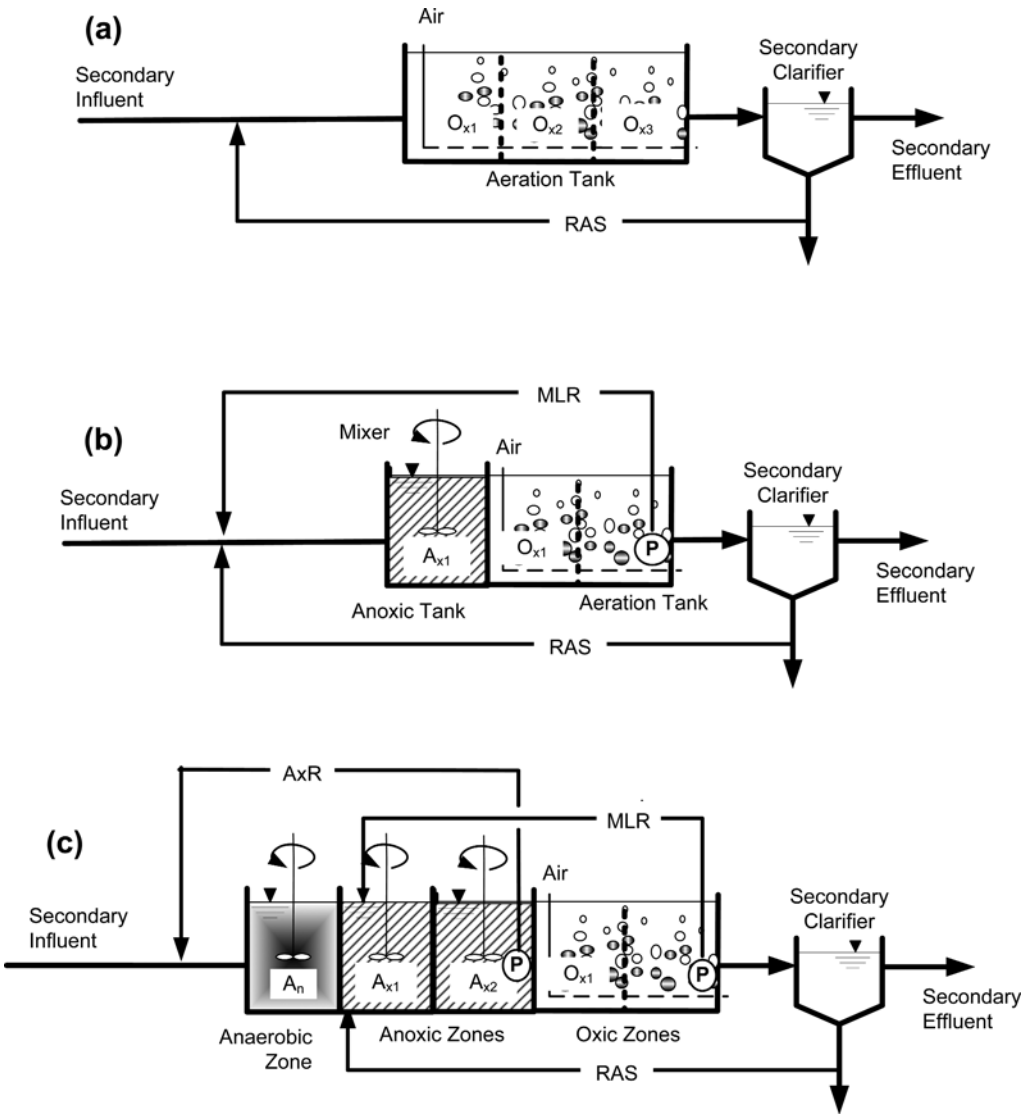
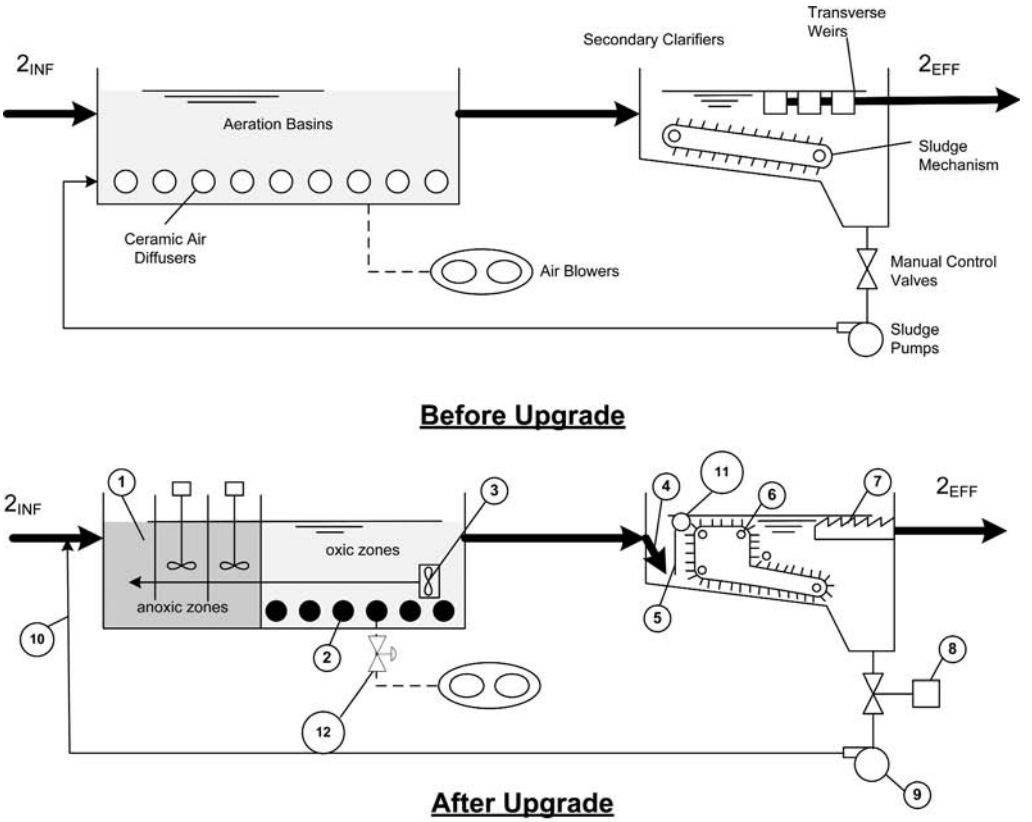


FIGURE 22.2 Selector growth zones.

splitting weirs, or launders), which inject air into the water. Entrained oxygen is detrimental to anoxic or anaerobic conditions, so air-entraining devices should be replaced with submerged weirs, gates, launders, or centrifugal pumps.

The water surface of a BNR reactor and a conventional activated sludge aeration basin look similar, but below the surface, the BNR reactor typically has a series of walls



Major Changes:

1. Anoxic zones with mixers to produce good settling sludge
2. New fine-bubble diffusers to increase aeration efficiency
3. Axial flow pumps for recycle and denitrification
4. Inlet diffuser to evenly distribute flow
5. Baffles to break up flow currents
6. Elevated scrapers to manage scum and foam
7. Longitudinal weirs to even overflow and reduce up-currents
8. Automatic-flow paced sludge drawdown valves
9. Increased sludge pumping
10. Relocate sludge discharge to primary effluent line for pre-RAS dN
11. New automatic scum skimmers
12. Airflow monitorying, distribution, and control system

FIGURE 22.3 Plant changes after BNR upgrade.

or partitions (called *baffles*) that define discrete treatment areas. Baffles are typically made of pressure-treated wood, fiberglass, reinforced concrete, or concrete block. They often include blockouts for piping, tank drainage, main plant flow-through, and maintenance access. The tops of some baffles are below the water surface, while others include overflow weirs that direct water from one zone to the next. Because they are elevated, overflow weirs can force foam into downstream aerated cells, rather than allowing back mixing to occur. During peak flows, however, this elevated water surface prevents the backflow of dissolved oxygen, which would allow readily biodegradable BOD to be consumed. This will interfere with denitrification or phosphorus removal by allowing the ORP to increase.

Numerous devices (e.g., diffused air, pontoon-mounted impellers, submersible impellers, and bridge-mounted turbine impellers) have been used to mix the contents of both anoxic and anaerobic selector zones. However, many wastewater treatment professionals think that diffused air introduces too much entrained oxygen for the zone to be truly anaerobic or anoxic. Some prefer the simplicity of pontoon-mounted impellers because the electrical motors are above the water surface, but most use submersible impellers. Submersible impellers are typically mounted on a vertical rod; they can be raised and lowered, and the horizontal angle can be adjusted for optimum mixing.

Denitrification is an integral part of most BNR systems. It typically involves recycling nitrified mixed liquor via low-head pumps to one of the anoxic cells. Low-head pumps (0.3 to 0.9 m of head) are used because the MLR typically is moved a short distance, needs little or no valving, and enters a wastewater surface only a few inches higher than the one it left. Mixed-liquor recycle pumps may include vertical turbine centrifugal, propeller pumps, or axial flow pumps.

Upgrading to a BNR process often requires a change in aeration equipment. However, more blowers may be unnecessary if the diffusers are very efficient or if the upgrade includes denitrification, which can recover about 63% of the molecular oxygen required to convert ammonia-nitrogen to nitrate-nitrogen. In a multiple-stage BNR process, the first oxic stages typically contain more fine-bubble diffusers because initial oxygen uptake rates are higher than in latter stages of treatment. Diffusers also are installed in the last anoxic zone, which typically is a swing cell. *Swing cells* are zones that have both mixers and diffusers so they can operate as either non-aerated or aerated reactors.

Biological nutrient removal processes may need a long MCRT to allow nitrification and denitrification to occur. However, long MCRTs typically lead to foam or filamentous bacteria problems. To control foam, treatment plants can spray the reactor surface with a chlorine wash or add a cationic polymer or foam suppressant. They also can

minimize sidestream recycling that may deposit foam-causing microorganisms or compounds in the reactor. In addition, treatment plant staff should eliminate any hydraulic traps that prevent foam from leaving the reactors. Some plants waste solids directly from the surface of the aeration basin to minimize foaming.

Many wastewater treatment plants originally were sized to remove carbonaceous BOD (CBOD) at 2 to 4 days of MCRT. To nitrify wastewater, the aeration basin may need to be operated at an MCRT that is two to three times longer. Operators can lengthen the MCRT by increasing the mixed-liquor suspended solids (MLSS) concentration. However, increasing the MLSS concentration or RAS flow will increase the solids load to the secondary clarifier, so when upgrading to BNR, both the secondary clarifier and RAS pumping capacity should be evaluated. [For more details on clarifier loading and design, see *Design of Municipal Wastewater Treatment Plants* (WEF, 1998b) and *Wastewater Engineering* (Metcalf and Eddy, Inc., 2003).]

Biological nutrient removal processes typically require more attention to the reactors' instrumentation and control system. Oxygen control can be automated or manual, depending on process needs and plant size. Dissolved oxygen probes in the aerated zones can be used to determine whether these areas have enough oxygen. On the other hand, systems with MLR pumping should reduce or eliminate aeration near the MLR pump suction point to minimize the amount of dissolved oxygen sent to anaerobic or anoxic cells. Oxidation–reduction potential probes can be used to determine the effectiveness of non-oxygenated cells. Other controls can be used to keep the RAS and MLR flows proportional to the influent flow rate.

YARDSTICKS FOR MEASURING BIOLOGICAL NUTRIENT REMOVAL.

The growth of nutrient-removing organisms is affected by many factors. Comparing the growth needs of autotrophic organisms, which nitrify wastewater, with those of heterotrophic bacteria, which oxidize CBOD, can help treatment plant staff better control both processes.

Mean Cell Residence Time. Mean cell residence time (also called *sludge age* or SRT) is the most commonly used parameter when operating a conventional activated sludge system. It measures the average length of time (in days) that microorganisms (sludge) are held in the system, and is calculated as follows:

$$\text{MCRT} = \frac{\text{Mass of MLSS in the aeration basin}}{\text{Mass of total suspended solids (TSS) wasted from the system per day}} \quad (22.1)$$

$$\text{MCRT} = \frac{\text{g MLSS in the aeration basin}}{\text{g/d TSS}_{\text{2EFF}} + \text{g/d TSS}_{\text{WAS}}} \tag{22.2}$$

If the MCRT is too short, then the biological system will not have enough bacteria to degrade the pollutants, resulting in poor effluent quality (Figure 22.4). The mean cell retention time required depends on the wastewater constituent and the growth rate of the microorganisms consuming it. For example, a simple carbon compound (e.g., acetate) is metabolized by fast-growing heterotrophic organisms; it requires an MCRT of less than 1 day to be synthesized. Conversely, ammonia is oxidized by slow-growing bacteria, so its MCRT is much longer. Many treatment plants that remove CBOD from wastewater may have been designed for 2 to 4 days of MCRT, but to remove ammonia, the MCRT may need to be twice as long, depending on temperature and other factors. If the basin size and MLSS are constant, then the MCRT will shorten as the sludge wasting rate increases and lengthen as the wasting rate decreases.

Calculating MCRT for BNR systems is different because the aeration basin may include anaerobic or anoxic selectors. For example, a sequencing batch reactor (SBR) may not be aerated 35 to 45% of the time. So, process control should include calculating both

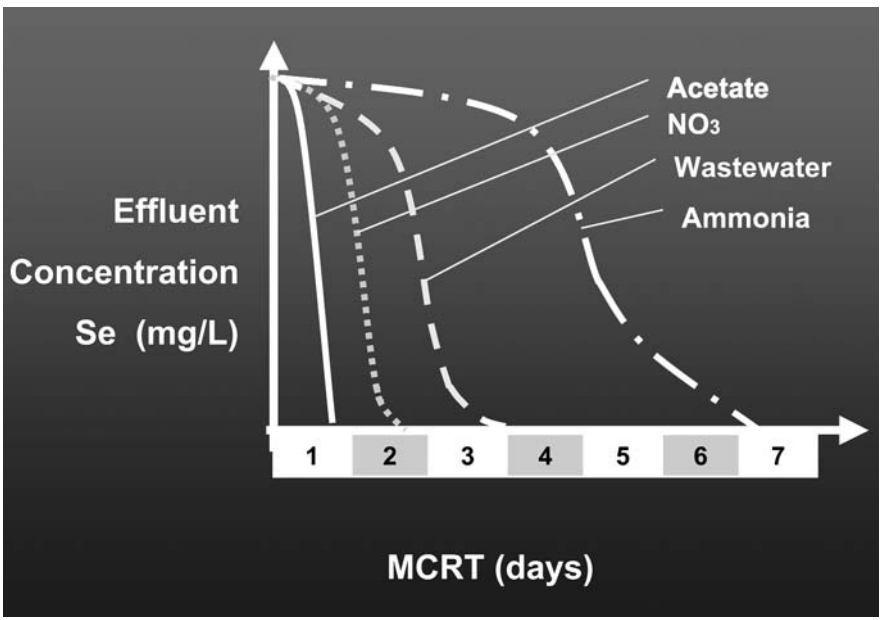


FIGURE 22.4 Effect of MCRT on pollutant removal.

the "aerobic" MCRT (for the aerated portion of the reactor) and the total "system" MCRT. The anaerobic or anoxic selector zones will require separate MCRT calculations. In BPR systems, experts recommend a 1-day anaerobic MCRT for proper growth of *Acinetobacter* organisms (Metcalf and Eddy, Inc., 2003). If the anaerobic contact is too long, the *Acinetobacter* organisms will release their stored phosphorus and take up carbon (this is called *secondary phosphorus release*).

Food-to-Microorganism Ratio. The food-to-microorganism (F:M) ratio measures the amount of food (BOD) available for the amount of mixed-liquor volatile suspended solids (MLVSS) present in the aeration basin:

$$\text{F:M} = \frac{\text{g/d of BOD in secondary influent}}{\text{g MLVSS in the aeration tank}} \tag{22.3}$$

If the treatment plant has primary clarifiers, then *F* is typically based on primary effluent. If not, then *F* is based on the raw wastewater's BOD load. The *M* for a conventional activated sludge system is typically based on the entire aeration basin's MLVSS. Most conventional activated sludge systems are designed for F:M ratios ranging from 0.2 to 0.4 (WEF, 1998a). In BNR systems with several cells (Figure 22.5), the selector may be configured to encourage the growth of nonfilamentous (floc-forming) organisms. Or the selector may be configured to encourage the growth of *Acinetobacter* organisms to increase the denitrification rate. In either case, the F:M ratio of each selector zone is important. When calculating the F:M ratio for a BNR system, *F* is based on the secondary influent BOD. If the reactors are operated in series, then the first cell's *M* is based on its volume and MLVSS concentration. The second cell's *M* is based on the combined volume of the first and second cells, and so on.

One recommendation (Albertson, 1987) is that BNR systems have at least three cells to create a high substrate concentration in the initial minutes of contact (Figure 22.5). Food-to-microorganism ratios of 6.0, 3.0, and 1.5 mg/d of BOD per 1.0 mg of MLVSS for the first, second, and third cells, respectively, have been recommended for a plug-flow reactor. However, if the F:M ratio is too high (more than 8.0 mg/d of BOD per 1.0 mg of MLVSS), then a viscous, nonfilamentous organism could dominate the reactor (this is called *slime bulking*).

Wastewater Characteristics. Today, wastewater treatment plants typically are designed based on complicated models that use a perplexing array of wastewater characteristics. In fact, one text lists nearly 40 wastewater constituents as "important" when designing wastewater treatment facilities (Metcalf and Eddy, Inc., 2003). Fortunately, operators of BNR facilities only need a fundamental understanding of the relationship between wastewater characteristics and plant operations to optimize plant performance.

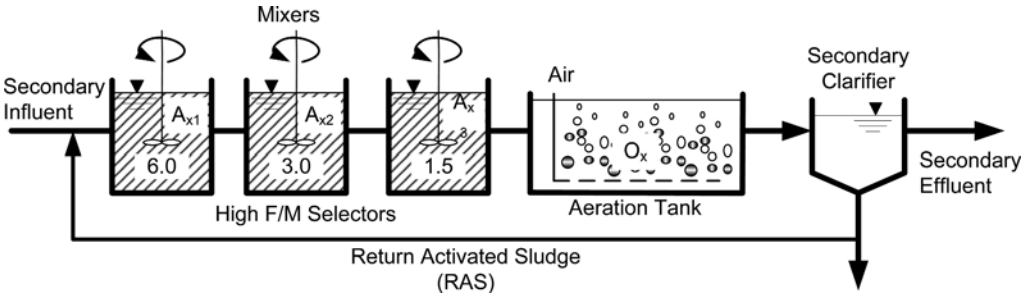


FIGURE 22.5 Selectors for controlling filamentous bacteria.

One of the key characteristics is the amount of inert TSS in biological treatment influent ($iTSS_{2INF}$). A high concentration of inert TSS will increase the percentage of nonbiodegradable solids in the MLSS, so a longer MCRT will be needed to treat the wastewater sufficiently. To calculate $iTSS_{2INF}$,

$$iTSS_{2INF} = TSS_{2INF} - VSS_{2INF} \tag{22.4}$$

Where

TSS_{2INF} = total suspended solids in secondary influent, and
VSS_{2INF} = volatile suspended solids (VSS) in secondary influent.

Operators also should better understand BOD's constituents. The soluble BOD measurement, for example, will indicate how much material is readily biodegradable. Soluble BOD typically is measured based on a 5-day BOD test in which wastewater is passed through a 0.45-μm filter. A 1-day BOD test will provide an estimate of readily biodegradable BOD—including the simple carbon compounds that are available for rapid bioassimilation.

Operators can learn other valuable information by assessing the influent BOD and waste activated sludge (WAS). In a conventional activated sludge system, for example, 5 mg of nitrogen and 1 mg of phosphorus will typically be used for every 100 mg of BOD removed. In a BPR process, 3 to 5 mg of phosphorus may be used for every 100 mg of BOD removed. If the BPR process is operated to remove total phosphorus, then a secondary-influent-BOD-to-total-phosphorus ratio of 20:1 or more may be needed to ensure that the treated effluent will contain less then 1.0 mg/L of phosphorus.

The required BOD-to-total-phosphorus ratio depends on process type and effluent goals. Processes that do not nitrify *and* denitrify [e.g., the anaerobic/oxic (A/O) process]

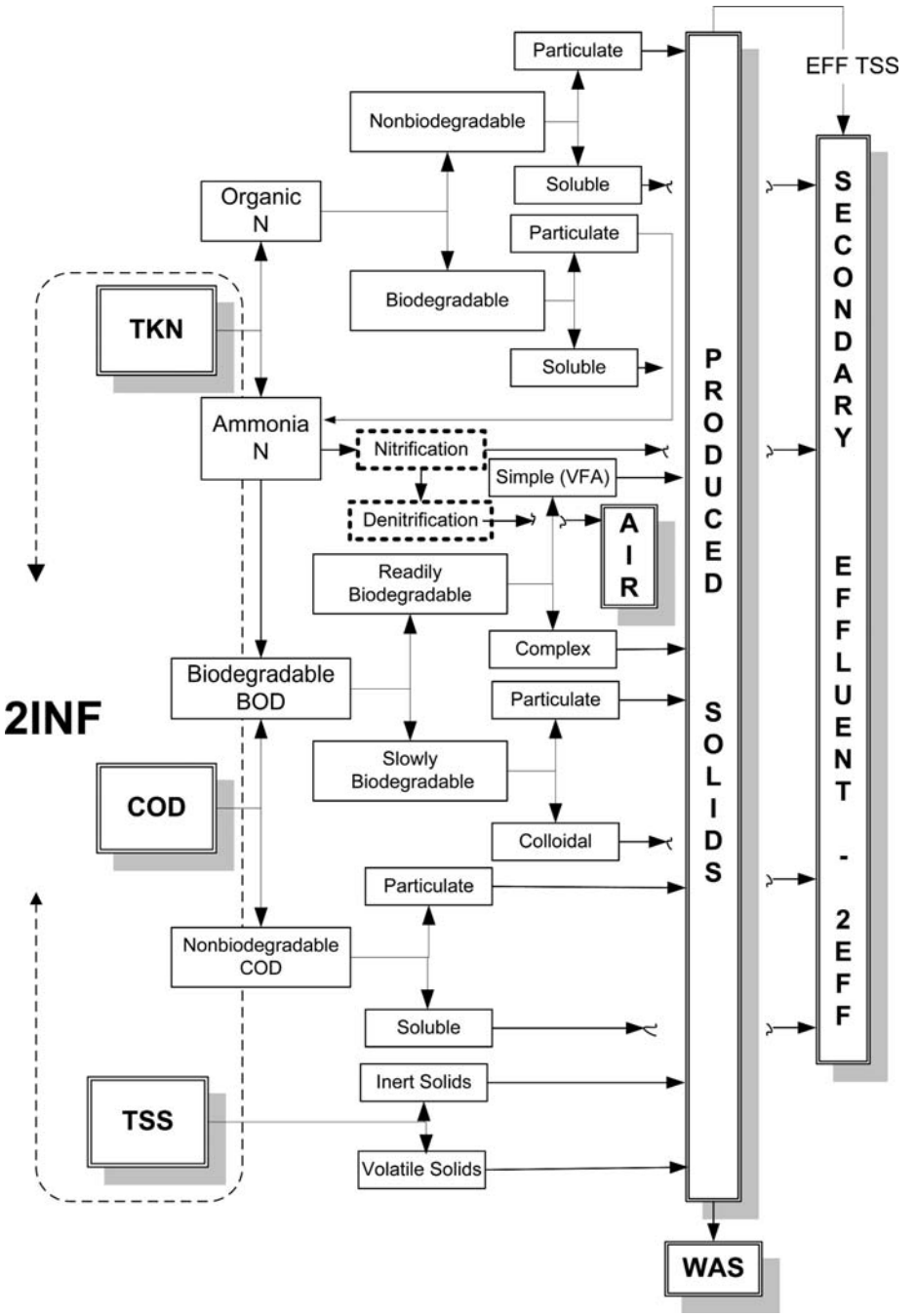


FIGURE 22.6 Interaction of nutrients.

may require a BOD-to-total-phosphorus ratio of 15:1, while those with full nitrification and denitrification may require a BOD-to-total-phosphorus ratio of 25:1 or more.

Aeration Requirements. Aeration systems designed for CBOD removal may need to be enlarged by 30 to 50% to provide enough oxygen to nitrify ammonia. Some plants accommodate the increased demand by replacing air diffusers with fine-bubble systems or other more efficient aerators. Some incorporate denitrification (the reduction of nitrate-nitrogen to nitrogen gas) into the BNR process because denitrification can theoretically reclaim 63% of the oxygen needed for nitrification. However, because denitrification typically only reduces about half of the nitrate-nitrogen in the wastewater (denitrification effluent typically contains 6 to 8 mg/L of nitrate-nitrogen), the actual amount of oxygen reclaimed may be closer to 30 to 40%.

Sludge Settleability and Foam. Many BNR facilities operate at a high MCRTs (more than 8 days) to fully nitrify and allow for denitrification. As a result, the facilities frequently have sludge-settleability or foam problems. Wastewater constituents (e.g., soap, oil, and grease) and streams recycled from solids handling processes can exacerbate these problems. If so, the facility may need spray nozzles to spread antifoaming chemicals.

Before RAS flows are raised to increase the basin MLSS concentration, plant staff should evaluate the solids loading ($g/m^2 \cdot d$) on the secondary clarifiers to determine if the capacity is adequate. Larger RAS pumps may be needed to obtain the higher MLSS concentration often desired in a BNR system.

Return Flows. Conventional activated sludge systems typically have only one return flow: RAS. Biological nutrient removal processes, on the other hand, may have more return flows (e.g., MLR). The return activated sludge pumping rates are typically 30 to 100% of the influent flow (Q). The MLR pumping rates may be 100 to 400% of the influent flow, depending on such factors as the target effluent nitrate concentration. They also may be transferred from an aerobic or oxic zone (MLR_{OX}) or from an anoxic zone (MLR_{AX}). The source of the MLR—and which zone receives it—often distinguishes one BNR process from another.

Alkalinity and pH. Biological nutrient removal systems also may need pH control or added chemicals (e.g., hydrated lime, soda ash, or caustic soda) to supplement the available alkalinity. Because alkalinity is consumed during nitrification, the chemicals can help maintain the minimum alkalinity level needed (typically, 60 to 100 mg/L of alkalinity as calcium carbonate). Low alkalinity not only lowers pH but may limit the growth of nitrifying organisms because they lack enough inorganic carbon to produce new cells.

Hydraulic Retention Time. The hydraulic retention time (HRT) required to maintain BNR depends on the size of the reactor, which in turn depends on the MCRT necessary for growth. Once the reactor size is known, then the HRT can be found by dividing the volume of the reactor (V) by the secondary influent flow (Q_{2INF}):

$$\underset{\text{(hours)}}{\text{Nominal HRT}} = \frac{V\ (m^3) \times 24\ hr/d}{Q_{2INF}\ (m^3/d)} \tag{22.5}$$

The result is a nominal value used to relate basin size to plant flow. The nominal value is typically used because internal recycle streams do not affect most of the reactions that are important to plant operators. For some parameters, however, the actual HRT may be affected by recycle streams, in which case, recycle flows (i.e., RAS and MLR) should be added to the denominator in Equation 22.5.

BIOLOGICAL NITROGEN REMOVAL PROCESSES

During secondary treatment, nitrogen's ultimate fate depends on the carbon compounds (measured as BOD and COD) involved, the type of sludge (measured as TSS and VSS) involved, and the oxidation methods used (Figure 22.4).

When nitrogen [total Kjeldahl nitrogen (TKN)] enters the wastewater treatment plant, it is composed of both organic nitrogen and ammonia-nitrogen. Domestic wastewater typically contains 40 mg/L of TKN, which consists of 25 mg/L of ammonia-nitrogen and 15 mg/L of organic nitrogen. Biological treatment of ammonia-nitrogen involves either incorporating it to the biological cells (MLVSS) or oxidizing it to nitrate (Figure 22.7). If incorporated to biological cells, then ammonia and the organic nitrogen are discharged with the WAS. If oxidized to nitrate, then the oxidized ammonia (nitrate) may be converted to nitrogen gas via denitrification and emitted to the atmosphere.

Wastewater characteristics can affect nutrient behavior. For example, if about 20% of the organic nitrogen (15 mg/L) hydrolyzes to become ammonia, then the total ammonia-nitrogen available for cell synthesis is:

$$(15\ mg/L)(0.2) + 25\ mg/L = 3.0\ mg/L + 25\ mg/L = 28\ mg/L \tag{22.6}$$

Typical effluent from the primary treatment process contains 160 mg/L of BOD. During secondary treatment, the equivalent of about 80 mg/L of biological VSS is produced (0.5 mg VSS/mg BOD). Ammonia is consumed during the production of VSS, as are 8 mg/L of nitrogen [(80 mg/L)(10/100)] and 1.6 mg/L of phosphorus [(80 mg/L)(2/100)]. The resulting biological sludge contains approximately 10% nitrogen and 2% phosphorus.

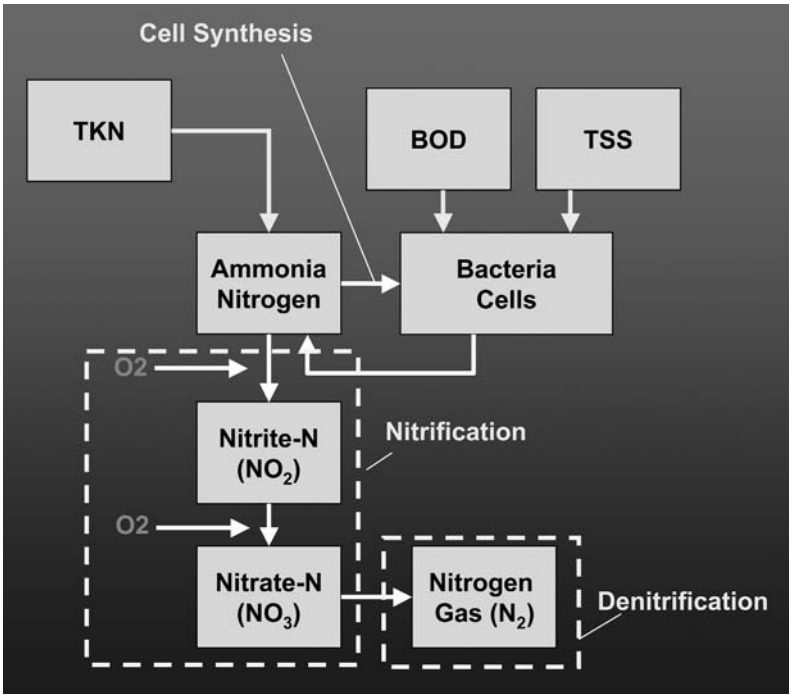


FIGURE 22.7 Nitrogen removal in wastewater treatment systems.

Treatment plant staff also should keep the following in mind:

- For a total nitrogen balance, staff should account for TKN;
- Because biological sludge consumes nitrogen, not all of the influent ammonia-nitrogen will need to nitrified. However, because organic nitrogen hydrolyzes, some more ammonia will become available.
- Changes in the influent BOD-to-nitrogen ratio will change the amount of ammonia requiring oxidation. As BOD increases, so will produced biosolids. An increase in biosolids production translates into more ammonia uptake for cell growth and less ammonia to nitrify.

If the wastewater characteristics are not "typical", then treatment plant staff will have to adjust the target MCRT, F:M ratio, or other criteria.

The difference between conventional activated sludge and BNR systems is that a conventional activated sludge system only removes nitrogen via sludge wasting. A biological nutrient removal facility can remove nitrogen via sludge wasting and a combined

biological reaction to oxidize the remaining ammonia (nitrification) and reduce oxidized nitrogen (denitrification). If the treatment plant only has an ammonia limit, it may only nitrify the wastewater. If the plant has both ammonia and oxidized nitrate limits, then it will need to both nitrify and denitrify the wastewater.

NITRIFICATION. *Nitrification* is the biological conversion of ammonia-nitrogen to nitrate-nitrogen.

Biochemistry. Nitrification is done by *autotrophic microorganisms*—organisms that use inorganic materials as a source of nutrients and photosynthesis or chemosynthesis as a source of energy. They oxidize ammonia-nitrogen and reduce carbon dioxide to produce new biomass, typically requiring 6 to 9 days of MCRT to produce up to 0.2 mg of VSS per 1.0 mg of ammonia removed.

The first step in nitrification is oxidizing ammonia-nitrogen to nitrite-nitrogen via *Nitrosomonas* bacteria. Then *Nitrobacter* bacteria oxidize nitrite-nitrogen to nitrate-nitrogen. The following equations illustrate the nitrification process:

$$2NH_4^+\text{-}N + 3O_2 \xrightarrow{\text{Nitrosomonas}} 2NO_2^- + 2H_2O + 4H^+ \quad (22.7)$$

$$2NO_2^- + O_2 \xrightarrow{\text{Nitrobacter}} 2\ NO_3^-\text{-}N \quad (22.8)$$

$$NH_4^+\text{-}N + 2O_2 \xrightarrow{\text{Nitrifiers}} NO_3^-\text{-}N + 2H^+ + H_2O \quad (22.9)$$

Nitrification is typically a complete reaction—meaning that the result is predominantly nitrate (little or no nitrite). However, treatment plants that nitrify seasonally may find that nitrite will accumulate until the slow-growing *Nitrobacter* becomes an established population. The nitrite buildup may lead to *nitrite lock*—excessive chlorine demand by incompletely oxidized nitrite (5 mg of chlorine per 1 mg of nitrite-nitrogen, Table 22.1).

Effective nitrification depends on sufficient oxygen and alkalinity (to maintain a suitable wastewater pH). *Nitrosomonas* and *Nitrobacter* require 4.57 mg of oxygen and 7.14 mg of alkalinity (as calcium carbonate) for each 1.0 mg of nitrate-nitrogen formed. They yield about 0.06 to 0.20 mg of VSS for each 1.0 mg of nitrate-nitrogen formed.

Influences. Autotrophic bacteria typically grow two to three times more slowly than heterotrophic bacteria, which are the predominant organisms in a biological treatment

system. Understanding the relationship between the bacteria's "growth rate" and MCRT (sludge age) can help treatment plant staff determine whether and how temperature, dissolved oxygen, and other factors affect biological treatment. The *biomass growth rate* (μ) is calculated as follows:

$$\mu = \frac{\text{amount of bacteria grown per day}}{\text{amount of bacteria present}} \tag{22.10}$$

The *maximum growth rate* (μ_{max}) for nitrifying bacteria at 20 °C is typically between 0.14 and 0.23 kg/d (0.3 and 0.5 lb/d). To put this in terms more familiar to plant staff, for a treatment system in equilibrium:

$$\mu = \frac{P_x}{MLSS_x} = \frac{TSS_{2EFF} + TSS_{WAS}}{MLSS_x} \tag{22.11}$$

Where

P_x = the amount of sludge produced per day (sludge wasted in the secondary effluent and planned WAS), and
$MLSS_x$ = amount of TSS in the aeration basin.

In other words, μ is the inverse of MCRT, which is used for process control:

$$MCRT = \frac{MLSS_X}{TSS_{2EFF} + TSS_{WAS}} \tag{22.12}$$

The minimum MCRT is the inverse of the maximum growth rate:

$$MCRT_{MIN} = \frac{1}{\mu_{MAX}} \tag{22.13}$$

Nitrification depends on the ammonia-nitrogen concentration, the dissolved oxygen concentration, and the wastewater temperature (Figure 22.8). Standard conditions used to describe the rate of removal are 20 °C, 2 mg/L of dissolved oxygen, and 10 mg/L of ammonia-nitrogen. If dissolved oxygen or ammonia concentrations drop, then nitrifier growth will slow down. If the conditions are not toxic, then lowering temperature below the standard will probably will have the most significant effect on reducing nitrifier growth rate.

Most wastewater treatment plants are designed based on the maximum growth rates at a given range of operating temperatures. When designing a plant, engineers are encouraged to use an MCRT that is 1.5 to 2.0 times greater than the MCRT theoretically

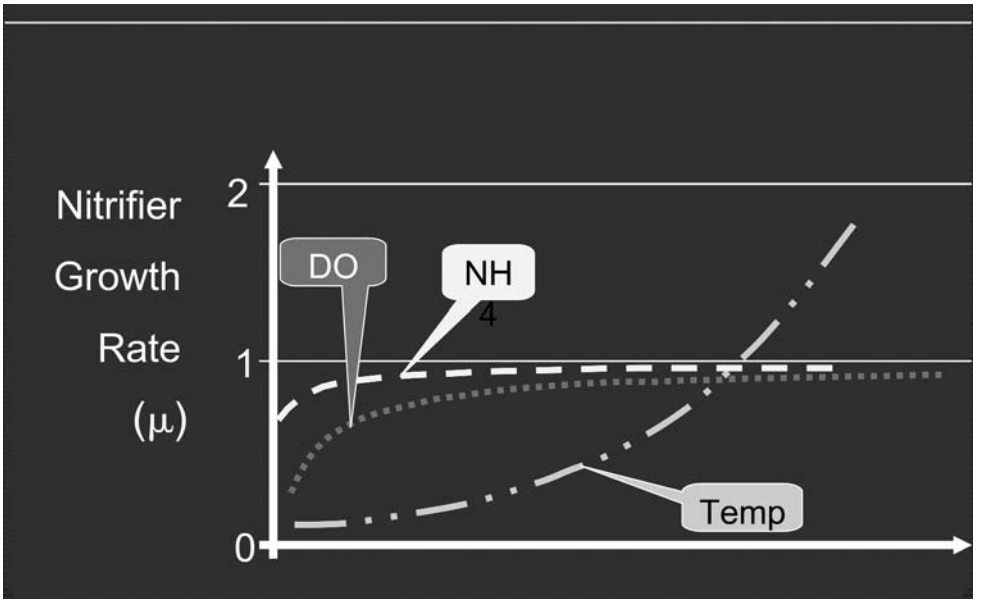


FIGURE 22.8 Key factors that affect nitrification.

needed for nitrification (Figure 22.9). For example, the calculated MCRT (using μ_{max}) may be 10 days at 10 °C, but a design engineer would probably make the aeration basin large enough to operate at a 15-day MCRT (factor of safety = 1.5) or a 20-day MCRT (factor of safety = 2.0). So, operators may find that the process nitrifies reliably at a shorter MCRT. (The actual "best" MCRT is plant-specific because of the number of variables involved.)

Nitrification is also affected by pH. The optimum pH is typically about 7.5. As the pH drops, so do the nitrifiers' growth rate and activity. Nitrification may be inhibited when the pH is less than 6.5, but some information sources have indicated that nitrifiers can acclimate to low pH.

Some metal, organic, and inorganic compounds can inhibit the growth of autotrophic bacteria. If plant personnel suspect that toxics are inhibiting bacteria growth, they should conduct a bench-scale test assessing the nitrification rate. Such tests can be conducted onsite, or samples may be sent to a contract laboratory for testing.

DENITRIFICATION. In denitrification, bacteria reduce nitrate to nitrogen gas (Figure 22.6). Nitrogen gas is not very water-soluble, so it is released into the atmosphere. The

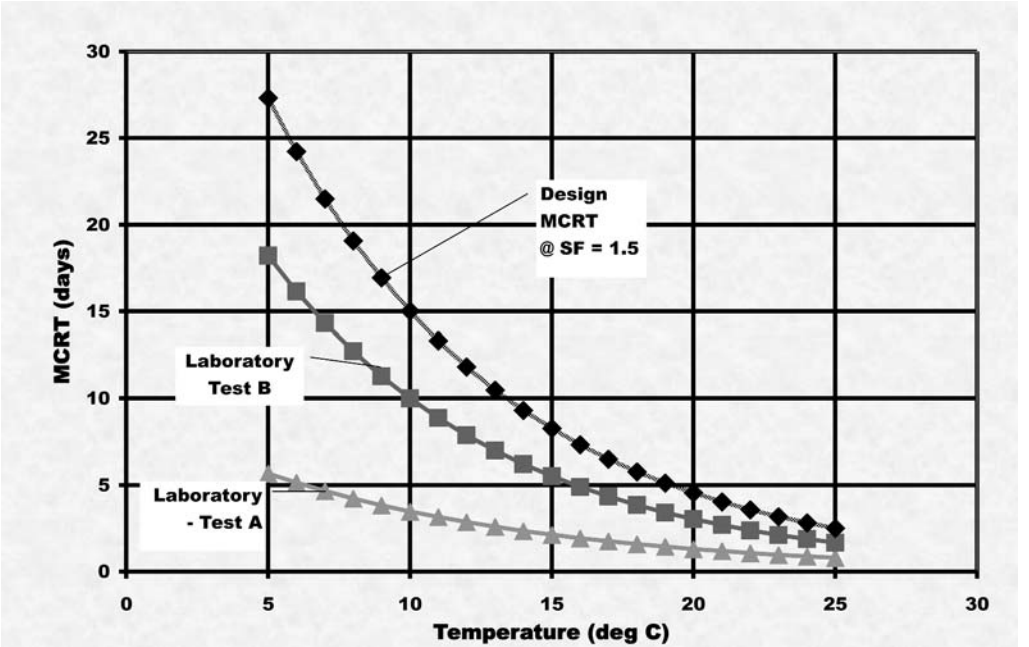


FIGURE 22.9 Design MCRT for nitrification.

atmosphere naturally consists of more than 70% nitrogen, so the emissions do not harm the environment.

Biochemistry. Denitrification is done by *heterotrophic microorganisms*—organisms that use organic materials as a source of nutrients and metabolic synthesis as a source of energy. Heterotrophic organisms spend less energy on synthesis than autotrophic organisms do, so they grow more quickly and yield more cell mass. They typically require 2 to 4 days of MCRT to produce 0.5 mg of VSS per 1.0 mg of BOD removed.

Numerous heterotrophic bacteria can denitrify wastewater. *Denitrifiers*—the bacteria that reduce nitrate—are "facultative" bacteria, meaning they can function in both oxic and anoxic environments. Denitrifiers prefer to use molecular oxygen, but if the environment contains less than 0.3 to 0.5 mg/L of dissolved oxygen, they will cleave the oxygen from nitrate-nitrogen molecules to synthesize carbon compounds (e.g., BOD) (Daigger et al., 1988):

$$NO_3^-\text{-N} + \text{carbon source} + \text{facultative bacteria} = N_2 + CO_2 + H_2O + OH^- + \text{new bacterial cells} \quad (22.14)$$

The biochemical reactions associated with denitrification are key factors in operating wastewater treatment plants (Table 22.1). For example, reducing nitrate-nitrogen eliminates some of the BOD demand, so the anoxic reactors help remove CBOD. If CBOD is the only treatment consideration, then MCRT and F:M ratio calculations could include the biomass in the denitrification process.

Theoretically, 2.86 mg of oxygen is recovered for every 1.0 mg of nitrate-nitrogen reduced to nitrogen gas. This is more than 60% of the oxygen needed for nitrification, so this recovered oxygen could be used to greatly reduce the amount of aeration equipment needed in other areas of the treatment plant.

Denitrification also results in new bacterial cells. The cell yield depends on the carbon source. For example, if methanol is the carbon source, then the cell yield is about 0.5 mg VSS per 1.0 mg of nitrate-nitrogen removed. If BOD is the source, then the cell yield is about 1.5 mg VSS per 1.0 mg of nitrate-nitrogen removed.

In addition, about 3.57 mg of alkalinity (as calcium carbonate) is produced for each 1.0 mg of nitrate-nitrogen removed. So, about 50% of the alkalinity lost during nitrification can be recovered during denitrification.

Influences. Denitrifiers are less sensitive than nitrifiers, so if the treatment plant environment does not inhibit the nitrifiers, then the denitrifiers should have no problem functioning at optimal growth rates.

The rate at which denitrifiers remove nitrate is the *specific denitrification rate* (SDNR):

$$\text{SDNR} = \frac{\text{kg } NO_3\text{-N removed per day}}{\text{kg VSS}} \tag{22.15}$$

This rate varies, primarily depending on the type of carbon source and amount of carbon available (as measured by the F:M ratio).

Nitrification and dentirification can occur in one treatment unit [this is called *simultaneous nitrification/denitrification* (SNDN)], or denitrification may occur separately in either post- or pre-anoxic reactors. In the 1970s, BNR and denitrification typically were done via post-anoxic reactors [Figure 22.10(a)] (Stensel, 2001). Methanol was the carbon source for denitrification (methanol's SDNR ranges from 0.1 to 0.3 mg NO_3-N/d·mg VSS). A relatively small post-aeration reactor followed the denitrification process to oxidize any remaining organics.

In the 1980s, many wastewater treatment plants were upgraded with selectors for controlling filamentous organisms [Figure 22.10(b)]. Those that nitrified their wastewater found that the anoxic zone was denitrifying RAS as well as controlling filaments. Because methanol is expensive and a hazardous material, most plants took advantage

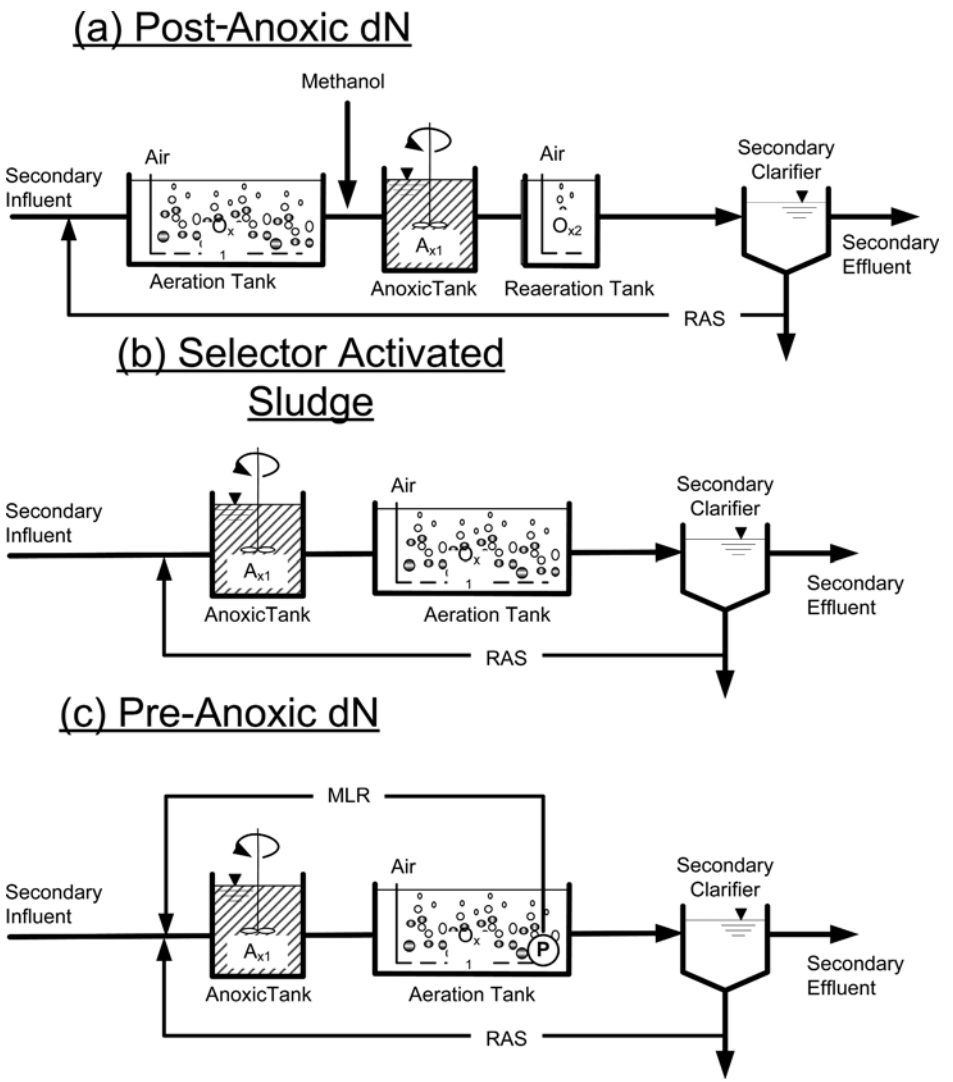


FIGURE 22.10 Selectors for denitrification.

of this lesson. They added an MLR system and used a pre-anoxic selector for denitrification [Figure 22.10(c)]. In this selector, either raw wastewater or primary effluent is used as the carbon source for denitrification (wastewater's SDNR typically ranges from 0.03 to 0.12 mg NO_3-N/d·mg VSS).

Overall, the denitrification rate drops as wastewater passes through various anoxic cells because less readily biodegradable BOD is available in downstream anoxic zones than

in upstream ones. When the denitrification process depends on endogenous respiration for nitrate reduction (i.e., has no external source of carbon), its SDNR ranges from 0.005 to 0.03 mg NO_3-N/d·mg VSS (U.S. EPA, 1993). Such rates may apply when denitrification occurs after a trickling filter or in a post-anoxic reactor without an added carbon source.

Temperature and pH also influence denitrification rates, but the most important parameter is molecular oxygen. Treatment plant staff should minimize the concentration of molecular oxygen in the wastewater. Selector cells should be sized to promote high F:M ratios, and MLR may need to be introduced in the second or third cell to avoid oxygen overload.

There is a practical limit to denitrification. Nitrate removal is a function of the nitrate produced in both the aerobic zone (P_{NO_x}) and in secondary effluent (NO_{X2EFF}). Increasing the MLR to lower the NO_X is subject to the law of diminishing returns. The mass of produced nitrate must equal the mass of effluent nitrate associated with the plant's effluent flow (Q), MLR, and RAS flow (Equation 22.15):

$$(Q)(P_{NO_x}) = NO_{X2EFF}(Q + MLR + RAS) \tag{22.16}$$

$$P_{NO_x} = \frac{NO_{X2EFF}\,(Q + MLR + RAS)}{Q} \tag{22.17}$$

$$P_{NO_x} = NO_{X2EFF}(1 + Mr + Rr) \tag{22.18}$$

Where

Mr = MLR/Q and
Rr = RAS/Q.

$$Mr = \frac{P_{NO_x}}{NO_{X2EFF}} - 1.0 - Rr \tag{22.19}$$

So, given the treatment plant illustrated in Figure 22.11, an Rr of 0.5, and 25 mg/L of produced nitrate, an Mr of 1.0 (MLR = Q) will result in an effluent nitrate concentration of about 11 mg/L. If the effluent nitrate limit is 5 mg/L, then Mr will need to be 3.5 (i.e., 350% of the treatment plant's influent flow) to achieve this limit. When effluent nitrate limits are less then 5 mg/L, a post-anoxic selector may be necessary to achieve the limit without having a Mr that is excessively large.

COMMON NITROGEN REMOVAL PROCESSES. Optimal operating parameters for nitrogen removal processes are plant-specific, but the parameters typically used for operation at design conditions are listed in Table 22.3. The advantages and

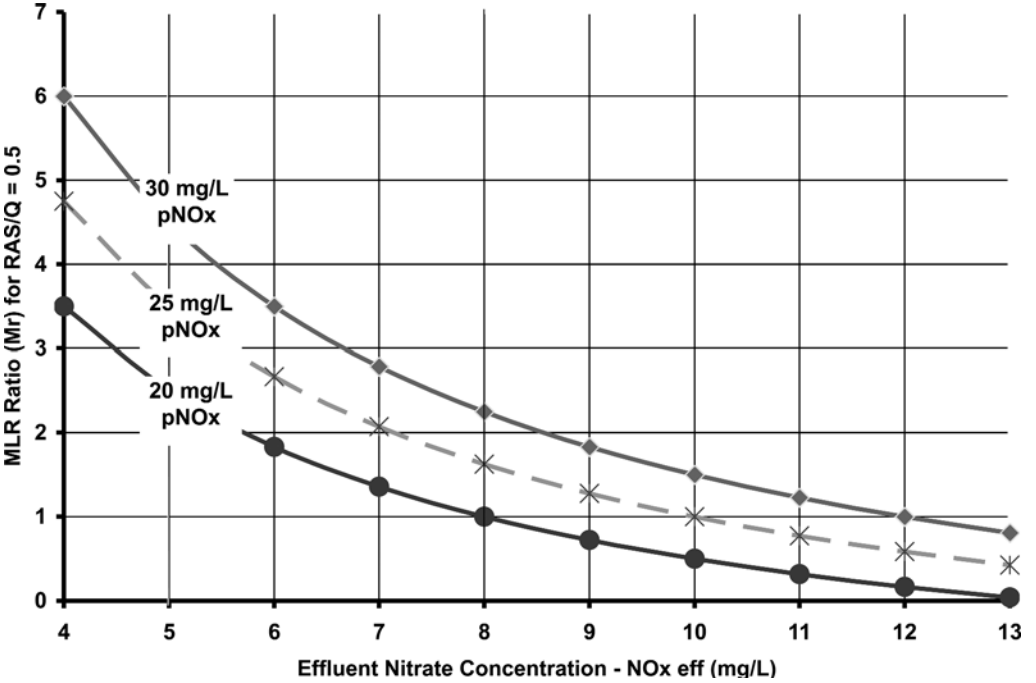


FIGURE 22.11 Effect of MLR ratio on affluent nitrate.

limitations of nitrogen removal processes are listed in Table 22.4 (Metcalf and Eddy, Inc., 2003). Descriptions of common nitrogen removal processes follow.

Ludzack–Ettinger Process. In the 1960s and 1970s, engineers made a number of modifications to the conventional activated sludge process to improve nitrogen removal. For example, researchers Ludzack and Ettinger developed a version in which RAS and secondary influent are combined in an anoxic zone that is followed by an aerobic zone [Figure 22.12(a)]. The nitrate formed in the aerobic zone is returned to the anoxic zone via RAS for denitrification.

Because the anoxic zone's only source of nitrate is the RAS, denitrification is limited by the amount of RAS flow. If the influent NO_X is 20 mg/L, the effluent nitrate concentration will be 15 mg/L, 13 mg/L, or 10 mg/L depending on whether the RAS recycle flow ratio is 0.3, 0.5, or 1.0, respectively. So, the process is only suitable for denitrification if nitrate limits are liberal or high RAS flows can be maintained.

Modified Ludzack–Ettinger Process. The difference between the modified Ludzack–Ettinger (MLE) process and the Ludzack–Ettinger (LE) process is that the MLE process

TABLE 22.3 Typical parameters for nitrogen removal.

Process	MCRT (days)	MLSS (mg/L)	HRT (hours)			RAS (% of Q)	MLR (% of Q)
			Total System	Ax Zone	Ox Zone		
mLE	7–20	3000–4000	5–15	1–3	4–12	50–100	100–200
SBR	10–30	3000–5000	20–30	Variable	Variable		
4-Stage Bardenpho	10–20	3000–4000	8–20	1–3 (1st stage) 2–4 (3rd stage)	4–12 (2nd stage) 0.5–1 (4th stage)		
Oxidation Ditch	20–30	2000–4000	18–30	Variable	Variable	50–100	
Anoxic Step Feed	7–20	2000–6000	4–12	0.5–2	3.5–10	30–75	

recycles mixed liquor from the oxic zone to the anoxic zone [Figure 22.12(b)]. The mixed-liquor flow may equal 100 to 300% of the secondary influent flow, depending on how much denitrification is desired. Effluent nitrate concentrations typically range from 4 to 7 mg/L.

The mixed-liquor pumps may be relatively small because short distances and large transfer pipes typically result in pumping heads of less than 0.9 m (3 ft). They also may resemble a fan rather than the conventional centrifugal pumps used at wastewater treatment facilities.

This design [Figure 22.12(b)] is the cornerstone of many other BNR processes, including those used for BPR, so the MLE process will be referred to in many subsequent process descriptions. Although Figure 22.12 shows the anoxic (or anaerobic) selector as one reactor, it probably consists of two or more cells, zones, or compartments operated in series. If nitrified effluent is recycled for denitrification, the MLR is typically transferred to the second or third cell in the anoxic selector to minimize dissolved oxygen in the first compartment, thereby better controlling filamentous bacteria and providing optimal conditions for *Acinetobacter* organisms.

Four-Stage Bardenpho Process. The four-stage Bardenpho process is an MLE process with subsequent anoxic and oxic zones [Figure 22.12(c)]. Developed by James Barnard, the process was originally used for both denitrification and BPR. (The process' name is a compilation of the first three letters of the inventor's name and the words *denitrification* and *phosphorus*.) Its original carbon source was acetic acid or methanol, but a later adaptation—called the enhanced MLE process—uses wastewater instead and is con-

TABLE 22.4 Advantages and limitations of nitrogen removal processes.

	Advantages	Limitations
General	Saves energy; BOD is removed before aerobic zone	
	Alkalinity is produced before nitrification Design includes an SVI selector	
MLE	Very adaptable to existing activated-sludge processes	Nitrogen-removal capability is a function of internal recycle
	5 to 8 mg/L TN is achievable	Potential *Nocardia* growth problem. Dissolved oxygen control is required before recycle
Step Feed	Adaptable to existing step-feed activated sludge processes	Nitrogen-removal capability is a function of flow distribution
	With internal recycle in last pass, nitrogen concentrations less than 5 mg/L are possible	More complex operation than mLE; requires flow split control to optimize operation
	5 to 8 mg/L TN is achievable	Potential *Nocardia* growth problem
		Requires dissolved oxygen control in each aeration zone
Sequencing Batch Reactor	Process is flexible and easy to operate	Redundant units are required for operational reliability unless aeration system can be maintained without draining the aeration tank
	Mixed-liquor solids cannot be washed out by hydraulic surges because flow equalization is provided	
	Quiescent settling provides low effluent TSS concentration	
		More complex process design Effluent quality depends upon reliable decanting facility
	5 to 8 mg/L TN is achievable	May need effluent equalization of batch discharge before filtration and disinfection
Batch Decant	5 to 8 mg/L TN is achievable Mixed-liquor solids cannot be washed out by hydraulic surges	Less flexible to operate than SBR Effluent quality depends on reliable decanting facility

TABLE 22.4 Advantages and limitations of nitrogen removal processes (*continued*).

	Advantages	Limitations
Bio-denitro™	5 to 8 mg/L TN is achievable	Complex system to operate
	Large reactor volume is resistant to shock loads	Two oxidation ditch reactors are required; increases construction cost
Nitrox™	Large reactor volume is resistant to shock loads	Nitrogen-removal capability is limited by higher influent TKN concentrations
	Easy and economical to upgrade existing oxidation ditch processes	Process is susceptible to ammonia bleed-through
	Provides SVI control	Performance is affected by influent variations
Bardenpho (4-stage)	Capable of achieving effluent nitrogen levels less than 3 mg/L	Large reactor volumes required
		Second anoxic tank has low efficiency
Oxidation Ditch	Large reactor volume is resistant to load variations without affecting effluent quality significantly	Nitrogen-removal capability is related to skills of operating staff and control methods
	Has good capacity for nitrogen removal; less than 10 mg/L effluent TN is possible	
Post-Anoxic with Carbon Addition	Capable of achieving effluent nitrogen levels less than 3 mg/L	Higher operating cost due to purchase of methanol
	May be combined with effluent filtration	Methanol feed control required
Simultaneous Nitrification/ Denitrification	Low effluent nitrogen level possible (3 mg/L lower limit)	Large reactor volume; skilled operation is required
	Significant energy savings possible Process may be incorporated into existing facilities without new construction	Process control system required
	SVI control enhanced Produces alkalinity	

figured with denitrification (rather than phosphorus removal) as the primary goal. Both processes can achieve effluent nitrate concentrations of less than 3 mg/L.

Anoxic Step-Feed Process. Anoxic zones can be established in a conventional step-feed process to increase mixed-liquor concentrations in the early stages, resulting in a four-stage BNR step-feed process with a 30 to 40% longer MCRT than that of a conventional plug-flow arrangement [Figure 22.12(d)]. If the anoxic and oxic reactors are the

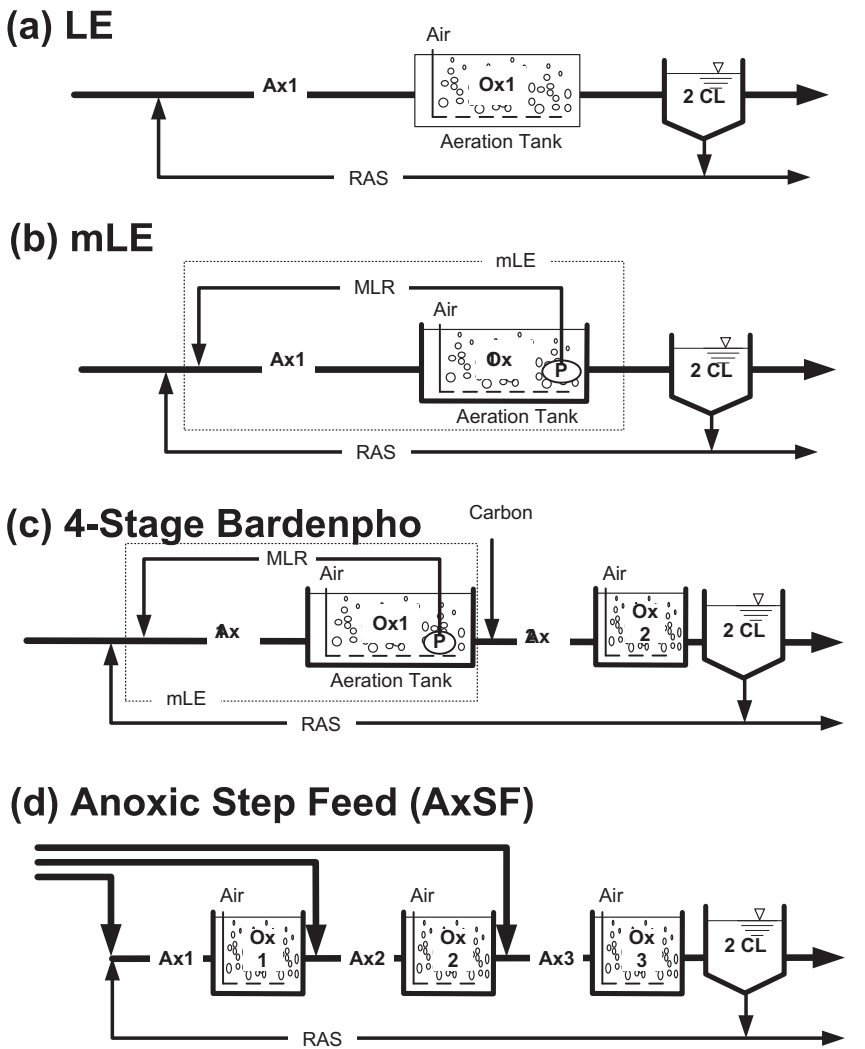


FIGURE 22.12 Suspended-growth pre-anoxic processes.

same size, a four-stage system should have an influent flow split of about 15:35:30:20% so the F:M ratio will be the same in each step. Each stage should have its own influent controls. The flow into the last step is critical because the nitrate produced there will not be reduced. So, the anoxic step-feed process is best used when the effluent nitrate limit is more than 6 to 8 mg/L.

Sequencing Batch Reactors. A conventional SBR, which is designed to remove CBOD, consists of four phases: fill, react, settle, and decant (Figure 22.13). To denitrify wastewater, the fill phase is adjusted to "mixed fill", in which the influent is stirred (but not aerated). At facilities with effluent nitrate limits less than 5 mg/L, a second anoxic phase may be added after the react cycle, and a carbon source (e.g., methanol) may be added to enhance denitrification before the settling and decant phases.

Oxidation Ditches. Oxidation ditches are typically sized based on long aerobic MCRTs (20 to 25 days), so excess volume is available for denitrification (Figure 22.14). This is typically achieved by turning off one or more aeration rotors to create an anoxic zone [Figure 22.14(a) and (b)]. Because the SDNRs are low, the zone must be large enough to provide the needed anoxic time.

Another approach is to cycle the aeration by turning the aerators off at least twice a day [Figure 22.14(c)]. Submerged mixers maintain recirculation in the ditch during the anoxic phases. A variation of cyclic aeration, called the Nitrox™ process, involves using ORP for control.

A third approach is phased ditch operation [Figure 22.14(d)]. In this process, two oxidation ditches are operated in series, and secondary influent is alternately pumped into them. When the influent enters the ditch, its aeration equipment is turned off, and the reactor becomes anoxic. Submerged mixers maintain recirculation. After a period of time (typically 1 to 2 hours), the influent is sent to the second ditch. At the time of the switch, the aerators are turned on in the first ditch, making it oxic, and the aerators on the second ditch are turned off. This cycle continues, allowing periods of aeration and anoxic fill to occur. A variation of phased ditch operation, called the Bio-denitro™ process, uses four phases to enhance oxidation and denitrification (Stensel and Coleman, 2000).

OTHER OR EMERGING NITROGEN REMOVAL PROCESSES. The following nitrogen removal processes are either emerging or not widely used.

Membrane Bioreactors. Membrane bioreactors (MBRs) combine activated sludge and membrane filtration systems (WERF, 2000a). The semi-permeable membranes used typically provide either ultrafiltration or microfiltration. An aeration basin converted into an MBR can operate at 8000 to 10 000 mg/L of MLSS. Its MCRT is typically 20 days or more to minimize biofouling of the membranes.

The system configuration and equipment involved depends on the manufacturer. One manufacturer installs the membranes directly in the aeration basin, drawing treated wastewater through the filters via a permeate pump. Another manufacturer installs the membranes in a tank outside the aeration basin. In this case, MLSS is pumped to the "membrane tanks", and separate vacuum pumps pull permeate through the membranes.

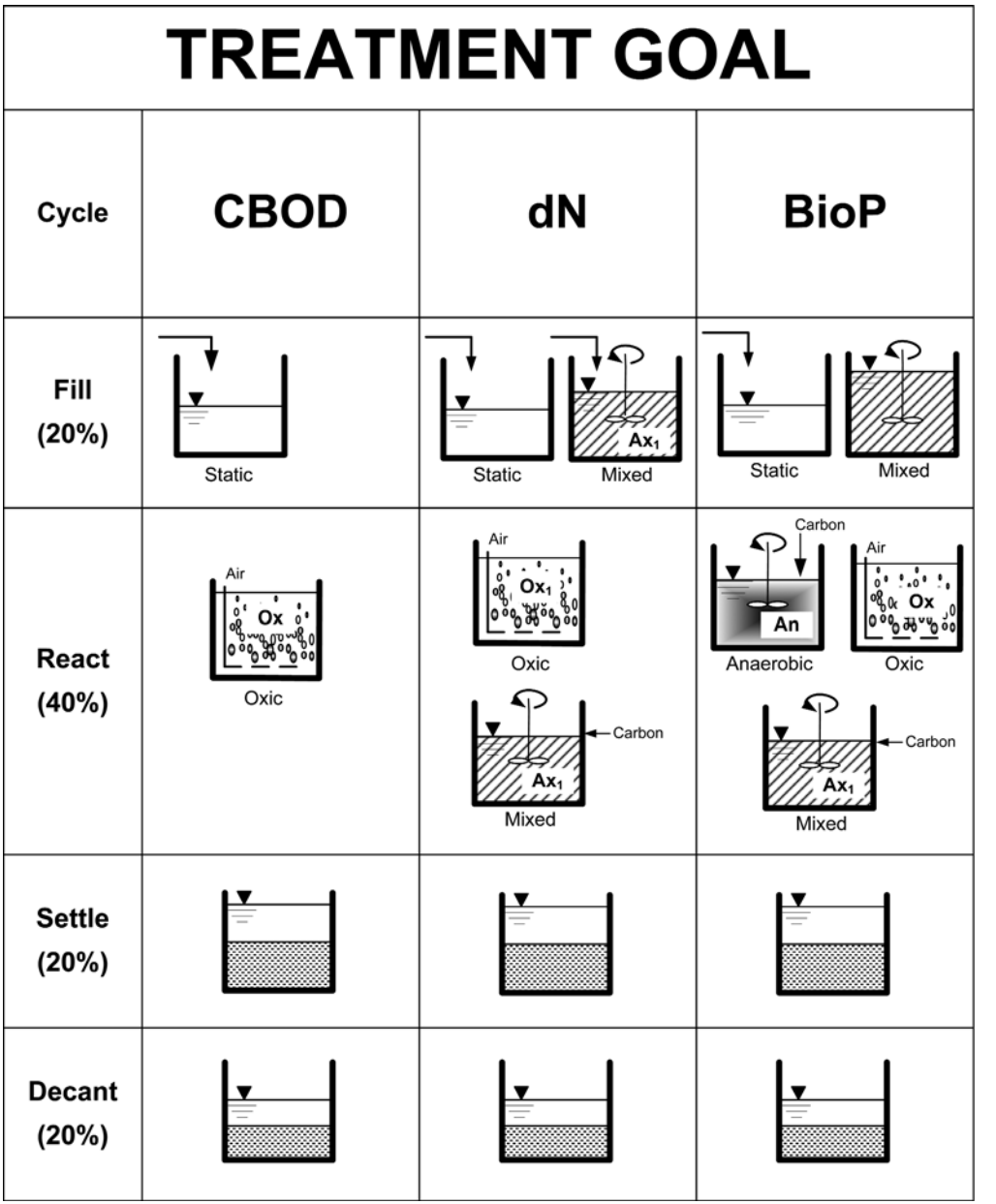


FIGURE 22.13 Sequencing batch reactor processes.

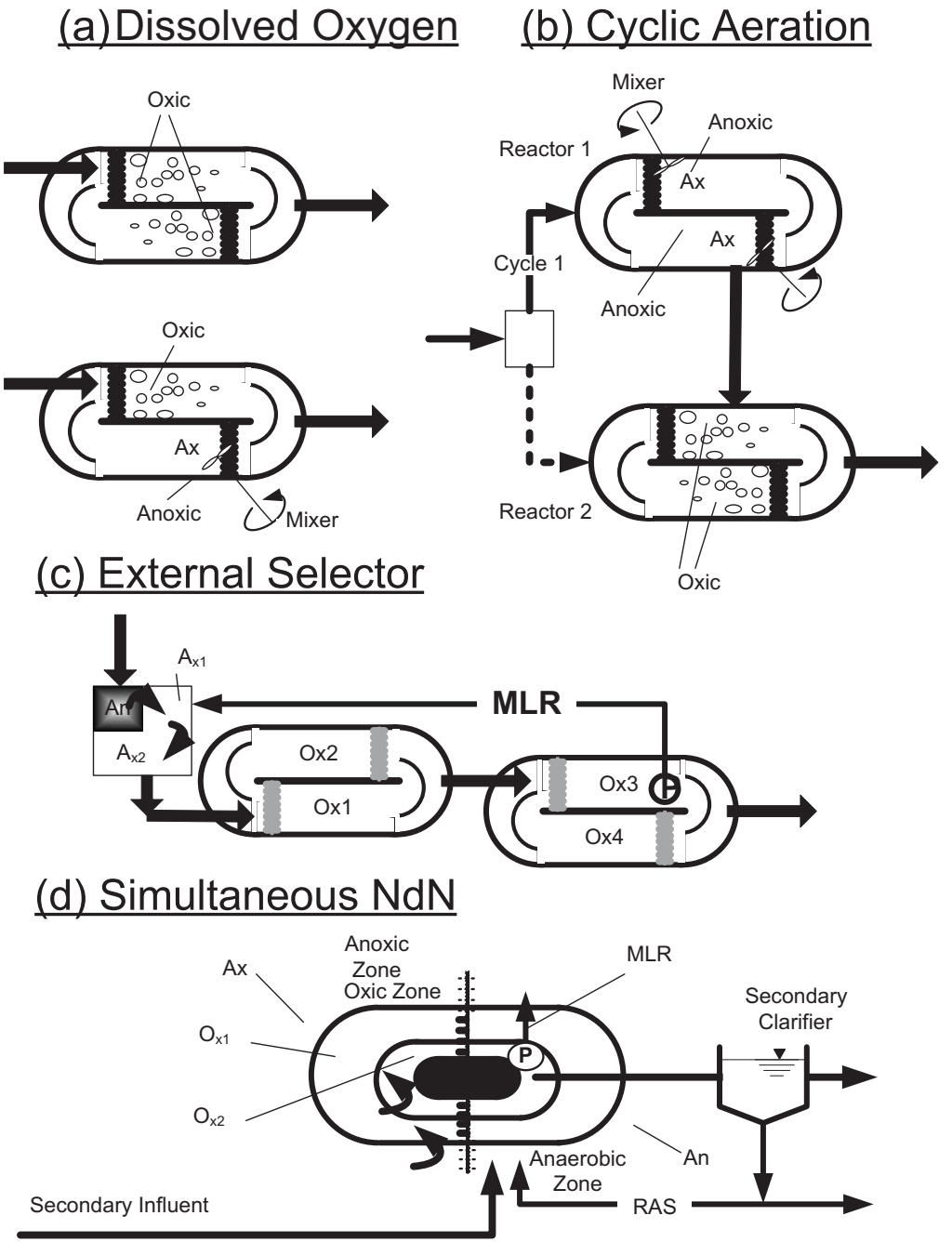


FIGURE 22.14 Oxidation ditch processes.

One benefit of MBRs is that their effluent requires no further biological treatment or filtration to meet water reuse standards.

Lagoons. Lagoons are probably one of the oldest nutrient removal technologies. However, their large size and loss of nitrification during cold weather have typically limited their use.

A number of facultative or partially aerated lagoons have been upgraded to *activated lagoons* by converting the lined earthen basins to aeration basins and adding secondary clarifiers and an RAS system. Conventional secondary clarifiers and RAS pumps can be used, but several manufacturers supply in-basin clarifiers with traveling-bridge sludge collectors and airlift RAS pumping.

Activated lagoons operate at 40 to 80 days of MCRT and 2000 to 3000 mg/L of MLSS. They can nitrify wastewater reliably and do not have the algae problems of conventional lagoons.

Fixed-Film Processes. Fixed-film (attached-growth) processes, such as trickling filters, biotowers, and RBCs, may be used to treat nitrogen alone or both nitrogen and BOD. They typically nitrify wastewater at about half of the organic loading needed for BOD removal. Nitrification is promoted when fixed-film reactors are operated in series (often called stages) and the oxygen concentration is high in the last stage. With series or staged configuration, BOD removal occurs in the first reactor whereas the majority of nitrifiers grow in the second-stage reactor. In the second stage, nitrifying organisms have little competition from heterotrophic bacteria and are able to convert ammonia to nitrate-nitrogen.

Fixed-film reactors are rarely used for denitrification or BPR because of the difficulty maintaining an anaerobic/anoxic environment using the relatively little carbon typically found in municipal wastewater. For detailed descriptions of fixed-film reactors, see *Aerobic Fixed-Growth Reactors* (WEF, 2000).

Combined Fixed-Film and Suspended-Growth Processes. A combination of fixed-film and suspended-growth processes has been used to remove both nitrogen and phosphorus from wastewater (Harrison, 1999). In such systems, the suspended-growth reactor typically is preceded by a biotower containing plastic filter media. If denitrification or phosphorus removal is required, then selector zones may be added in the RAS stream or the anaerobic/anoxic zones that precede the biotower. When the selector zones precede the biotower, the filter media are "activated" by pumping the mixed liquor over them. Both biotower and RBC media can be activated so long as the media are strong enough to accommodate added weight and provisions are made for enhanced sloughing.

Deep-Bed Effluent Filters. Deep-bed effluent filters—typically downflow units containing about 1.8 m (6 ft) of sand, anthracite, or another coarse media—may be used for denitrification and TSS removal. Methanol or another carbon source typically is added to encourage denitrification. The units follow a biological treatment system (including secondary clarification) that provides nitrification.

Because the filter media are large, more solids can be stored in the filter bed, and filter runs between backwashes may be longer than those of a conventional effluent filter. Effective cleaning typically involves a combination of air and water scouring.

Fluidized Beds. A fluidized bed is an attached-growth reactor filled with sand, on which the biomass grows. Wastewater enters the bottom of the reactor and flows upward with enough velocity to expand (fluidize) the sand bed. Rather than backwashing the entire filter, a small volume of media is continuously removed from the reactor, separated from treated wastewater, and then scoured to remove the biomass.

Although fluidized beds can nitrify or denitrify wastewater at biomass concentrations ranging from 25 000 to 30 000 mg/L, thereby minimizing space requirements, they are often difficult to operate. Difficulties have included loss of media, difficulty separating biogrowth from the media, and high maintenance.

Integrated Fixed-Film Activated Sludge Processes. In an integrated fixed-film activated sludge (IFAS) process, filter media are added to an aeration basin to increase the overall microbe population (WERF, 2000b). Like a conventional activated sludge process, an IFAS process uses a secondary clarifier to settle sludge and recirculate RAS. However, its MCRT is 40 to 50% longer than a conventional activated sludge process with the same MLSS and volume, according to tests.

The filter media could be made of rope (tassels tied to a main string), sponge (cubes suspended in some type of housing), or plastic (corrugated sheets, specially designed webs, or cubes). They often are placed over conventional coarse-bubble air diffusers, which should be sized to both meet the process' oxygen demand and control biomass on the filter media. Also, fine-mesh screens should be installed at the influent end to minimize hair, plastic, and other materials that could blind the filter media.

ENHANCED BIOLOGICAL PHOSPHORUS REMOVAL

A conventional activated sludge system removes phosphorus from wastewater naturally when its microorganisms take up soluble phosphorus to generate new biomass. Each milligram of VSS (dry weight) produced in such systems contains about 2% phosphorus. If 0.5 mg of VSS is produced per 1 mg of BOD removed, then about 1.0 mg of

phosphorus is converted to cell mass per 100 mg of BOD removed (Table 22.1). So, traditional sludge wasting reduces phosphorus by about 1 to 2 mg/L.

Acinetobacter (BioP) microorganisms consist of up to 35% phosphorus, so mixed liquor with a high percentage of *Acinetobacter* organisms may contain about 6% phosphorus. Systems designed to select for such organisms are called *enhanced biological phosphorus removal* (EBPR) systems. They can reduce phosphorus concentrations by 3 to 6 mg/L.

Chemicals can also be used to precipitate phosphorus, but EBPR minimizes the need for them, thereby reducing their side effects: alkalinity loss and extra sludge production. Enhanced biological phosphorus removal systems also produce a better settling sludge.

The disadvantages of EBPR include a higher capital cost (for baffles and mixers to create selector zones), sensitivity to nitrate or oxygen toxicity, and more complex operations (WEF, 1998a).

BIOCHEMISTRY. Enhanced biological phosphorus removal works because *Acinetobacter* organisms, which are heterotrophic, have a metabolic quirk: they can absorb soluble BOD under anaerobic conditions and store it until they are in an aerobic environment, where they then metabolize it. (Most heterotrophic bacteria cannot transfer soluble BOD under anaerobic conditions.) So, in the right environment with the right type and amount of BOD—they prefer short-chain carbon compounds—*Acinetobacter* organisms will predominate.

Enhanced biological phosphorus removal is a two-step process in which an anaerobic environment is followed by an aerobic one (Figure 22.15). In the anaerobic selector, *Acinetobacter* organisms release phosphorus, thereby obtaining the energy to uptake readily biodegradable organics. This ability enables *Acinetobacter* organisms to become dominant. It also tends to result in orthophosphorus concentrations as high as 40 mg/L. Phosphorus release typically occurs within 0.5 to 1 hour of HRT.

When the mixed liquor enters the aerobic zone, *Acinetobacter* organisms grow new biomass and take up phosphorus—typically more than the amount they released in the anaerobic zone. EBPR effluent may contain less than 1.0 mg/L of soluble phosphorus. Soluble BOD also drops from between 70 and 80 mg/L to 1.0 mg/L (Figure 22.15). In addition, some wastewater facilities have reported that operating in the EBPR mode provides superior sludge settling

Acinetobacter organisms grow slowly, but faster than nitrifying bacteria. To avoid washout, the process' overall MCRT should be between 2 and 3 days. Longer MCRTs (up to 40 to 60 days) do not hurt *Acinetobacter* organisms, but the RAS' nitrate concentration could prevent the first zone from being truly anaerobic. Ideally, an EBPR facility

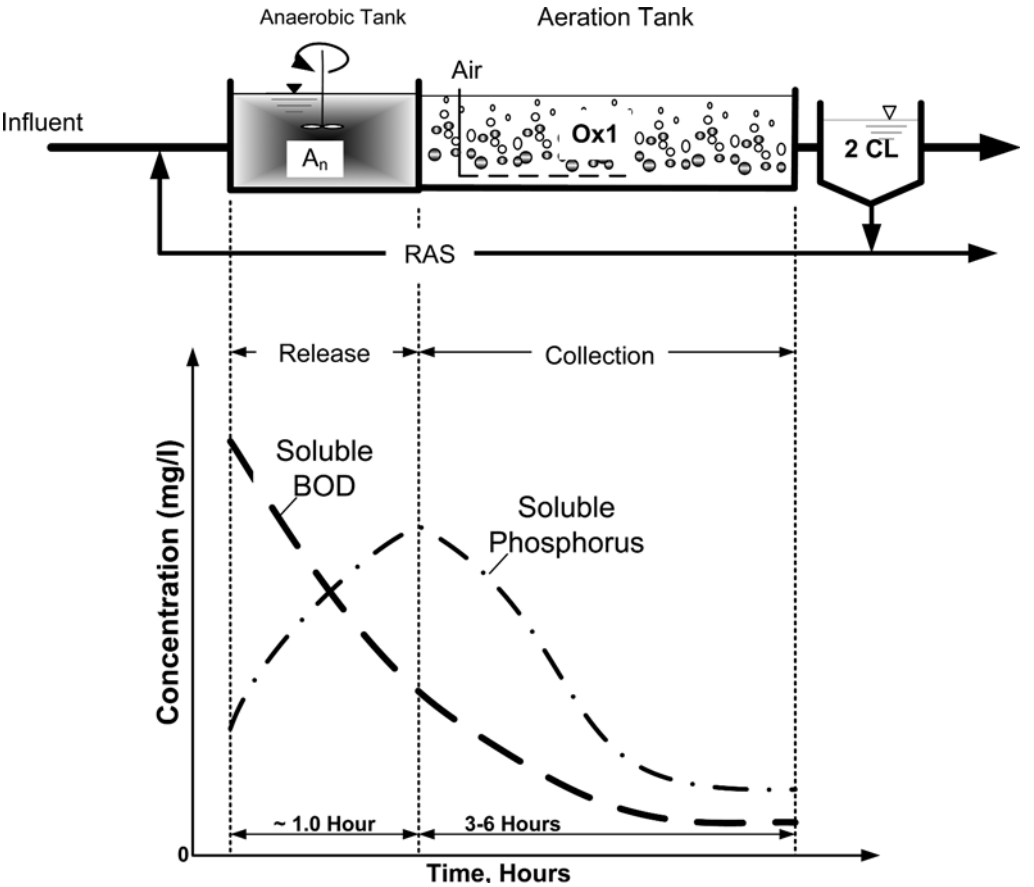


FIGURE 22.15 Biological phosphorus timeline.

should avoid nitrification, but if both nitrification and BPR are necessary, then plant staff should take steps to eliminate interference from combined oxygen.

Settled or waste sludge from EBPR processes must be managed carefully to avoid *secondary release*—phosphorus emitted from sludge when it is held under anaerobic conditions. Such phosphorus can be inadvertently recycled to the process reactors.

INFLUENCES. Good BPR depends on the right environment (low ORP) and the right type and amount of organic matter. Most wastewater will contain enough readily biodegradable BOD to allow EBPR. *Acinetobacter* organisms prefer short-chain carbon compounds, also called VFAs. If the treatment plant is in a warm climate or the collec-

tion system has an extended retention time so septic conditions can occur, then the wastewater typically will have enough VFAs.

In areas with colder climates or wastewater diluted by infiltration and inflow (I/I), staff may need to supplement naturally occurring VFAs. Some treatment plants generate VFAs by holding primary sludge (only 20 or 30% may need processing) in a gravity-based thickener called a *primary sludge fermenter*. Others maintain a sludge blanket in the primary clarifier. In either approach, staff maintain a sludge blanket with a 1- to 3-day MCRT to generate enough VFAs so the overflow can supplement the treatment plant influent and allow EBPR to occur.

To optimize EBPR, either nitrate-nitrogen must be removed from the RAS, or the RAS flow must be reduced (typically 20 to 30%) to minimize dissolved oxygen entrainment. The ratio of BOD to total phosphorus is also important. A ratio of 25:1 or more is considered necessary to achieve good phosphorus removal (the actual BOD-to-total phosphorus ratio needed depends on the process involved).

Suspended solids at an EBPR facility may have a phosphorus concentration of 6% or more, compared to 2% at a conventional biological treatment system. Likewise, a secondary effluent with 30 mg/L of TSS will contain 1.8 mg/L of particulate phosphorus at an EBPR facility, but only 0.6 mg/L at a conventional plant. So, effluent filtration may be necessary to meet low total phosphorus limits.

COMMON COMBINED NITROGEN AND PHOSPHORUS REMOVAL PROCESSES.

Optimal operating parameters for BPR processes are plant-specific, but the parameters typically used for operation at design conditions are listed in Table 22.5. The advantages and limitations of BPR processes are listed in Table 22.6 (Metcalf and Eddy, Inc., 2003). Descriptions of common BPR processes follow. Most remove both nitrogen and phosphorus.

Anaerobic/Oxic Process. Developed in the 1970s and patented in the early 1980s, the A/O process has a similar flow scheme to that of the LE process [Figure 22.12(a)] except it uses an anaerobic zone rather then an anoxic one. The main difference between the LE process and the A/O process is that A/O does not nitrify. Typically, its anaerobic zone's HRT is between 30 and 60 minutes to select for *Acinetobacter* organisms, and its oxic zone's MCRT is between 2 to 4 days to discourage nitrification. The A/O process typically is not used at treatment plants that need both nitrogen and phosphorus removal because other processes do both more effectively.

Anaerobic/Anoxic/Oxic Process. The proprietary anaerobic/anoxic/oxic (A^2/O^{TM}) process is a modification of the A/O process in which an anoxic zone denitrifies the MLR. Essentially, it is an MLE process preceded by an anaerobic zone [Figure 22.16(a)].

TABLE 22.5 Typical parameters for phosphorus removal processes.

Process	MCRT (days)	MLSS (mg/L)	HRT (hours)			RAS (% of Q)	MLR (% of Q)
			An Zone	Ax Zone	Ox Zone		
A/O	2–5	3000–4000	0.5–1.5	—	1–3	25–100	
A^2/O	5–25	3000–4000	0.5–1.5	0.5–1	4–8	25–100	100–400
UCT	10–25	3000–4000	1–2	2–4	4–12	80–100	200–400 (Ax) 100–300 (Ox)
VIP	5–10	2000–4000	1–2	1–2	4–6	80–100	100–200 (Ax) 100–300 (Ox)
Bardenpho (5-stage)	10–20	3000–4000	0.5–1.5	1–3 (1st stage) 2–4 (2nd stage)	4–12 (1st stage) 0.5–1 (2nd stage)	50–100	200–400
SBR	20–40	3000–4000	1.5–3	1–3	2–4		

Typically, its anaerobic zone is about the same size as that in the A/O process, while the anoxic zone has an HRT of 1 hour and the MLR is 100 to 400% of the secondary influent.

The A^2/O process allows *Acinetobacter* organisms to be competitive in the anaerobic zone—even while nitrification is occurring—by lowering the nitrate content in the RAS. It can achieve good denitrification via proper sizing of the anoxic zone.

Modified University of Capetown Process. The modified University of Capetown (UCT) process has anaerobic and anoxic zones preceding what is essentially an MLE process [Figure 22.16(b)]. It returns denitrified mixed-liquor recycle (MLR_{Ax}) from the first anoxic zone to the anaerobic zone to maintain nitrates at a lower concentration than most other EBPR processes can achieve. The UCT process is especially beneficial when treating weak wastewater, which may lack the proper nutrient ratios, because it allows *Acinetobacter* organisms to compete with other microorganisms in dilute wastewater.

Sometimes the UCT process is modified with selector zones to operate at higher hydraulic rates. In this case, the HRT may be 1 to 2 hours because the mixed liquor in the anaerobic zone will be less than in a comparable A/O process. The flow rate for the MLR_{Ax} is typically twice the secondary influent flow.

A variation of the modified UCT process is the Virginia Initiative Plant (VIP) process, which has a similar flow schematic [Figure 22.16(b)] but its anoxic and oxic zones are staged to allow operation at a lower MCRT. In this process, the RAS is mixed with the MLR_{Ox} before the anoxic zone to minimize dissolved oxygen recycle.

TABLE 22.6 Advantages and limitations of phosphorus removal processes.

	Advantages	Limitations
A/O	Operation is relatively simple when compared to other processes	Phosphorus removal declines if nitrification occurs
	Low BOD/P ratio possible	Limited process control flexibility is available
	Relatively short hydraulic retention time	
	Produces good settling sludge	
	Good phosphorus removal	
A^2/O	Removes both nitrogen and phosphorus	RAS containing nitrate is recycled to anaerobic zone, thus affecting phosphorus-removal capability
	Provides alkalinity for nitrification	
	Produces good settling sludge	
	Operation is relatively simple	Nitrogen removal is limited by internal recycle ratio
	Saves energy	Needs higher BOD/P ratio than the A/O process
UCT	Nitrate loading on anaerobic zone is reduced, thus increasing phosphorus-removal capability	More complex operation
		Requires additional recycle system
	For weaker wastewater, process can	
	achieve improved phosphorus removal	
	Produces good settling sludge	
	Good nitrogen removal	
VIP	Nitrate loading on anaerobic zone is reduced, thus increasing phosphorus-removal capability	More complex operation
		Requires additional recycle system
	Produces good settling sludge	More equipment required for staged operation
	Requires lower BOD/P ratio than UCT	
Bardenpho (5-stage)	Can achieve 3 to 5 mg/L TN in unfiltered effluent	Less efficient phosphorus removal
	Produces good settling sludge	Requires larger tank volumes
SBR	Both nitrogen and phosphorus removal are possible	More complex operation for N and P removal
	Process is easy to operate	Needs larger volume than SBR for N removal only

TABLE 22.6 Advantages and limitations of phosphorus removal processes (*continued*).

	Advantages	Limitations
	Mixed-liquor solids cannot be washed out by hydraulic surges	Effluent quality depends on reliable decanting facility
	Quiescent settling may produce lower effluent TSS concentration	Design is more complex
	Flexible operation	Skilled maintenance is required
		More suitable for smaller flowrates
PhoStrip	Can be incorporated easily into existing activated sludge plants	Requires lime addition for phosphorus precipitation
	Process is flexible; phosphorus-removal performance is not controlled by BOD/phosphorus ratio	Requires higher mixed-liquor dissolved oxygen to prevent phosphorus release in final clarifier
		Additional tank capacity required for stripping
	Significantly less chemical usage than mainstream chemical precipitation process	Lime scaling may be a maintenance problem
	Can achieve reliable effluent orthophosphate concentrations less than 1 mg/L	

Five-Stage Bardenpho Process. When an anaerobic zone precedes the four-stage Bardenpho process [Figure 22.12(c)], the resulting five-stage process can be used to encourage the growth of *Acinetobacter* organisms. The flow schematic of a five-stage (modified) Bardenpho process resembles the A^2/O process followed by a second anoxic zone and a reaeration (oxic) zone [Figure 22.16(c)]. This process is typically designed to operate with a total HRT of about 22 hours, although the HRTs vary for each zone: anaerobic (2 hours), anoxic (3 hours), aerobic (12 hours), secondary anoxic (2 hours), and reaeration (1 hour).

Johannesburg Process. Originally used in Johannesburg, South Africa, this process is essentially a simpler version of the modified UCT process. The Johannesburg (sidestream denitrification) process minimizes the amount of nitrate fed to the anaerobic zone by including an anoxic zone in the RAS flow pattern [Figure 22.16(d)]. It uses the bacteria's endogenous respiration to denitrify the RAS, while a second (mainstream) anoxic zone denitrifies the MLR. Its anaerobic zone can operate at a higher MLSS concentration than the modified UCT process, thereby reducing the HRT necessary for BPR.

OTHER OR EMERGING PHOSPHORUS REMOVAL PROCESSES. The following phosphorus removal processes are either emerging or not widely used.

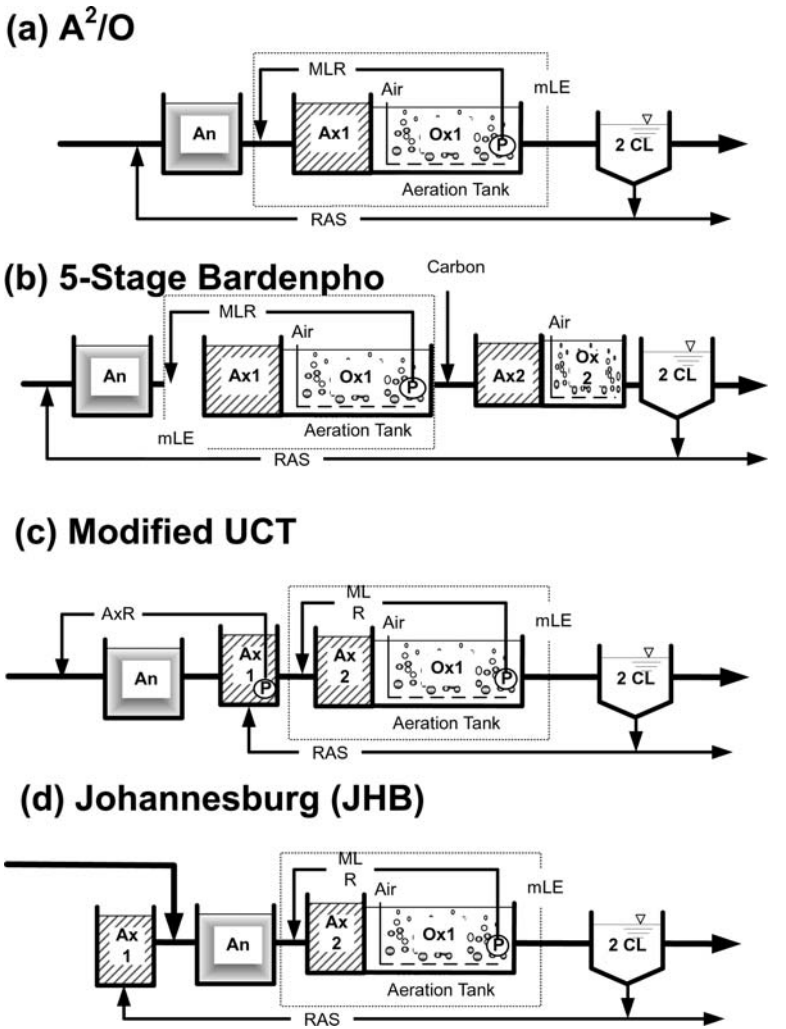


FIGURE 22.16 Suspended-growth processes for phosphorous removal.

Sequencing Batch Reactors. Typically used for denitrification and CBOD removal, SBRs can also be modified to remove phosphorus (Figure 22.13). This is done by inserting an anoxic period and adding carbon (typically methanol) after the aerated react period. This ensures that little nitrate remains during the fill period, so the following anaerobic period will encourage the growth of *Acinetobacter* organisms. Adding methanol after the react period (while aeration is shut off) allows nitrate to be consumed. The following short aerated react period ensures that the methanol is totally consumed and

will not contribute to BOD in the final effluent. To ensure that enough VFAs are available, a carbon source is also added during the initial mix–react period.

These modifications typically cut the SBR's cycles to three to four per day. The reduced cycles and extra complexity make BPR difficult to achieve, compared to conventional, constant-flow BNR processes.

Oxidation Ditches. Oxidation ditches (Figure 22.14) typically are not considered a BPR process because of the difficulty associated with achieving truly anaerobic conditions when nitrates are being recycled (Stensel and Coleman, 2000). However, good BPR can be achieved by constructing an external selector, which may incorporate flexible cells allowing a mainstream BPR process to be used with the oxidation ditch [Figure 22.14(c)]. One oxidation ditch manufacturer promotes dissolved oxygen control in the outer reactor ring as a means of accomplishing BPR [Figure 22.14(d)].

PhoStrip Process. The "PhoStrip" process, which removes phosphorus via a side-stream process, was first introduced in the 1970s before any mainstream BPR processes existed. Although seldom used today because of its chemical requirements and complex operations, the PhoStrip method of removing phosphorus from RAS deserves description. It involves transferring about one-third of the RAS to an anaerobic stripper tank (typically a gravity thickener) for a HRT of between 8 and 12 hours. A small amount of primary effluent or raw wastewater may be added to the tank to enhance anaerobic conditions. After fermentation, supernatant from the stripper tank is transferred to a separate reactor, where lime is added to raise the pH and precipitate soluble phosphorus (Figure 22.15).

Although it uses lime, PhoStrip is considered a biological process because the RAS in the stripper tank promotes the proliferation of *Acinetobacter* organisms.

Combined Fixed-Film and Suspended-Growth Processes. Although uncommon, BPR may also be incorporated into flow schemes using fixed-film reactors, including rock-media trickling filters. For example, a trickling filter/solids contact (TF/SC) process used an anaerobic selector in the RAS stream and added a carbon source to reduce nitrates and enhance the growth of *Acinetobacter* organisms. After the enhancement, the RAS is returned to the mainstream (solids contact reactor) after the rock trickling filter. Biological phosphorus removal has also been successful in biotowers when anoxic and anaerobic selectors preceded the fixed-film reactor. In this case, MLSS from the suspended-growth selector processes was pumped to the biotower. The biotower may also be followed by a solids contact or activated sludge aeration basin if nitrification is required.

PROCESS CONTROL

Operators of BNR facilities need more process-control knowledge than those of conventional treatment facilities to keep them operating smoothly. The key operating parameters for a BNR facility typically include

- MCRT,
- F:M ratio,
- HRT,
- Oxygen levels,
- Alkalinity and pH control,
- Denitrification,
- Recycle flows, and
- Secondary clarification.

MEAN CELL RESIDENCE TIME. The mean cell residence time (defined in Equation 22.2) is the key to understanding whether the BNR process has enough time to function effectively. When evaluating MCRT, operators should answer such questions as

- Is the MCRT long enough to establish nitrification?
- How much sludge should be wasted to maintain a desired MCRT?
- Can the MCRT be increased by maintaining a higher MLSS?

Nitrifying facilities, such as conventional activated sludge, A^2/O, and MLE processes, typically need between 5 and 15 days of MCRT. Facilities with intricate recycling patterns, such as the UCT process, need between 10 and 25 days of MCRT. Other processes, such as extended aeration systems, SBRs, and oxidation ditches, need between 15 and 30 days of MCRT. In cold climates (less than 12 °C), nitrification systems need at least 30 days of MCRT to function reliably.

$$\text{MCRT} = \frac{\text{MLSS}}{\text{TSS}_{\text{2EFF}} + \text{TSS}_{\text{WAS}}}$$

Where

MLSS = TSS in the aeration basin,
TSS_{2EFF} = TSS in secondary effluent, and
TSS_{WAS} = TSS in WAS.

Example 22.1: Determine Whether the MCRT is Sufficient for Nitrification. Given the plant shown in Figure 22.17, what is its MCRT? Will it nitrify wastewater reliably at 12 °C? Assume that MLSS = 2000 mg/L, TSS_{WAS} = 7000 mg/L, and Q_{WAS} = 31 000 gpd.

1. Determine the biomass in the system:

$$M_{AX1} = (0.035 \text{ mil. gal})(8.34)(2000 \text{ mg/L}) = 584 \text{ lb TSS}$$

$$M_{AX1} = (0.035 \text{ mil. gal})(8.34)(2000 \text{ mg/L}) = 584 \text{ lb TSS}$$

$$M_{AX2} = (0.055 \text{ mil. gal})(8.34)(2000 \text{ mg/L}) = 917 \text{ lb TSS}$$

$$M_{Ox} = (0.375 \text{ mil. gal})(8.34)(2000 \text{ mg/L}) = 6255 \text{ lb TSS}$$

Total M = 8340 lb TSS

2. Determine the biomass wasted each day:

$$TSS_{WAS} = (0.031 \text{ mgd})(8.34)(7000 \text{ mg/L}) = 1810 \text{ lb/d}$$

$$TSS_{2EFF} = (1.5 \text{ mgd})(8.34)(20 \text{ mg/L}) = 250 \text{ lb/d}$$

Total wasted TSS = 2060 lb/d

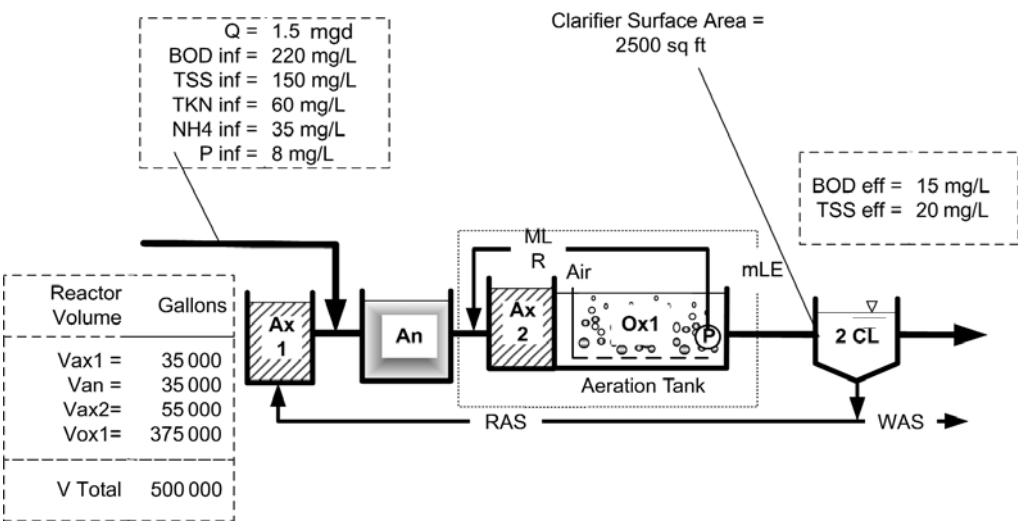


FIGURE 22.17 Biological nutrient removal example.

3. Determine the MCRT

   a. For the entire system:

$$\text{MCRT} = \frac{8340 \text{ lb TSS}}{2060 \text{ lb/d TSS}} = 4.05 \text{ days}$$

   b. For the aerobic (oxic) treatment process:

$$\text{MCRT}_{Ox} = \frac{6255 \text{ lb TSS}}{2060 \text{ lb/d TSS}} = 3.04 \text{ days}$$

4. Evaluate MCRT_{Ox} for nitrification potential:

   a. Figure 22.9 indicates that under optimal laboratory conditions, nitrification could occur if the MCRT is between 2.5 and 8 days. At 12 °C, however, the process needed an MCRT of about 11 days (using a safety factor = 1.5).

   b. Calculations showed that the MCRT_{Ox} is about 3 days.

   c. Conclusion: Nitrification will NOT occur at 12 °C.

Example 22.2: Increase the MCRT. Again, given the plant shown in Figure 22.17, how much should operators reduce the waste flow (Q_{WAS}) to increase the MCRT_{Ox} from about 3 days to 5.5 days over a 5-day period?

Start by determining how many pounds of MLSS must be maintained to achieve the desired MCRT:

$$\begin{aligned}\text{Target TSS}_{WAS} + \text{TSS}_{2EFF} &= M_{Ox}/\text{MCRT}_{Ox} \\ &= 6255 \text{ lb TSS}/5.5 \text{ days} \\ &= 1137 \text{ lb/d TSS}\end{aligned}$$

$$\begin{aligned}\text{Target TSS}_{WAS} &= 1137 \text{ lb/d TSS} - 250 \text{ lb/d TSS} \\ &= 887 \text{ lb/d TSS}\end{aligned}$$

$$\begin{aligned}\text{Target } Q_{WAS} &= (887 \text{ lb/d}/8.34)(7000 \text{ mg/L}) \\ &= 0.0152 \text{ mgd (15 200 gpd)}\end{aligned}$$

$$\begin{aligned}\text{Change in } Q_{WAS} &= 31\,000 \text{ gpd} - 15\,200 \text{ gpd} \\ &= 15\,800 \text{ gpd}\end{aligned}$$

$$\begin{aligned}\text{Amount to reduce per day} &= 15\,800 \text{ gpd}/5 \text{ days} \\ &= 3160 \text{ gpd}\end{aligned}$$

Operators should evaluate the process and recheck their calculations before making process changes.

Example 22.3: Determine the MCRT an SBR Needs to Achieve Nitrification. A sequencing batch reactor facility has the following characteristics:

- Total basin volume (V_B) = 0.5 mil. gal,
- Influent flow (Q) = 425 000 gpd,
- Influent BOD (BOD_{2INF}) = 220 mg/L,
- Aerobic react time = 60%,
- Produced solids (P_X) = 700 lb/d TSS,
- Temperature = 12 °C, and
- MLSS = 2000 mg/L.

The facility does not meet its ammonia limit when winter temperatures are 12 °C or lower. What MCRT would ensure that nitrification occurs?

1. Determine the existing MCRT:

$$\text{MCRT} = \frac{\text{M}}{\text{P}_x} = \frac{(0.5)(8.34)(2000\ \text{mg/L})}{700\ \text{lb/d}} = \frac{8340\ \text{lb TSS}}{700\ \text{lb/d}}$$

$$\text{MCRT} = 11.9\ \text{days}$$

2. Determine MCRT_{Ox} and compare it to the target values suggested to maintain nitrification in Figure 22.9:

$$\text{MCRT}_{Ox} = \frac{\text{MCRT (percent time or volume oxic)}}{100}$$

$$= \frac{11.9\ \text{days}\ (60\%)}{100}$$

$$= 7.14\ \text{days}$$

According to Figure 22.9, the target MCRT_{Ox} should be 12 days when the temperature is 12 °C.

3. Adjust the MCRT for oxic conditions at 12 days:

$$\text{MCRT} = \frac{\text{MCRT}_{Ox}\ (100)}{\text{(Percent time)}} = \frac{12\ \text{days}\ (100)}{60\%}$$

$$= 20\ \text{days required for nitrification}$$

FOOD-TO-MICROORGANISM RATIO. The F:M ratio measures the amount of "food" (*F*; typically BOD) available for the population of "bugs" (*M*; MLVSS) present in the aeration basin. *F* is typically based on the BOD load in primary effluent, or in raw wastewater if the treatment plant lacks primary clarifiers. When the reactors operate in series, the first cell's *M* is calculated using the first cell's volume and MLVSS concentration; the second cell's *M* is calculated using the combined volume and MLVSS concentrations of the first and second cells, etc.

$$\text{F:M} = \frac{\text{BOD of secondary influent}}{\text{MLVSS in the reactor}}$$

The F:M ratio is a good indicator of how well selector reactors will promote the growth of floc-forming bacteria. When the F:M ratio is high, floc-forming bacteria have a competitive advantage over filamentous bacteria.

Selector loading also helps ensure that nuisance bacteria will not cause operating problems. The selector cells should be arranged so BOD is taken up rapidly.

Example 22.4: Determine the F:M Ratio of a BNR Facility. Given the BNR facility described in Figure 22.17, determine its F:M ratio.

1. Determine the incoming BOD load (*F*):

$$\begin{aligned} \text{F} &= (8.34)(1.5 \text{ mgd})(220 \text{ mg/L BOD}) \\ &= 2752 \text{ lb BOD/d} \end{aligned}$$

2. Determine *M* for each treatment zone. If the MLSS is 80% volatile, then the cumulative *M* is:

		Zone *M*	**Cumulative *M***
M_{Ax1} = (0.035 mil. gal)(8.34)(2000 mg/L)(0.8)	=	467	467
M_{An1} = (0.035 mil. gal)(8.34)(2000 mg/L)(0.8)	=	467	934
M_{Ax2} = (0.055 mil. gal)(8.34)(2000 mg/L)(0.8)	=	734	1668
M_{Ox} = (0.375 mil. gal)(8.34)(2000 mg/L)(0.8)	=	5004	6672
Total M	=	**6672 lb**	

3. Calculate the F:M ratio in each selector zone and for the entire system:

$$F:M_{An1} = \frac{2752 \text{ lb/d BOD}}{467 \text{ lb VSS}} = 5.9 \text{ d}^{-1}$$

$$F:M_{Ax1} = \frac{2752 \text{ lb/d BOD}}{934 \text{ lb VSS}} = 2.9 \text{ d}^{-1}$$

$$F:M_{Ax2} = \frac{2752 \text{ lb/d BOD}}{1668 \text{ lb VSS}} = 1.6 \text{ d}^{-1}$$

$$\text{System } F:M = \frac{2752 \text{ lb/d BOD}}{6672 \text{ lb VSS}} = 0.41 \text{ d}^{-1}$$

With consecutive cells (e.g., An_1, Ax_1, Ax_2, or O_x), *F* is the "applied" BOD in the first compartment. *M* increases as greater portions of the reactor are considered in F/M calculations.

HYDRAULIC RETENTION TIME. The hydraulic retention time for maintaining BNR depends on reactor size, which is determined by the MCRT necessary for growth. Once the biological reactor or basin size is known, then the HRT can be calculated by dividing the reactor volume (*V*) by the secondary influent flow (*Q*):

$$\text{HRT} = \frac{(\text{mil. gal of V})(24 \text{ hr/d})}{\text{mgd of Q}}$$

Although not used in daily BNR operations, HRT indicates whether the plant is operating within a normal contact time. Nitrifying facilities, such as conventional activated sludge, A^2O, and MLE processes, typically have an HRT between 5 and 15 hours. Facilities with more intricate recycle patterns, such as the UCT process, typically have HRTs between 10 and 18 hours. Other processes, such as extended aeration, SBR, and oxidation ditch systems, have HRTs between 18 and 36 hours.

Example 22.5: Determine the HRT of a BNR Facility. Given the BNR facility shown in Figure 22.17, calculate the HRT of each zone. Assume that RAS = 0.5 mgd and MLR = 3.0 mgd.

Zone No.	Volume (mil. gal)	Cumulative volume (mil. gal)	Incoming flow Q + RAS + MLR	Nominal HRT (hr)	Actual HRT (hr)
An1	0.035	0.035	2.0	0.56	0.42
Ax1	0.035	0.070	2.0	0.56	0.42

Ax2	0.055	0.125	5.0	0.88	0.16
Ox1	0.375	0.500	5.0	6.00	1.13
Total	**0.500**			**8.00**	

OXYGEN REQUIREMENTS AND AERATION EQUIPMENT. When a conventional activated sludge system is converted into a BNR facility, its dissolved oxygen requirements typically increase, requiring changes in the aeration equipment or diffuser layout. A maximum of 1.2 mg of oxygen is required to treat 1.0 mg of 5-day BOD ($BOD_{5)}$. Approximately 4.57 mg of oxygen is required to oxidize 1.0 mg of ammonia-nitrogen (Table 22.1). If the plant also denitrifies, however, then 2.86 mg of oxygen is recovered for each 1.0 mg of nitrate-nitrogen removed.

When determining aeration equipment needs, treatment plant staff should begin by consulting with equipment suppliers or environmental engineers, because aeration efficiency varies widely. The equipment should be assessed based on field conditions, not laboratory or "standard" conditions (aeration rates in clean water, which may be more than twice the rate possible in wastewater). The field rates for high-speed surface aerators, for example, can range from 1.0 to 2.0 lb of oxygen/hp/hr.

Diffuser equipment calculations are more complicated because of the wide variety of diffusers available. However, the typical field rate for coarse-bubble diffusers in domestic wastewater is 0.375% per foot of submergence. The standard rate for fine-bubble diffusers in clean water is about 0.66% per foot of submergence.

Following are other useful conversion factors:

- 1 standard cu ft of air = 0.0173 lb of oxygen,
- Blower horsepower = (cu ft/min)(lb/sq in. at blower)(0.006), and
- The annual power cost of an aerator or diffuser = \$650/hp if electricity costs \$0.10/kWh.

Example 22.6: Determine the Oxygen Demand for a BNR Facility. If a 2.3-mgd BNR facility nitrifies completely, its influent ammonia = 25 mg/L, and its BOD_{2INF} = 140 mg/L, then:

- What is the oxygen demand for BOD removal alone,
- What is the oxygen demand for BOD removal and nitrification, and
- How much money will the facility save in aeration costs if electricity costs \$0.12/kWh and the plant denitrifies to 8 mg/L of nitrous oxides?

1. Calculate the amount of oxygen required for CBOD removal:

$$O_2 = \frac{(140 \text{ mg/L BOD})(1.2 \text{ mg/L } O_2)(2.3 \text{ mgd})(8.34)}{1.0 \text{ mg/L BOD}}$$

$$= 3223 \text{ lb/d } O_2$$

2. Calculate the oxygen demand after nitrification (without denitrification):

   a. NOD = (25 mg/L NH_4-N)(8.34)(4.57 mg oxygen/mg NH_4-N)(2.3 mgd)

   = 2192 lb/d O_2

   b. TOD = CBOD + NOD

   = 3223 lb/d O_2 + 2192 lb/d O_2

   = 5415 lb/d O_2

   (Note: The above is a simplified approach for a rough approximation.)

3. Calculate how much aeration energy will be saved if the plant also adds denitrification.

   a. Determine how much nitrate will be produced:

$$P_{NO_X} = NH_4\text{-}N_{2INF} - NO_{X2EFF}$$

$$NO_x = (25 \text{ mg/L } NH_4\text{-N} - 8 \text{ mg/L } NO_3\text{-N})(8.34)(2.3 \text{ mgd})$$

$$= 326 \text{ lb/d } NO_3\text{-N}$$

   b. Calculate the amount of oxygen saved:

$$\text{lb } O_2 = \frac{326 \text{ lb } NO_X}{1 \text{ day}} \times \frac{2.9 \text{ lb } O_2 \text{ recovered}}{1 \text{ lb } P_{NO_X}}$$

$$= 946 \text{ lb/d } O_2 \text{ recovered}$$

   c. Determine how much money is saved each year if electricity costs \$0.12/kWh (assume the facility uses surface high-speed aerators with a field transfer rate of 1.3 lb O_2/hp/hr):

$$\text{Electricity} = \frac{(946 \text{ lb } O_2)}{1 \text{ day}} \times \frac{1 \text{ hp-hr}}{1.3 \text{ lb } O_2} \times \frac{1 \text{ day}}{24 \text{ hrs}}$$

$$= 30.3 \text{ hp saved}$$

$$\text{Savings} = 30.3 \text{ hp} \times \frac{\$650}{\text{hp} \cdot \text{year} \cdot \$0.10/\text{kWh}} \times \frac{\$0.12}{\text{kWh}}$$
$$= \$23,630/\text{yr}$$

Example 22.7: Determine How Much More Air Blower Capacity a Treatment Plant Needs to Nitrify Wastewater. Suppose an activated sludge plant must nitrify its wastewater (its previous limits were for CBOD only), and its aeration basin has coarse-bubble diffusers that are 14 ft below the water surface. Plant staff already know that they need 1600 lb/d more oxygen to nitrify the wastewater. So, how much more horsepower is needed?

1. Calculate the coarse-bubble diffusers' efficiency at 14-ft submergence:

$$\text{Percent efficiency} = (0.375\%/\text{ft})(14 \text{ ft})$$
$$= 5.25\% \text{ field transfer for coarse bubble}$$

[Note: For fine-bubble diffusers, the percent efficiency = (0.66%/ft)(14 ft) = 9.24%]

2. Then determine the required airflow rate:

$$\text{Airflow} = \frac{(100)(\text{lb/d } O_2 \text{ Required})}{(0.0173 \text{ lb } O_2/\text{cu ft})(\text{Percent efficiency})(1440 \text{ min/d})}$$

$$\text{Airflow} = \frac{(100)(1600 \text{ lb/d } O_2)}{(0.0173 \text{ lb } O_2/\text{cu ft})(5.25\%)(1440 \text{ min/d})}$$
$$= \frac{1600 \text{ lb/d } O_2}{(0.2491)(5.25)}$$
$$= 1220 \text{ cfm}$$

3. Estimate the discharge pressure at the blower [assume 4-ft headlosses in air piping and equipment (line losses)]:

$$\text{Total head at blower} = \text{Static} + \text{Line headloss}$$
$$= 14 \text{ ft} + 4 \text{ ft}$$
$$\text{Total head} = 18 \text{ ft or } 7.8 \text{ psi}$$

(Note: 1 psi = 2.31 ft of water)

4. Calculate the additional blower horsepower needed:

$$\text{Blower hp} = (\text{cfm})(\text{psi})(0.006)$$
$$= (1220 \text{ cfm})(7.8 \text{ psi})(0.006)$$
$$= 57 \text{ hp}$$

(Note: These calculations are strictly illustrative. See equipment curves, etc., for more precise calculations.)

ALKALINITY AND pH CONTROL. Every time 1 mg of ammonia-nitrogen is oxidized to nitrate, 7.14 mg of alkalinity is consumed. Likewise, every time 1 mg of nitrate is converted to nitrogen gas, 3.57 mg of alkalinity is recovered.

Example 22.8: Chemical Addition for pH Control. To maintain stable operations, an effluent's alkalinity must be maintained at 80 mg/L of calcium carbonate. Suppose a 1.4 mgd wastewater treatment plant's effluent alkalinity is 120 mg/L, and it plans to nitrify 22 mg/L of ammonia. How much hydrated lime should plant staff add to nitrification effluent to maintain the desired alkalinity?

1. Calculate the amount of alkalinity required for nitrification:

   According to Table 22.2,

$$\text{Alkalinity depletion from N} = \frac{7.14 \text{ mg } CaCO_3}{1 \text{ mg N oxidized}}$$

   so the

$$\text{Alkalinity required} = 22 \text{ mg/L } NH_3\text{-N} \times \frac{7.14 \text{ mg } CaCO_3}{1 \text{ mg } NH_3\text{-N}}$$
$$= 157 \text{ mg/L } CaCO_3$$

2. Determine how much alkalinity must be added:

$$\text{Alkalinity added} = (\text{Alkalinity goal}) + (\text{Alkalinity required}) - (\text{Alkalinity present})$$
$$= 80 \text{ mg/L} + 157 \text{ mg/L} - 120 \text{ mg/L} = 117 \text{ mg/L as } CaCO_3$$

3. Estimate the amount of lime needed (assume 1.33 lb alkalinity/1 lb lime).

   a. Alkalinity added (lb/d) = (117 mg/L)(8.34)(1.4 mgd)

$$= 1366 \text{ lb/d as } CaCO_3$$

b. $$\text{Lime needed} = \frac{1366 \text{ lb } CaCO_3/d}{1.33 \text{ lb alkalinity}/1 \text{ lb lime}}$$
$$= 1027 \text{ lb/d}$$

DENITRIFICATION REQUIREMENTS. Facilities required to remove nitrate will need to consider whether there are suitable conditions for NO_X removal. The following calculations provided examples of how to determine if there is sufficient reactor volume and if the rate of denitrification is adequate to achieve treatment goals.

Example 22.9: Determine the Anoxic Selector Size Needed to Achieve a Specific Nitrate Limit. Suppose a 2.3-mgd wastewater treatment plant plans to convert to the MLE process. Its secondary influent has a BOD concentration of 160 mg/L. The wastewater in the 0.6-mil. gal aeration basin is about 15 °C and contains 3000 mg/L of MLSS (VSS = 2400 mg/L). The plant needs to denitrify 18 mg/L of produced nitrate. What size must the anoxic selector be to meet an effluent nitrate limit of 7 mg/L?

1. Estimate a selector size based on experience (typically 20 to 40% of the aeration basin volume). Assume that 30% of the basin will be converted to an anoxic selector:

$$V_{ax} = (0.3)(0.6 \text{ mil. gal})$$
$$= 0.18 \text{ mil. gal}$$

2. Calculate the amount of nitrate to be removed:

$$NO_x \text{ removed} = (P_{NO_x} - NO_{X2EFF})$$
$$= 18 \text{ mg/L} - 7 \text{ mg/L}$$
$$NO_x \text{ removed} = 11 \text{ mg/L}$$
$$= (11 \text{ mg/L})(8.34)(2.3 \text{ mgd})$$
$$NO_x \text{ removed} = 211 \text{ lb/d}$$

3. Determine the selector's SDNR:

$$\text{SDNR} = \frac{NO_X}{\text{lb MLVSS}}$$
$$= \frac{211 \text{ lb/d } NO_X}{(8.34)(2400 \text{ mg/L})(0.18 \text{ mil. gal})}$$

$$= \frac{211 \text{ lb/d } NO_X}{3603 \text{ lb MLVSS}}$$

$$= \frac{0.059 \text{ lb } NO_X}{1 \text{ lb/d MLVSS}}$$

4. Compare the calculated SDNR with the range of SDNRs published in Metcalf and Eddy, Inc. (2003) to confirm that too much nitrate will not be applied to the anoxic zone.

Actual SDNRs vary widely because of wastewater characteristics, operating temperature, and the F:M ratio. Let's suppose the SDNRs in the literature range from 0.03 to 0.12. The calculated SDNR is in the lower end of this range, so the anoxic volume may be acceptable. However, to better ensure the performance of the denitrification process, plant staff could

- Enlarge the anoxic selector zone,
- Operate it at a higher MLVSS concentration, and
- Divide the anoxic selector into three or four cells to increase the F:M ratio.

OXIDATION–REDUCTION POTENTIAL. Automated control systems for the internal anoxic mixing process measure the ORP so they can detect nitrate depletion in the mixed liquor. This variable indirectly measures nitrate availability in an aqueous media, although there is no direct correlation between any specific ORP value and nitrate concentration.

Oxidation–reduction potential measures the net electron activity of all oxidation–reduction reactions occurring in wastewater. It is affected by temperature, pH, biological activity, and the system's chemical constituents, but its response pattern to changes in a solution's oxidative state is reproducible in a specific system.

In continuous-flow suspended-growth systems, the control system's ORP breakpoints must be constantly reviewed and revised. In batch systems (e.g., SBR or cyclic aeration systems), however, a characteristic "knee" (change in ORP values) indicates when the system is changing from an oxidized state to a reduced one.

RECYCLE FLOWS. For wastewater facilities with either ammonia and/or nitrate limitations, it will be necessary to adjust recycle flows (typically RAS flow and/or MLR_{Ox}) to achieve operational goals. The following are examples of calculations and that may be required.

Example 22.10: The Effect of BNR on RAS and MLR. Suppose that a 1.7-mgd activated sludge plant has a 0.4-mil. gal aeration basin, 32 mg/L of ammonia-nitrogen in its secondary influent, 1500 mg/L of MLSS, and 8000 mg/L of TSS in its RAS. To nitrify its wastewater, the plant will need to operate at an MLSS of 3000 mg/L. The plant will also be converted to the MLE process, with MLR returned to the anoxic zone for denitrification. Its new nitrous oxide standard will be 12 mg/L. With this in mind, determine the RAS flow needed to maintain 3000 mg/L of MLSS, and calculate the MLR to the anoxic zone (MLR_{Ox}).

1. Determine the Q_{RAS}:

   The mass balance around the secondary clarifier is

   $$\text{Incoming solids} = \text{Outgoing solids}$$

   $$(MLSS)(Q + Q_{RAS}) = (TSS_{2EFF})(Q) + (TSS_{RAS})(Q_{RAS})$$

   Because the TSS_{2EFF} is small, assume it equals zero and rearrange the equation so

   $$\frac{Q}{Q_{RAS}} = \frac{TSS_{RAS}}{MLSS} - 1$$

Therefore

$$\frac{1.7 \text{ mgd}}{Q_{RAS}} = \frac{8000 \text{ mg/L}}{3000 \text{ mg/L}} - 1 = 1.67$$

$$Q_{RAS} = 1.7/1.67$$

$$= 1.02 \text{ mgd}$$

2. Calculate the MLR_{Ox} (Equations 22.15 to 22.18). First, determine how much nitrous oxide must be removed to achieve the limit (assume 1 mg/L of produced nitrous oxide for each 1 mg/L of influent ammonia):

$$Mr = \frac{P_{NO_x}}{NO_{X2EFF}} - 1 - Rr \tag{22.20}$$

Where

Mr = MLR/Q (MLR flow ratio),
Rr = Q_{RAS}/Q (RAS flow ratio),
P_{NO_x} = Produced NO_3-N + mg/L of NO_2, and
NO_{X2EFF} = mg/L of NO_3-N + NO_2 in the effluent.

So

$$Mr = \frac{32 \text{ mg/L}}{12 \text{ mg/L}} - 1 - \frac{1.02 \text{ mgd}}{1.7 \text{ mgd}}$$

$$Mr = 1.07 = \frac{MLR_{Ox}}{Q} = \frac{MLR_{Ox}}{1.7 \text{ mgd}}$$

Therefore

$$MLR_{Ox} = (1.7 \text{ mgd})(1.07)$$

$$= 1.8 \text{ mgd}$$

SECONDARY CLARIFICATION. It is essential that the secondary clarifier be able to both separate biological solids from the treated effluent and also concentrate the solids without a buildup of sludge within the clarifier. Parameters of concern with clarification are the hydraulic loading rate (HLR) and the solids loading rate (SLR).

Example 22.11: Calculate Secondary Clarifier Capacity. Given the activated sludge system in Example 22.10, assume that peak flows are three times the average. Therefore, plant data are as follows:

	Present	Future
Flow (mgd)		
Q average	1.7	1.7
Q peak	5.1	5.1
Q_{RAS}	0.4	1.02
MLSS (mg/L)	1500	3000
RAS (mg/L)	8000	8000

Suppose the plant has two 47-ft-diameter secondary clarifiers (total clarifier area = 3470 ft^2). Calculate the current and future clarifier loading.

1. First, check the clarifier's HLR (only one calculation is shown):

$$HLR = \frac{(Q)(1 \text{ mil. gal/mgd})}{\text{Clarifier area}}$$

$$HLR_{1.7} = \frac{(1.7 \text{ mgd})(1 \text{ mil. gal/mgd})}{3470 \text{ sq ft}}$$

$$= 490 \text{ gpd/sq ft}$$

A summary of HLRs for present and future is:

Condition	Present	Future
Average flow (1.7 mgd)	490	490
Peak flow (5.1 mgd)	1470	1470

When these HLRs are compared to those typically suggested for operations, the average HLRs are within the range typically suggested for good performance (400 to 600 gpd/sq ft). Future peak HLRs, however, fall slightly above the recommended range (800 to 1200 gpd/sq ft).

2. Next, check the clarifier's SLR (only one calculation is shown):

$$\text{SLR} = \frac{(Q + Q_{RAS})(8.34)(\text{MLSS})}{\text{Clarifier area}}$$

$$\text{Present SLR}_{1.7} = \frac{(1.7 \text{ mgd} + 0.4 \text{ mgd})(8.34)(1500 \text{ mg/L})}{3470 \text{ sq ft}}$$

$$= 7.6 \text{ lb TSS/d/sq ft}$$

A summary of SLRs for present and future is:

Condition	Present	Future
Average flow (1.7 mgd)	7.6	19.6
Peak flow (5.1 mgd)	19.8	48.1

When these SLRs are compared to those typically suggested for operation, the average SLRs are below that recommended for BNR plants (20 lb TSS/d/sq ft).

Future peak SLRs are slightly above that recommended for BNR plants (35 lb TSS/d/sq ft).

So, the secondary clarifiers seem to be adequate for average loading but marginal for peak loads. Success depends on the clarifier design and configuration. Sludge settleability and characteristics will determine whether more clarifiers should be constructed.

TROUBLESHOOTING

Some of the most common operating problems at BNR facilities are foam control and bulking (nonsettling) sludge (Table 22.7, 22.8, and 22.9).

TABLE 22.7 Troubleshooting nitrification and denitrification facilities.

Observations	Solutions
BOD $<$ 25 mg/L, NH_4-N $>$ 3 mg/L	Ensure MCRT is sufficient for design temperature
Effluent NH_4-N varies erratically, $>$ 3 mg/L and $<$ 2 mg/L, in a short period of time	Waste sludge operation not stabilized, stop wasting until NH_4-N is $<$ 2 mg/L for 3 consecutive days; restart a careful sludge-wasting operation
Effluent NH_4-N $>$ 3 mg/L, dark brown or black MLSS	Check aeration zone DO, should be $>$ 2 mg/L; check MLSS solids balance; MCRT may be too high
Brown clumps of sludge floating on final clarifier surface; effluent NH_4-N $<$ 2 mg/L, BOD $<$ 30 mg/L	Nitrogen gas bubbles being produced in stagnant sludge in clarifier; check return sludge recycle rate, increase frequency of cleaning of clarifier walls and weirs
Effluent NH_4-N $>$ 10 mg/L, BOD $>$ 25 mg/L	Check MCRT, check mixed liquor DO, check MLSS; if all appear satisfactory, plant may be receiving inhibitor of of nitrification from industry; check pretreatment program
Effluent NO_3-N $>$ 7 mg/L, NH_4-N $<$ 2 mg/L	DO in anoxic zone, should be less than 0.2 mg/L

FOAM CONTROL. Activated sludge processes typically have foam (froth) floating in the biological reactor. In a well-operated process, a 50- to 80-mm (2- to 3-in.) layer of light tan foam will cover between 10 and 25% of the reactor surface. Excessive foam, however, can degrade operations. Three types of foam typically are problematic: stiff, white foam; brown foam (either greasy and dark tan or thick, scummy, and dark brown); and very dark or black foam.

TABLE 22.8 Troubleshooting biological phosphorus removal facilities.

Observations	Solutions
Effluent SP $>$ 1 mg/L, TP $>$ 2 mg/L, BOD $<$ 20 mg/L	Ensure DO in anaerobic zone is $<$ 0.2 mg/L, NO_3-N in anaerobic zone is $<$ 5 mg/L
Effluent SP $<$ 1 mg/L, TP $>$ 2 mg/L, BOD $<$ 25 mg/L, SS $>$ 30 mg/L	Check SS frequently, use polymer or metal salt to control SS; find reason for high SS, such as high flow rates, high return sludge recycle rate, or bulking
Effluent SP $<$ 0.2 mg/L, TP $<$ 1 mg/L, BOD $>$ 30 mg/L	Plant may be organically overloaded; check F:M ratio
Effluent SP $>$ 1 mg/L, TP $>$ 2 mg/L, BOD $<$ 15 mg/L	May not be enough low molecular weight acids in anaerobic zone; consider adding anaerobic digester supernatant to this zone
Thin-looking MLSS, effluent TP $>$ 2 mg/L, BOD $<$ 30 mg/L	Sludge may be forming a blanket in secondary clarifier, check sludge blanket depth, adjust recycle rate if necessary
Effluent TP $>$ 2 mg/L, BOD $<$ 25 mg/L, SS $<$ 25 mg/L	Start or increase dose of metal salt to assist in precipitating TP

TABLE 22.9 Troubleshooting facilities that remove both nitrogen and phosphorus.

Observations	Solutions
Effluent TP < 2 mg/L, NH_4-N < 2 mg/L, NO_3-N > 7 mg/L	Check recirculation rate between aerobic zone and anoxic zone, increase rate if necessary; check DO in anoxic zone, should be < 0.2 mg/L
Effluent TP < 2 mg/L, NH_4-N < 2 mg/L, NO_3-N < 2 mg/L, BOD > 30 mg/L	Check feed rate of optional chemical dosing pump for adding organics to second anoxic zone
Effluent TP < 2 mg/L, NH_4-N > 3 mg/L, NO_3-N < 5 mg/L, BOD < 25 mg/L	Check DO in aerobic zone, should be > 2 mg/L

Stiff, White Foam. If stiff, white foam builds up and the wind can blow it onto walkways and other structures, where it looks unsightly and makes working conditions hazardous. This foam also can be odorous and transport pathogens. If it overflows to the secondary clarifiers, this foam tends to collect behind the influent baffles, creating more cleaning problems, and can plug the scum-removal system.

This type of foam indicates a "young" sludge (low MCRT); it is typically found in new or underloaded plants when the MLSS concentration is too low and the F:M ratio is too high. The foam may consist of detergents or proteins that cannot be converted to food by the type of bacteria that are predominant in the mixed liquor. Such foam may occur when

- Activated sludge is not returned to the biological reactor;
- MLSS is low because the process is being started up;
- MLSS is low because of excessive sludge wasting or a high organic load from an industry (typically occurs after low-load periods, such as weekends and early mornings);
- Operations conditions are unfavorable (toxic or inhibiting materials are present, pH is less than 6.5 or more than 9.0, dissolved oxygen or nutrient concentrations are too low, or seasonal temperature changes have reduced microorganism activity and growth);
- Secondary clarifier effluent loses biomass unintentionally because of excessive (shock) hydraulic loads or biological upset;
- A high sludge blanket in the secondary clarifier because of leaking seals or open dewatering valves; or
- Wastewater or RAS is improperly distributed among multiple biological reactors.

Excessive Brown Foam. Brown foam occurs in plants operating at low loading ranges. Nitrification plants operating in nitrifying mode, for example, typically have low to moderate amounts of chocolate brown foam. If *Nocardia* (a filamentous organism) is present, the foam will be strong (not easily collapsed), greasy, and dark tan. It also will overflow onto the clarifier surface. Filamentous organisms containing scum should be wasted from the system rather than returned to the biological reactors in order not to concentrate foam-causing organisms.

Treatment plants that re-aerate sludge typically have heavy, greasy, dark brown foam in their aeration stage. A thick, scummy, dark brown foam indicates an old sludge (long MCRT). This foam can build up behind influent baffles in the clarifier, creating a scum disposal problem.

Overall, brown foam is likely to occur when

- The F:M ratio is low because of nitrification and denitrification;
- The MLSS concentration is high because of insufficient sludge wasting (can happen unintentionally when seasonal temperature changes increase microorganism activity and, therefore, sludge production);
- Sludge is re-aerated (especially if the F:M ratio is low); or
- The wasting controls are insufficient.

Very Dark or Black Foam. Very dark or black foam occurs when aeration is insufficient (anaerobic conditions) or industrial wastes, such as dyes and inks, are present. To correct this problem, operators should

- Increase aeration;
- Investigate industrial waste sources for dyes or inks; and
- Reduce the MLSS concentration.

BULKING SLUDGE. If the supernatant above poorly settling sludge is clear, filamentous microorganisms are hindering settling. To correct this problem, operators should

- Add nutrients, such as nitrogen, phosphorus, and iron;
- Raise the dissolved oxygen concentration in the biological reactor; or
- Correct the pH (either raise or stabilize it).

If the supernatant above poorly settling sludge is cloudy, the problem is dispersed-growth bulking caused by improper organic loading, overaeration, or toxics.

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Chapter 23

Natural Biological Processes

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INTRODUCTION

Stabilization lagoons and land treatment processes are natural systems that are commonly used to treat municipal wastewater of small communities with populations of less than 20 000. Stabilization lagoons typically provide secondary treatment; land treatment systems often provide higher levels of treatment. According to the U.S. Environmental Protections Agency's (U.S. EPA's) Report to Congress, *Municipal Wastewater Lagoon Study* (U.S. EPA, 1987) and its *1988 Needs Survey Report to Congress: Assessment of needed Publicly Owned Wastewater Treatment Facilities in the United States* (U.S. EPA, 1989), more than 5 500 lagoons and 1 225 land treatment systems are operated in the U.S.

This chapter provides information that will enable the operator of lagoons and land treatment systems to prevent problems, solve those that occur, and improve the performance of these natural systems.

LAGOONS

DESCRIPTION OF PROCESSES. Lagoons are typically basins constructed entirely of earth. By using cut and fill to remove the original topsoil, lagoons are built above ground by enclosing an area with earthen dikes. Traditionally, lagoons have been lined with compacted, natural materials such as clay. With current groundwater concerns, newly constructed lagoons are often lined with synthetic barriers, or composites of natural and synthetic barriers. Groundwater monitoring, although traditionally not extensive, is receiving more emphasis today. The microorganisms existing within the lagoon make the wastewater treatment lagoon work. Lagoons are generally classified according to the biological processes that occur within the basin. These classifications of lagoons are aerobic, anaerobic, and aerobic-anaerobic. They are further classified according to how oxygen is imparted to the system. Unaerated lagoons are systems that do not require mechanical assistance for oxygen addition. Conversely, aerated lagoons require mechanical facilities for the addition of oxygen.

The oxygen distribution within the lagoon determines the type of lagoon required. Aerobic lagoons have oxygen distributed throughout the water. Anaerobic lagoons

have no oxygen. Facultative lagoons have both an aerobic layer and an anaerobic layer. The degree of waste stabilization achieved is governed primarily by the particular biological community established within the lagoon and affecting the oxygen demand.

Lagoons can be constructed in a series of ponds. Sedimentation of solids and anaerobic decomposition of settled organic material occurs in the first cell, called the *primary cell*. Secondary treatment, whereby organic matter is oxidized aerobically into stable products, reducing the biochemical oxygen demand (BOD) and suspended solids (SS), is accomplished in the primary and secondary cells. A third step is often included to polish the treated wastewater. The cells of this third step, referred to as *tertiary* or *polishing* lagoons, are lightly loaded to remove additional BOD and suspended matter. Figure 23.1 presents typical flow schematics for lagoons.

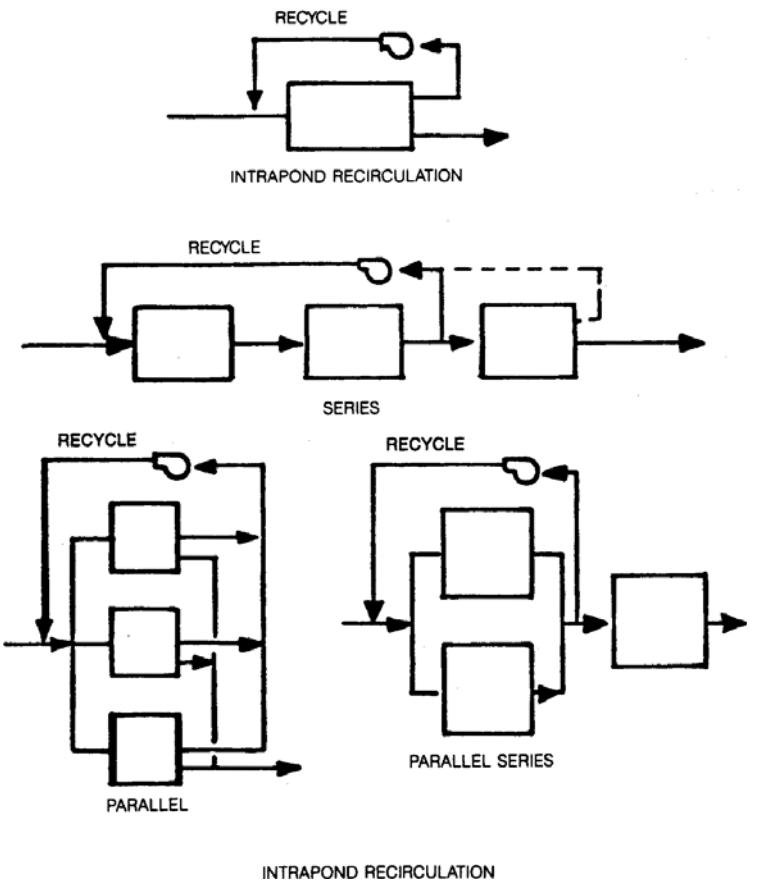


FIGURE 23.1 Common lagoon configurations and recirculation systems (U.S. EPA, 1983).

Unaerated Stabilization Lagoons. An unaerated lagoon can be aerobic, anaerobic, or facultative. Organic contaminants in the wastewater are assimilated by aerobic and facultative bacteria. Oxygen required for aerobic bacterial respiration is provided by the natural transfer of oxygen at the air-water interface and by photosynthetic algae. During photosynthesis, algae use energy from sunlight and byproducts excreted by bacteria to produce sugars and oxygen.

The amount of natural oxygen transfer at the water surface depends on the amount of wind-induced turbulence. Oxygen transfer is also affected by the solubility of oxygen, which is a function of the water temperature. Oxygen solubility is greater at lower temperatures than at higher temperatures. Unaerated stabilization lagoons are shallow ponds with 0.9 to 1.5 m (3 to 5 ft) of liquid depth.

Aerobic Lagoons. In aerobic lagoons, contaminants are biologically degraded in the presence of dissolved oxygen (DO). The physical dimensions, temperature, amount of sunlight, and amount of natural or artificial turbulence are used to maintain a desired DO concentration. Aerobic lagoons are typically 0.9 to 2.4 m (3 to 8 ft) deep. It should be noted that, in practice, it is not possible to maintain a completely aerobic lagoon. The bottom sediments will contain some facultative bacteria. An example of an aerobic lagoon is a polishing lagoon.

Anaerobic Lagoons. In an anaerobic lagoon, where no DO is present, bacterial degradation of waste produces reduced products such as methane (CH_4) and hydrogen sulfide (H_2S). The conversion of organic acids to methane and carbon dioxide by methane bacteria is affected by dissolved oxygen, pH, and temperature; therefore, the efficiency of the anaerobic lagoon process is sensitive to these parameters.

An anaerobic lagoon is quite often used as a roughing process before an aerobic or facultative lagoon (Burkhead and O'Brien, 1974). With this serial design, intermediate products from the anaerobic process can be oxidized in the aerobic process. The water depth in an anaerobic lagoon is typically greater than 3 m (10 ft). Economy, groundwater level, and heat retention considerations dictate the lagoon depth.

Facultative Lagoons. Most lagoons are facultative. They are designed and operated to provide zones in which DO is absent (for anaerobic decomposition of waste) and zones in which DO is present (for aerobic degradation of anaerobic byproducts and other waste constituents) (U.S. EPA, 1983). As wastewater enters a lagoon, the heavy solids settle out near the inlet bottom where anaerobic bacteria stabilize the organic

matter. Waste stabilization of settled solids occurs anaerobically in two steps (Middlebrooks et al., 1982, and Zickefoose and Hayes, 1977):

- Acid bacteria break down the complex organics by feeding on the soluble matter, thereby converting it to organic acids.
- The methane bacteria feed on the organic acids, thereby converting them to carbon dioxide, ammonia, hydrogen sulfide, and methane gas.

The aerobic bacteria in the upper layers of the basin feed on the liquid and gaseous byproducts from the anaerobic decomposition of organic matter (see Chapter 30). Aerobic bacteria use the soluble organics in the raw waste and the soluble organics from anaerobic decomposition to produce some inert material, dissolved sulfate, nitrate, phosphate, and carbonate compounds that are a source of energy for anaerobic bacteria. Algal photosynthesis, atmospheric reaeration, and/or mechanical aeration provide oxygen sources for the aerobic bacteria. Facultative lagoons are typically 0.9 to 1.8 m (3 to 6 ft.) in depth.

Aerated Lagoons. Unlike the shallower unaerated stabilization lagoons, aerated lagoons do not depend on algal photosynthesis to furnish oxygen for bacterial respiration. Dissolved oxygen is provided by mechanical or diffused air aeration equipment. Lagoons designed for mechanical aeration are typically 3 to 4.5 m (10 to 15 ft) deep (McKinney, 1970). There are several types of aerated lagoons including completely mixed aerated lagoons, partially mixed facultative lagoons, and a combination of the two. These lagoons vary by the amount of DO in the lagoon profile and in the DO concentration variation during the day.

PHYSICAL CONFIGURATION OF LAGOONS. Most lagoon systems are designed with earthen dikes and inlet and outlet works. Designs are normally based on a balanced cut and fill so that dikes can be constructed from excavated material. The outside slopes of the dikes are either 3:1 (horizontal:vertical) or flatter to permit grass mowing.

Interior slopes are steeper, ranging from 2:1 to 3:1. However, lagoons with surface aerators may have interior slopes of 4:1 to minimize erosion. Grass slopes steeper than 3:1 may be difficult to maintain. Larger lagoons include a minimum of 0.6 to 0.9 m (2 to 3 ft) of freeboard that provides stability to the dike and room for ice accumulation in colder climates (Townshend and Knoll, 1987). Lagoons that are greater than 4 ha (10 ac) or are located in windy areas should be protected from wave erosion.

The dike is commonly protected by rip-rap from 0.3 m (1 ft) below the minimum water surface to the top of freeboard to protect against wave action.

Seepage from the lagoon should not exceed 6 mm/d (0.25 in./day) (U.S. EPA, 1983). Some states require significantly lower seepage rates. To prevent seepage from the lagoon, a natural clay liner is normally provided. Bentonite and vinyl liners have also been used to limit seepage. Finished clay seals are at least 0.3 m (1 ft) thick. Plastic liners need proper bedding and cover materials to protect and hold the liners in place. Exposed plastic liners are easily damaged by sunlight, animals, equipment, and vandalism. Some liners materials on the market today, such as chlorosulfonated polyethylene, are resistant to ultraviolet light damage.

The inlet structure for small lagoons is at the center, whereas large lagoons employ inlet diffusers with multiple outlet ports to distribute the waste over a larger area. Transfer and outlet structures should permit lowering of the water level at a rate less than 300 mm/wk (1 ft/wk) when the system is receiving normal flow. Although a common practice to control depth (Middlebrooks et al., 1982) is to use manhole-type structures with either valved piping or adjustable stop log-type overflow gates, the logs may swell and jam in their retaining grooves making them difficult to remove (Oswald, 1968). Because the logs may not be watertight after they have been removed and later replaced, valved overflow and drain pipes are a more favorable alternative.

DESIGN PARAMETERS. Table 23.1 presents typical design parameters for various types of stabilization lagoons. Several empirical and rational design equations have been developed for facultative lagoons (Gloyna, 1976; Marais, 1970; Metcalf & Eddy, 1991; Middlebrooks et al., 1982; Neel et al., 1961; Thirumurthi, 1969 and 1974; U.S. EPA, 1975; and Wehner and Wilhelm, 1956). The main design parameter for sizing unaerated and facultative lagoons is organic mass loading per unit of area (kg BOD_5/ha·d [lb/ac/day]). Because anaerobic biochemical reactions are a function of detention time, anaerobic lagoons should be designed on the basis of volumetric loading (kg BOD_5/m^3·d [lb BOD_5/ac-ft/day]), not on surface area.

Hydraulic detention times and wastewater depth for each process can vary widely depending on climatic conditions and waste loads. For example, anaerobic lagoons have successfully operated at design detention times ranging from 5 to 180 days (in colder climates) with wastewater depths from 1.5 to 6 m (5 to 20 ft), depending on waste loads, climatic conditions, treatment requirements, and other variables (Middlebrooks et al., 1982).

SYSTEM START-UP. Lagoons can be operated in parallel or series. For parallel systems, distribution chambers or splitter boxes with adjustable weirs or splitter arrangements are used to evenly divide influent waste streams between primary cells.

TABLE 23.1 Typical design parameters for stabilization ponds.

	Type of pond					
Parameter	**Aerobic low rate[a]**	**Aerobic high rate**	**Aerobic maturation**	**Aerobic-anaerobic facultative[b]**	**Anaerobic pond**	**Aerated lagoon**
Flow regime	Intermittently mixed	Intermittently mixed	Intermittently mixed	Mixed surface layer		Completely mixed
Pond size, acres	<10 multiples	0.5–2	2–10 multiples	2–10 multiples	0.5–2 multiples	2–10 multiples
Operation[c]	Series or parallel	Series	Series or parallel	Series or parallel	Series	Series or parallel
Detention time[c,d]	10–40	4–6	5–20	5–30	20–50	3–10
Depth, ft	3–4	1–1.5	3–5	4–8	8–16	6–20
pH	6.5–10.5	6.5–10.5	6.5–10.5	6.5–8.5	6.5–7.2	6.5–8.0
Temperature range, °C	0–30	5–30	0–30	0–50	6–50	0–30
Optimum temperature, °C	20	20	20	20	30	20
BOD_5 loading,[d] lb/acre·d	60–120	80–160	≤15	50–180	200–500	
BOD_5 conversion, %	80–95	80–95	60–80	80–95	50–85	80–95
Principal conversion	Algae, CO_2, bacterial cell tissue	Algae, CO_2, bacterial cell tissue	Algae, CO_2, bacterial cell tissue NO_3	Algae, CO_2, CH_4, bacterial cell tissue	CO_2, CH_4, bacterial cell tissue	CO_2, bacterial cell tissue
Algal concentration, mg/L	40–100	100–260	5–10	5–20	0–5	
Effluent suspended solids,[e] mg/L	80–140	150–300	10–30	40–60	80–160	80–250

[a]Conventional aerobic ponds designed to maximize the amount of oxygen produced rather than the amount of algae produced.
[b]Pond includes supplemental aeration. For ponds without supplemental aeration, typical BOD_5 loadings are about one-third of those listed.
[c]Depends on climatic conditions. Many cold climate states require 180 days of detention time.
[d]Typical values. Much higher values have been applied at various locations. Loading values are often specified by state regulatory agencies.
[e]Includes algae, microorganisms, and residual suspended solids. Values are based on an influent soluble BOD_5 of 200 mg/L and, with the exception of the aerobic ponds, an influent suspended solids of 200 mg/L.
Note: acre × 0.404 7 = ha; ft × 0.304 8 = m; lb/acre·d × 1.120 9 = kg/ha·d.

In lagoons operated in series, the quality of the effluent improves as it is transported through each lagoon. Therefore, series operation is used when higher quality effluent is required. However, it should be noted that the design of each lagoon must be based on the influent conditions to that lagoon, and not on an average of conditions to all the lagoons in series.

The optimal season for startup to avoid low temperatures and possible freezing is either spring or summer. If it is necessary to start the system in the late fall or winter, the water level should be brought to 0.75 to 1 m (2.5 to 3 ft) and no discharge allowed until late spring (Zickefoose and Hayes, 1977). The procedure outlined below is generally for facultative lagoons and is intended to minimize weed growth and anaerobic conditions during system start-up:

- Fill the primary cell to the 0.6 m (2 ft) level, using fresh water.
- Start the addition of wastewater to the primary cell.
- Maintain the pH above 7.5 (see Chapter 17).
- Check DO daily.
- Begin introducing fresh water to successive cells when the water level in the primary cell reaches 1 m (3 ft).
- Add fresh water to a depth of 0.6 m (2 ft).
- Begin transferring water from the previous cell using only the top draw-off. Do not draw off water from the bottom 45 cm (18 in.), to avoid transferring settled solids to the next cell.
- Do not allow the water level in the previous cell to fall to less than 1 m (3 ft).
- To equalize the water depths in all the cells, do not discharge until all the cells are filled. If available, use an effluent box with gates or valves to recycle the effluent to any cell in the system to raise the water level. Raise the water level in each cell in 15-cm (6-in.) increments until cells are at their operating depth.
- Implement the designed operating strategy once a healthy growth of organisms has formed in the systems, the appropriate chemical and biological tests have been made, and state permission has been received.

PROCESS CONTROL. Control structures in the system should allow different water levels, flow rate control, complete shutoff, complete draining, and changing direction of flow to allow either series and/or parallel operation (Figures 23.2 and 23.3). The goal of a stabilization lagoon is to meet the National Pollutant Discharge Elimination System (NPDES) permit requirements for BOD_5 and suspended solids. Consequently, it is best to discharge when the system is producing the highest quality effluent that will have the least adverse impact on the quality of the receiving stream.

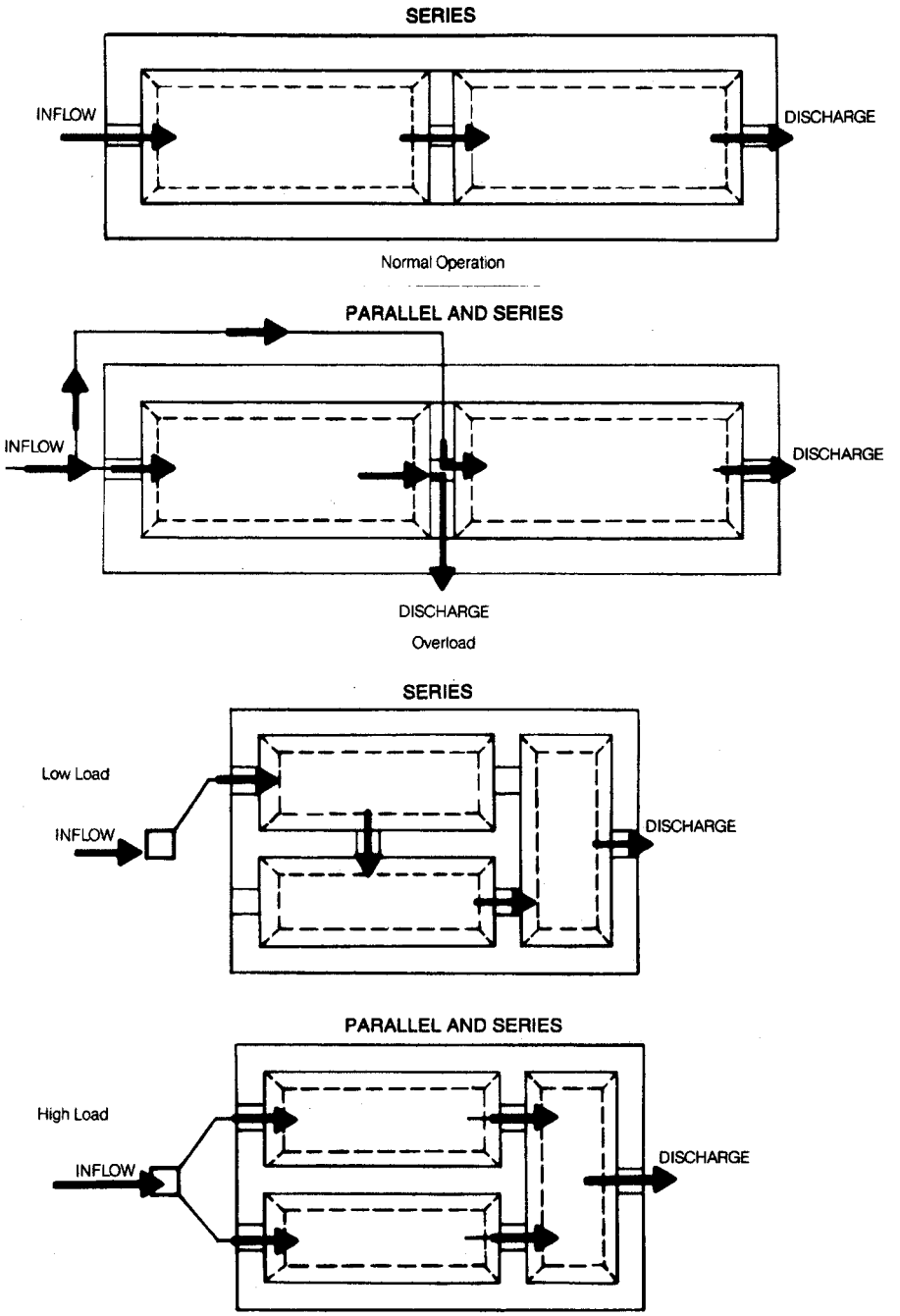


FIGURE 23.2 Wastewater flow for two- and three-cell lagoons.

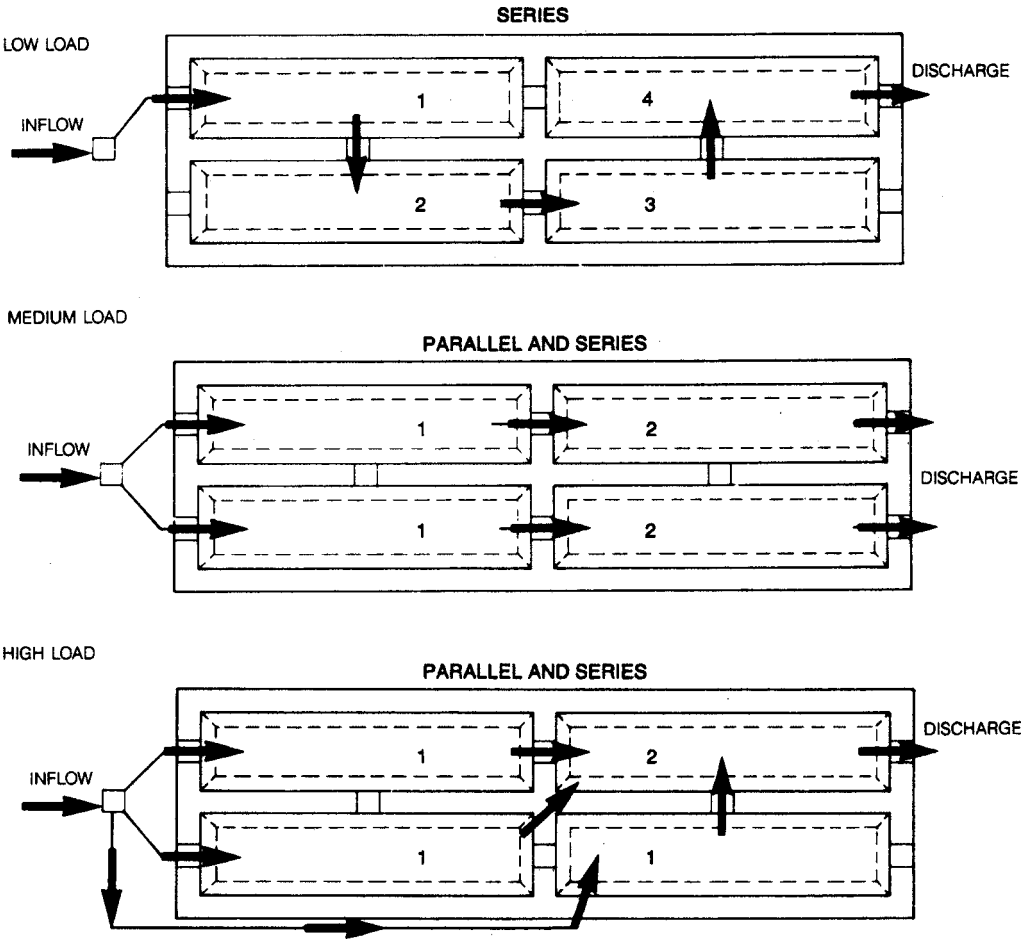


FIGURE 23.3 Wastewater flow for four-cell lagoons.

Mixing. Mixing not only distributes the influent throughout the lagoon, but in aerobic and facultative lagoons it also transports the oxygen produced through algal activity within the lagoon. In lagoons, wind action at the air-liquid interface and the arrangement of the inlet and outlet are the primary factors affecting mixing. Density currents resulting from differential temperatures between influent and contents cause mixing. In addition, temperature gradients resulting from the solar heating of the water, evaporative cooling, radiation from the liquid, and conductive heat exchange with the surrounding air and soil will cause mixing. During windy periods, wave action observed on the surface of the lagoons will provide good oxygen transfer. Lack of wave action

may result either in an oily surface or in anaerobic conditions. A possible method of increasing the effectiveness of the wave action is to raise the water level of the lagoon, where hydraulically feasible, to allow the wind more access to the water surface.

Solids Accumulation. Although solids accumulation has not been noticeable in aerobic or facultative lagoons that are not heavily loaded, deposits have been found in the vicinity of the inlet structure (U.S. EPA, 1983). In facultative and anaerobic lagoons, accumulations around the inlet can be buoyed up by the gases formed by anaerobic decomposition of the solids. These floating masses can be blown into the corners of the lagoon. While inlet configuration affects the spatial distance covered by deposition, siltation is believed to affect the accumulation (Clare et al., 1961). Over time, approximately 10 to 20 years, the operator should consider the potential for accumulation in other parts of the lagoon.

In facultative lagoons, organic solids are decomposed by bacteria, and the byproducts are used by algae. The bulk of the algal biomass produced is transported out of the lagoon with the effluent. In cold climates, the accumulation of solids in anaerobic lagoons has been observed to vary from 0.25 to 0.40 m^3 (9 to 14 cu ft)/100 people/day, which is the maximum accumulation likely to occur in anaerobic lagoons treating domestic wastewater (U.S. EPA, 1983). If accumulation continues, periodic removal may be required. In addition, the operator should check to ensure that the loadings on the lagoons are within the design values. If they are not, operational options to be considered include parallel operation, and/or improved flow distribution.

Aerobic and Facultative Lagoons. During the warmer months, primary cells should be highly productive and have a green color indicating high pH and DO. Secondary or final lagoons should have a high DO and produce an effluent that meets permit requirements. In the late fall and winter, biological activity will decrease and the color of the lagoons will change to brown and then gray. A brown color indicates a reduction in photosynthetic activity possibly caused by a lack of sunlight, low temperatures, or toxic substances (Hiatt, 1970). Dead algae will impart a gray color to the lagoon. Lagoon wastewater color indicates the condition of the lagoon:

- Dark sparkling green: good; high pH and DO (it should be noted that there is the possibility for too much algae, resulting in potential BOD and total suspended solids violations).
- Dull green to yellow: not so good; pH and DO are decreasing; blue-green algae are becoming established.
- Gray to black: bad; anaerobic conditions.

- Tan to brown: all right if caused by algae bloom; not good if resulting from silt or dike erosion.
- Red or pink: presence of purple sulfur bacteria (anaerobic conditions) or red algae (aerobic conditions). Daphnia blooms can also cause a red color. This is generally not a problem, except when they die off and may create a large oxygen demand that can lead to anaerobic conditions.
- Milky appearance: indicates system is approaching or is septic, typically from being overloaded.

Photosynthetic activity beneath any ice cover may continue to provide some DO. Snow cover on the ice, however, will limit algal activity and anaerobic conditions may develop. With prolonged cold weather, biodegradation of the organic matter will be retarded and settleable organic contaminants will accumulate in the lagoon. Spring overturn of the lagoon will reintroduce the stored organic mass throughout the entire lagoon and cause a high bacterial oxygen demand, thereby creating anaerobic conditions and resulting odor problems. If sufficient hydraulic detention time and DO are not available to allow bacterial assimilation of these organic contaminants, effluent quality will be degraded. Potential improvements include mechanical aeration.

Anaerobic Lagoons. Anaerobic lagoons operate with no DO. The primary purpose of anaerobic lagoons is the decomposition and stabilization of organic matter, not the purification of water. Anaerobic lagoons are typically used as sedimentation basins to reduce organic loads on subsequent treatment units.

If the anaerobic lagoon is operated well, a dense scum blanket that helps maintain an anaerobic environment and limits the emission of odors will cover the entire surface. The formation of the scum layer can be encouraged by minimizing excessive wave action. Odors can also be controlled by creating an aerobic zone at the surface to oxidize the volatile compounds that cause odors. Recirculation of effluent from an aerobic lagoon applied to the surface of the primary anaerobic lagoon can provide DO to minimize odors (Oswald, 1968).

Methane bacteria are quite sensitive to factors such as pH, heavy metals, detergents, changes in alkalinity, ammonia nitrogen, temperature, and sulfides. It should be noted that at cold temperatures, treatment will be reduced. Consideration needs to be given to adequate storage during these periods, or to another method of treatment. Table 23.2 presents the optimum and extreme ranges of environmental factors for methane fermentation.

Aerated Lagoons. The DO concentration in an aerated lagoon is the best means to determine if the lagoon is operating properly. Typical practice is to keep 1 to 2 mg/L

TABLE 23.2 Environmental factors for methane fermentation (Middlebrooks et al., 1982).

Variable	Optimum	Extreme
Temperature, °C	30–35	25–40
pH	6.8–7.4	6.2–7.8
Oxidation-reduction potential, MV	−520 to −530	−490 to −550
Volatile acids, mg/L as acetic	50–500	2 000
Alkalinity, mg/L as $CaCO_3$	2 000–3 000	1 000–5 000

DO in the lagoon. A minimum DO level of 1 mg/L should be maintained in the lagoon during the heaviest loading periods (Zickefoose and Hayes, 1977). Often the heaviest oxygen demand is during the night when the algae are respiring. The pH range in the lagoon should range from 7 to 8 (Barlow, 1972 and 1973). The pH can exceed 9 during algal blooms, especially in low-alkalinity wastewaters. Surface mechanical aerators, when used, should produce good turbulence and a light amount of froth.

DATA COLLECTION. Regular testing of several parameters is essential to properly evaluate the performance of a lagoon system. System performance data are also required to satisfy the requirements of the wastewater treatment plant's (WWTP's) NPDES discharge permit. Table 23.3 presents significant parameters and suggested frequencies of their measurement. Arrangements for competent, well-managed laboratory facilities for regular monitoring of BOD_5, suspended solids, and coliform counts are particularly important for determining the performance of the lagoon system. Because each lagoon system will have slightly different requirements, a site-specific standard data sheet should be developed to enter the required data. An example data sheet is provided in Figure 23.4.

TROUBLESHOOTING. Poor effluent quality may be caused by (Barsom, 1973).

- Overloading;
- Low ambient temperatures;
- Ice formation;
- Toxic materials in influent;
- Nutrient deficiencies;
- Short-circuiting;
- Loss of liquid volume due to deposition, leakage, and evaporation;
- Aeration equipment malfunction;

TABLE 23.3 Lagoon contents parameters to be measured and frequency of measurement.

Parameters	Measurements frequency (minimum/ideal)[a]			
	Unaerated aerobic lagoons	Facultative lagoons	Anaerobic lagoons	Aerated lagoons
Flow				
Plant influent	(1/day)/continuous	(1/day)/continuous	(1/day)/continuous	(1/day)/continuous
Plant effluent				
Continuous discharge	1/wk	1/wk	Capability only	Capability only
Short-period discharge	—	1/day	—	—
Recirculation and cell to cell	Not required	Not required	Not required	Not required
pH (in each lagoon cell)	(1/wk) (1/day)	(1/wk) (1/day)	1/day	(3/wk) (1/day)
Dissolved oxygen (in each lagoon cell)				
Except during short-period discharge	(1/wk) (1/day)	(1/wk) (1/day)	—	1/day
During short-period discharge	3/day	3/day	—	—
Liquid temperature in each lagoon cell	(1/wk) (1/day)	(1/wk) (1/day)	1/day	1/day
Liquid level				
Except during short-period discharge	1/wk	1/wk	—	—
During short-period discharge	1/day	1/day	—	—
Biochemical oxygen demand				
Plant influent	(2/month)(1/wk)	(2/month)(1/wk)	1/wk	1/wk
Unit effluent	—	—	1/wk	1/wk
Plant effluent				
Except during short-period discharge	(2/month)(1/wk)	(2/month)(1/wk)	1/wk	1/wk (after settling tank, if any)
During short-period discharge	—	5/wk(each a composite of 3/day)	—	—
Suspended solids				
Plant influent	(2/month)(1/wk)	(2/month)(1/wk)	1/wk	1/wk
Unit effluent	—	—	1/wk	1/wk (after settling tank, if any)

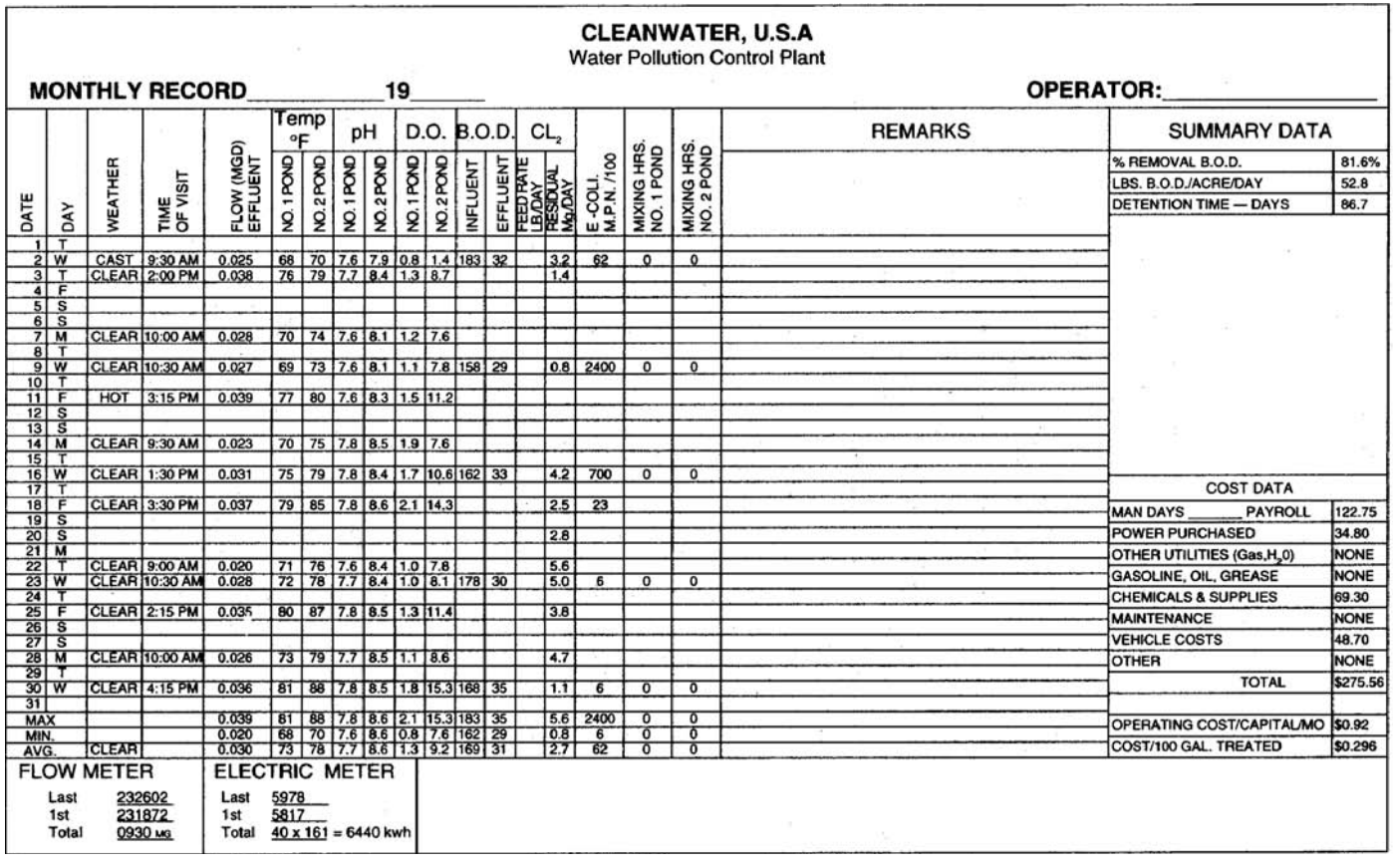
TABLE 23.3 Lagoon contents parameters to be measured and frequency of measurement (*continued*).

Parameters	Measurements frequency (minimum/ideal)[a]			
	Unaerated aerobic lagoons	Facultative lagoons	Anaerobic lagoons	Aerated lagoons
Plant effluent				
Except during short-period discharge	1/wk	1/wk	1/wk	1/wk (after settling tank, if any)
During short-period discharge	—	5/wk (each a composite of 3/day)	—	—
Coliforms (total or fecal)				
Plant influent	1/month	1/month	2/month	2/month
Unit effluent	—	—	—	—
Plant effluent				
Except during short-period discharge	1/wk	1/wk	1/wk	1/wk
During short-period discharge	—	5/wk	—	—
Dissolved solids (influent and effluent)	Optional/(1/wk)	Optional/(1/wk)	(2/month)/(1/wk)	Optional/(1/wk)
Chlorine residual in effluent (when chlorine is used as specified in effluent discharge permit)				
Automatic control	1/wk	1/wk	2/wk	2/wk
Manual control	1/day	1/day	Not recommended	1/day
Sludge level				
In lagoon	1/(3 months)	1/(3 months)	1 month	1/(3 months) if followed by a settling pond; 1/month otherwise.
In settling pond following lagoon	—	—	—	1/month
Nitrogen and phosphorus species	Not required	Not required	Not required	Not required
Volatile acids and alkalinity	—	—	Not ordinarily required	—
Heavy metals and toxic organic compounds	Not ordinarily required	Not ordinarily required	Not ordinarily required	Not ordinarily required

TABLE 23.3 Lagoon contents parameters to be measured and frequency of measurement (*continued*).

Parameters	Measurements frequency (minimum/ideal)[a]			
	Unaerated aerobic lagoons	**Facultative lagoons**	**Anaerobic lagoons**	**Aerated lagoons**
Ice cover, % or area (seasonal requirements)				
Continuous discharge	2/wk	2/wk	—	2/wk
Short-period discharge	1/day	1/day	—	—
Ice thickness (when 100% covered)	1/month, safety permitting	1/month, safety permitting	1/month, safety permitting	—
Weather				
Ambient air temperature	Daily	Daily	Daily	Daily
Cloud cover	—	—	—	—
Precipitation	—	—	—	—
Wind direction	Daily[b]	Daily[b]	Daily[b]	Daily[b]
Wind speed	—	—	—	—
Humidity	—	—	—	—
Descriptive summary	—	—	—	—
Power consumption (cumulative)				
Surface aerators or rotary blowers	—	—	—	Weekly
Pumps and miscellaneous equipment	Monthly	Monthly	Monthly	Monthly
Air flow (for diffused air systems)	—	—	—	Weekly
Air pressure (on discharge header of diffused air system)	—	—	—	Weekly

[a]Sampling frequencies listed are intended to apply to domestic wastes; units receiving substantial proportions of industrial wastewaters may require other parameters or frequencies.
[b]Records of nearby weather stations may be used.



CLEANWATER, U.S.A
Water Pollution Control Plant

MONTHLY RECORD _____ 19_____ **OPERATOR:** _____

DATE	DAY	WEATHER	TIME OF VISIT	FLOW (MGD) EFFLUENT	Temp °F NO. 1 POND	Temp °F NO. 2 POND	pH NO. 1 POND	pH NO. 2 POND	D.O. NO. 1 POND	D.O. NO. 2 POND	B.O.D. INFLUENT	B.O.D. EFFLUENT	CL_2 FEED RATE LB/DAY	CL_2 RESIDUAL Mg/DAY	E.-COLI. M.P.N./100	MIXING HRS. NO. 1 POND	MIXING HRS. NO. 2 POND	REMARKS
1	T																	
2	W	CAST	9:30 AM	0.025	68	70	7.6	7.9	0.8	1.4	183	32		3.2	62	0	0	
3	T	CLEAR	2:00 PM	0.038	76	79	7.7	8.4	1.3	8.7				1.4				
4	F																	
5	S																	
6	S																	
7	M	CLEAR	10:00 AM	0.028	70	74	7.6	8.1	1.2	7.6								
8	T																	
9	W	CLEAR	10:30 AM	0.027	69	73	7.6	8.1	1.1	7.8	158	29		0.6	2400	0	0	
10	T																	
11	F	HOT	3:15 PM	0.039	77	80	7.6	8.3	1.5	11.2								
12	S																	
13	S																	
14	M	CLEAR	9:30 AM	0.023	70	75	7.8	8.5	1.9	7.6								
15	T																	
16	W	CLEAR	1:30 PM	0.031	75	79	7.8	8.4	1.7	10.6	162	33		4.2	700	0	0	
17	T																	
18	F	CLEAR	3:30 PM	0.037	79	85	7.8	8.6	2.1	14.3				2.5	23			
19	S																	
20	S													2.8				
21	M																	
22	T	CLEAR	9:00 AM	0.020	71	76	7.6	8.4	1.0	7.8				5.6				
23	W	CLEAR	10:30 AM	0.028	72	78	7.7	8.4	1.0	8.1	178	30		5.0	6	0	0	
24	T																	
25	F	CLEAR	2:15 PM	0.035	80	87	7.8	8.5	1.3	11.4				3.8				
26	S																	
27	S																	
28	M	CLEAR	10:00 AM	0.026	73	79	7.7	8.5	1.1	8.6				4.7				
29	T																	
30	W	CLEAR	4:15 PM	0.036	81	88	7.8	8.5	1.8	15.3	168	35		1.1	6	0	0	
31																		
MAX				0.039	81	88	7.8	8.6	2.1	15.3	183	35		5.6	2400	0	0	
MIN.				0.020	68	70	7.6	8.6	0.8	7.6	162	29		0.8	6	0	0	
AVG.		CLEAR		0.030	73	78	7.7	8.6	1.3	9.2	169	31		2.7	62	0	0	

SUMMARY DATA	
% REMOVAL B.O.D.	81.6%
LBS. B.O.D./ACRE/DAY	52.8
DETENTION TIME — DAYS	86.7

COST DATA	
MAN DAYS _____ PAYROLL	122.75
POWER PURCHASED	34.80
OTHER UTILITIES (Gas, H_20)	NONE
GASOLINE, OIL, GREASE	NONE
CHEMICALS & SUPPLIES	69.30
MAINTENANCE	NONE
VEHICLE COSTS	48.70
OTHER	NONE
TOTAL	$275.56
OPERATING COST/CAPITAL/MO	$0.92
COST/100 GAL. TREATED	$0.296

FLOW METER
Last 232602
1st 231872
Total 0930 MG

ELECTRIC METER
Last 5978
1st 5817
Total 40 x 161 = 6440 kwh

FIGURE 23.4 Example data sheet (mgd $\times$ $[4.383 \times 10^{-2}]$ = m^3/s; lb/d $\times$ 5.250 = mg/s; $[°F - 32] \times 0.555\ 6$ = °C; lb/ac/d $\times$ $[1.297 \times 10^{-9}]$ = $kg/m^2 \cdot s$; gal $\times$ $[3.785 \times 10^{-3}]$ = m^3; mil. gal $\times$ $[3.785 \times 10^{3}]$ = m^3; and kWh $\times$ 3.600 = mJ) (Kerri, 1980).

- Mixing or agitation equipment malfunction;
- Operating levels too deep for light to penetrate the full depth;
- Interference of light penetration by high turbidity, algal mats, duckweed cover, or scum;
- Blockage of light by plant growth on dikes; and
- Groundwater contamination caused by leakage through the bottom or sides.

When not specifically designed for, anaerobic conditions in a lagoon can cause odor problems. Other possible nuisance problems are

- Foaming and spray problems in aerated lagoons,
- Insect propagation, and
- Aesthetics.

In addition, erosion of the dikes, the presence of burrowing animals, and the growth of rooted woody plants can destroy the structural stability of the lagoon walls, and thereby create a hazardous condition. Table 23.4 presents a troubleshooting guide for lagoons that will enable the operator to quickly identify problems and their possible solutions.

MAINTENANCE. Weeds within the lagoon must be prevented to allow wave action and help control insect populations. Table 23.5 lists some herbicides used to control aquatic plants. Herbicides should only be added as approved by the appropriate regulatory agencies. Grass on the dikes above the waterline should be mowed and maintained to prevent soil erosion and insect problems. At the edge of the water, soil erosion can be controlled by riprap, broken concrete rubble, or a poured concrete pad. In addition, inlet and outlet structures should be cleaned of floating debris, scum, and other material that might cause odors. Mechanical equipment needs maintenance according to a well-prepared maintenance schedule; lubrication and maintenance records are essential to a good maintenance program.

Aerated lagoons using surface mechanical aerators must be free of logs or large pieces of wood that could damage the aerator. Furthermore, the DO in each cell should be measured daily. For systems using diffused air over the entire bottom, the aeration pattern should be visually inspected for dead spots or line ruptures.

Several lagoon problems can be prevented through proper maintenance. A maintenance schedule is helpful for planning and conducting these activities (see Table 23.6). Most of the maintenance items are either visual observations or operations that require little time if performed regularly.

TABLE 23.4 Troubleshooting guide for lagoons (Zickefoose and Hayes, 1977).

Indicators/observations	Probable cause	Solutions
Weeds	Poor circulation/maintenance, insufficient water depth	Pull weeds by hand if new growth
		Mow weeds with a sickle bar mower
		Lower water level to expose weeds, then burn with gas burner
		Allow the surface to freeze at a low water level, raise the water level and the floating ice will pull the weeds as it rises
		Increase water depth to above tops of weeds
		Use riprap; caution: if weeds get started in the riprap, they will be difficult to remove but can be sprayed with acceptable herbicides; get appropriate regulatory agencies' approval to use herbicides
		To control duckweed, use rakes or push a board with a boat, then physically remove duckweed from pond
Burrowing animals	Bank conditions that attract animals; high population in area adjacent to ponds	Remove food supply such as cattails and burr reed from ponds and adjacent areas
		Muskrats prefer a partially submerged tunnel; if the water level is raised, the tunnel will extend upward and if lowered sufficiently, the muskrat may abandon the tunnel completely; they may be discouraged by raising and lowering the level 0.15 to 0.20 (6 to 8 in.) over several weeks; trapping or other methods of animal removal may be used if permitted by all appropriate regulatory agencies
High weed growth, brush, trees, and other vegetation	Poor maintenance	Periodic mowing is the best method
		Sow dikes with a mixture of fescue and blue grasses on the shore and short native grasses elsewhere; it is desirable to select a grass that will form a good sod, drive out tall weeds, bind the soil, and outcompete undesirable growth

TABLE 23.4 Troubleshooting guide for lagoons (Zickefoose and Hayes, 1977) (*continued*).

Indicators/observations	Probable cause	Solutions
		Spray with approved weed control chemicals
		Some small animals, such as sheep, have been used; may increase fecal coliform, especially to the discharge cell; some regulatory agencies advise against using animals for vegetation control due to concerns for liner and dike intergrity
		Practice rotation grazing to prevent destroying individual species of grasses; an example schedule for rotation grazing in a three-pond system would be graze each pond area for 2 months over a 6-month grazing season
Undesirable scum formations	Pond bottom is turning over with sludge floating to the surface; poor circulation and wind action; high amounts of grease and oil in influent will also cause scum	Use rakes, a portable pump to get a water jet, or motor boats to break up scum formations; broken scum usually sinks
		Any remaining scum should be skimmed and disposed of by burial or hauled to landfill with approval of regulatory agency
Odors that are a nuisance	The odors are generally the result of overloading, long periods of cloudy weather, poor pond circulation, industrial wastes, or ice melt; use parallel feeding to primary cells to reduce loading; also, weeds and sometimes riprap will serve as areas for organic material accumulation resulting in odors	Apply chemicals such as sodium nitrate, or 1,2-dibromo-2,2-dichloroethyl dimethylphosphate to introduce oxygen; application rate: 5 to 15% sodium nitrate/mil. gal (mil. gal $\times$ [3.785 $\times$ 10^3] = m^3); repeat at a reduced rate on succeeding days; use 100 lb sodium nitrate/ac (112 kg/ha) for first day, then 50 lb/ac/day (56 kg/ha·d) thereafter if odors persist; apply in the wake of a motorboat
		Install supplementary aeration such as floating aerators, caged aerators, or diffused aeration to provide mixing and oxygen; daily trips over the lagoon area in a motorboat also help; note: stirring the pond may cause odors to be worse for short periods but will reduce total length of odorous period

TABLE 23.4 Troubleshooting guide for lagoons (Zickefoose and Hayes, 1977) (*continued*).

Indicators/observations	Probable cause	Solutions
		Recirculate pond effluent to the pond influent to provide additional oxygen and to distribute the solids concentration; recirculate on a 1:6 ratio
		Eliminate septic or high-strength industrial wastes
Blue-green algae	Blue-green algae is an indication of incomplete treatment, overloading, or poor nutrient balance	Use three applications of a solution of copper sulfate
		If the total alkalinity is above 50 mg/L, apply 10 lb of copper sulfate/mil. gal in cell (1 200 kg/m^3); if alkalinity is less than 50 mg/L, reduce the amount of copper sulfate to 5 lb/mil. gal (600 kg/m^3)
		Some states do not approve the use of copper sulfate because, in concentrations greater than 1 mg/L, it is toxic to certain organisms and fish; also, extensive use of copper sulfate may cause a buildup of copper in the sludge, making sludge disposal a problem
		Break up algal blooms by motorboat or a portable pump and hose; motorboat motors should be air cooled as algae may plug water-cooled motors
		Provide shading, increase dissolved oxygen (DO), add plankton and algae-eating fish
Mosquitoes, midges	Poor circulation and maintenance	Keep pond clear of weeds and allow wave action on bank to prevent mosquitoes from hatching
		Keep ponds free of scum
		Stock pond with *Gambusia* (mosquito fish)
		Spray with larvacide as a last resort; check with state regulatory officials for approved chemicals

TABLE 23.4 Troubleshooting guide for lagoons (Zickefoose and Hayes, 1977) (*continued*).

Indicators/observations	Probable cause	Solutions
High algal suspended solids in pond effluent	Weather or temperature conditions that favor particular population of algae	Draw off effluent from below the surface by use of a good baffling arrangement
		Use multiple ponds in series
		Intermittent sand filters and submerged rock filters may be used but will require modification and the services of a consulting engineer
		Provide shading, increase DO, add plankton and algae-eating fish
		In some cases, alum dosages of 20 mg/L have been used in final cells, used for intermittent discharge, to improve effluent quality; dosages at or less than this level are not toxic
Lightly loaded ponds that may produce filamentous algae and moss, which limit sunlight penetration	Overdesign, low seasonal flow	Increase the loading by reducing the number of cells in use
		Use series operation
A low, continued downward trend in DO	Poor light penetration, low detention time, high biochemical oxygen demand (BOD) loading, or toxic industrial wastes (daytime DO should not drop below 3.0 mg/L during warm months)	Remove weeds, such as duckweed, if covering greater than 40% of the pond
		Reduce organic loading to primary cells by going to parallel operation
		Add supplemental aeration (surface aerators, diffusers, or daily operation of a motorboat)
		Add recirculation by using a portable pump to return final effluent to the head works
		Apply sodium nitrate (see "Odors that are a nuisance" [above] for rate)
		Determine if overload is owing to industrial source and remove it

TABLE 23.4 Troubleshooting guide for lagoons (Zickefoose and Hayes, 1977) (*continued*).

Indicators/observations	Probable cause	Solutions
Overloading, which results in incomplete treatment of the wastewater; overloading problems can be detected by offensive odors or a yellow, dull green, or gray color; laboratory tests showing low pH, DO, and excessive BOD loading per unit area should be considered	Short-circuiting, industrial wastes, poor design, infiltration, new construction (service area expansion), inadequate treatment, and weather conditions	Bypass the cell and let it rest Use parallel operation Apply recirculation of pond effluent Look at possible short-circuiting Install supplementary aeration equipment
Decreasing trend in pH; pH should be on the alkaline side, preferably about 8.0 to 8.4	A decreasing pH is followed by a drop in DO as the green algae die off; this is most often caused by overloading, long periods of adverse weather, or higher animals such as *Daphnia* feeding on the algae	Bypass the cell and let it rest Use parallel operation Apply recirculation of pond effluent Check for possible short-circuiting Install supplementary aeration equipment if problem is persistent and results from overloading Look for possible toxic or external causes of algae die off and correct at source
Odor problems, low DO in parts of the pond, anaerobic conditions, and low pH found by checking values from various parts of the pond and noting on a plan of the pond; differences of 100% to 200% may indicate short-circuiting; after recording the readings for each location, the areas not receiving good circulation are characterized by a low DO and pH	Poor wind action because of trees or poor arrangement of inlet and outlet locations; may also be due to shape of pond, weed growth, or irregular bottom	Cut trees and growth at least 500 ft (150 m) away from pond if in direction of prevailing wind Install baffling around inlet location to improve distribution Add recirculation to improve mixing; provide new inlet-outlet locations including multiple inlets Clean out weeds Fill in irregular bottoms; investigate potential for sludge accumulation in various parts of the pond

TABLE 23.4 Troubleshooting guide for lagoons (Zickefoose and Hayes, 1977) (*continued*).

Indicators/observations	Probable cause	Solutions
Facultative pond that turned anaerobic, resulting in high BOD, suspended solids, and scum in the effluent in continuous discharge ponds, unpleasant odors, the presence of filamentous bacteria, yellowish-green or gray color, and placid surface, indicating anaerobic conditions	Overloading, short-circuiting, poor operation, or toxic discharges	Change from series to parallel operation to divide load; helpful if conditions exist at a certain time each year and are not persistent Add supplemental aeration if pond is continuously overloaded Change inlets and outlets to eliminate short-circuiting Add recirculation (temporary-use portable pumps) to provide oxygen and mixing In some cases, temporary help can be obtained by adding sodium nitrate at rates suggested for odor control Eliminate sources of toxic discharge
High BOD concentrations that violate NPDES or other regulatory agency permit requirements; visible dead algae	Short detection times, poor inlet and outlet placement, high organic or hydraulic loads, and possible toxic compounds	Check for collection system infiltration and eliminate at source Use portable pumps to recirculate the water Add new inlet and outlet locations Reduce loads from industrial sources if greater than design level Prevent toxic discharges; convert to parallel operation
Fluctuating DO, fine pin floc in final cell effluent, and frothing or foaming	Shock loading, overaeration, industrial wastes, and floating ice	Control aeration system by using timeclock to allow operation during high-load periods; monitor DO to set up schedule for even operation, holding approximately 1 mg/L or more Vary operation of aeration system to obtain solids that flocculate or clump together in the secondary cell but are not torn apart by excessive aeration

TABLE 23.4 Troubleshooting guide for lagoons (Zickefoose and Hayes, 1977) (*continued*).

Indicators/observations	Probable cause	Solutions
		Locate industrial wastes that may cause foaming or frothing and eliminate or pretreat such wastes as slaughterhouse, milk, and some vegetable wastes
Ice interfering with the operation of aerated ponds	Floating ice	Operate units continuously during cold weather to prevent freezing damage or remove completely if not a type that will prevent freeze-up
Odors in anaerobic ponds, caused by hydrogen sulfide (rotten egg) odors or other disagreeable conditions due to sludge in a septic condition	Lack of cover over water surface and insufficient load to have complete activity that eventually forms scum blanket	Use straw cast over the surface or polystyrene planks as a temporary cover until a good surface sludge blanket has formed
		Recirculate aerobic pond effluent to anaerobic pond
		Distribute over anaerobic pond by spraying to establish thin layer of aerobic water
Low pH in anaerobic ponds; a pH below 6.5 accompanied by odors, results from acid bacteria working in the anaerobic condition	Acid formers working faster than methane formers in an acid condition	The pH can be raised by adding a lime slurry of 100 lb of hydrated lime/50 gal (500 kg/200 L) of water at a dosage rate of 1 lb of lime/10 000 gal (120 g/10 000 L) in the pond; the slurry should be mixed while being added; the best place to put in the lime is at the entrance to the lagoon so that it is well mixed as it enters the pond
Groundwater contamination	Leakage through bottom or sides	Potential major capital improvements

TABLE 23.5 Herbicides used around lagoons (Zickefoose and Hayes, 1977).

Chemical	Marketed by	To control
Dalapon™	Dow	Cattails
Silvex™	Dow	Willows and emergent weeds
Copper sulfate	—	Filamentous algae
Endo-thal™	Ortho	Suspended weeds
Simazine (use qualified ticketed sprayer)	—	Weeds

Note: These herbicides should only be used as permitted by the appropriate regulatory agencies.

LAND TREATMENT SYSTEMS

DESCRIPTION OF PROCESSES. Land treatment of wastewater is the controlled application of wastewater to the land surface to achieve a designed degree of treatment through physical, chemical, and biological processes within the plant-soil-water matrix. The basic soil properties that influence the success of land treatment of waste include soil texture, soil structure, permeability, infiltration, available water capacity, and cation exchange capacity (Alexander, 1967).

Wastes are removed physically through filtration by the soil, and their concentrations are altered by dilution, either on entering the groundwater or in the soil that contains natural rainfall or snowmelt. Filtration is limited by clogging of soil pores with SS. This clogging of the soil can be avoided by pretreatment and rest periods between applications.

Adsorption and precipitation are the main processes involved in the retention of wastes in the soil. The effectiveness of soil in the removal of waste depends on the type of waste being treated, the contact between dissolved substances, and the soil phases.

Biological processes decompose organic matter. The rate of decomposition depends on many factors including the composition and form of the waste being applied, and the temperature of the soil-water environment.

The ability of soil to treat wastes is limited by the loading of nitrogen, phosphorus, water, the addition of potentially toxic substances, and the sodium adsorption ratio (SAR) of the soil. In most situations, nitrogen is the major factor limiting the application of waste to the soil.

Normally, soil permeability and nitrogen removal limitations govern design hydraulic loading rates to land application systems. Hydraulic loading rates are used to determine land area and storage requirements. Land treatment processes employ wastewater application and drying cycles to stimulate the nitrification-denitrification processes.

TABLE 23.6 Example operation and maintenance schedule for lagoons (Zickefoose and Hayes, 1977).

Operational and preventive maintenance	Daily	Weekly	Monthly	3 Months	As necessary
Plant survey					
Drive around perimeters of ponds taking note of the following conditions:					
Any buildup of scum on pond surface and discharge outlet boxes	x				
Signs of burrowing animals	x				
Anaerobic conditions; noted by odor and black color	x				
Water-grown weeds	x				
Evidence of dike erosion	x				
Dike leakage	x				
Fence damage	x				
Ice buildup in winter					x
Evidence of short-circuiting	x				
Plan, schedule, and correct problem found (use troubleshooting section of this manual for information)					x
Permit requirements					
If discharge is once or twice per year, the discharge permit may require the following:					
Odor		x			
Aquatic plant coverage of pond		x			
Pond depth		x			
Dike condition		x			
Ice cover		x			
Flow (influent)	x				
Rainfall (or snowfall)	x				
If discharge is continuous, the discharge permit may require the following information:					
Weather	x				
Flow	x				
Condition of all cells	x				
Depth of cells	x				

TABLE 23.6 Example operation and maintenance schedule for lagoons (Zickefoose and Hayes, 1977) (*continued*).

Operational and preventive maintenance	Daily	Weekly	Monthly	3 Months	As necessary
Lagoon effluent:					
Dissolved oxygen and pH grab sample	x				
Chlorine residual (as specified in effluent discharge permit)	x				
Biochemical oxygen demand and sludge solids run on composited samples					x
Fecal coliform					x
Record pounds of chlorine remaining and used	x				
Other tests and frequency information will be defined in the individual permit for the WWTP					x
Preliminary treatment					
Clean inlet, screens, and properly dispose of trash	x				
Check inlet flow meter and float well	x				
Mechanical equipment					
Check mechanical equipment and perform scheduled preventive maintenance on the following pieces of equipment according to the manufacturer's recommendations:					
Pump stations:					
Remove debris	x				
Check pump operation	x				
Run emergency generator		x			
Log running times	x				
Clean floats, bubblers, or other control devices		x			
Lubricate					x
Comminuting devices:					
Check cutters		x			
Lubricate					x

TABLE 23.6 Example operation and maintenance schedule for lagoons (Zickefoose and Hayes, 1977) (*continued*).

Operational and preventive maintenance	Daily	Weekly	Monthly	3 Months	As necessary
Aerators:					
Log running time	x				
Check amperage				x	
Chlorinators:					
Check feed rate	x				
Change cylinders					x
Flow measuring devices:					
Check and clean floats	x				
Verify accuracy				x	
Valves and gates:					
Check to see if set correctly	x				
Open and close to be sure they operate			x		

Note: Each state has requirements for data collected prior to and during discharge that are defined in the plant discharge permit.

Preliminary treatment processes are usually selected before determining the hydraulic loading because pretreatment can affect the quality of the wastewater applied to the land. Basically, the three reasons for preliminary treatment of wastewater are

- Protection of public health,
- Prevention of nuisance conditions, and
- Prevention of operating problems in the distribution system.

The three major land treatment processes are slow rate, rapid infiltration, and overland flow (see Figure 23.5). Wetlands treatment is an extension of overland flow with the application of varying types of vegetation. Wetlands are not discussed in this chapter.

Slow-Rate Process. Slow-rate land treatment systems use the capabilities of WWTPs, the microbial community, and the soil to remove or degrade contaminants as the wastewater flows through the plant-soil matrix. Some wastewater application techniques include such farming techniques as ridge-and-furrow, border strip flooding

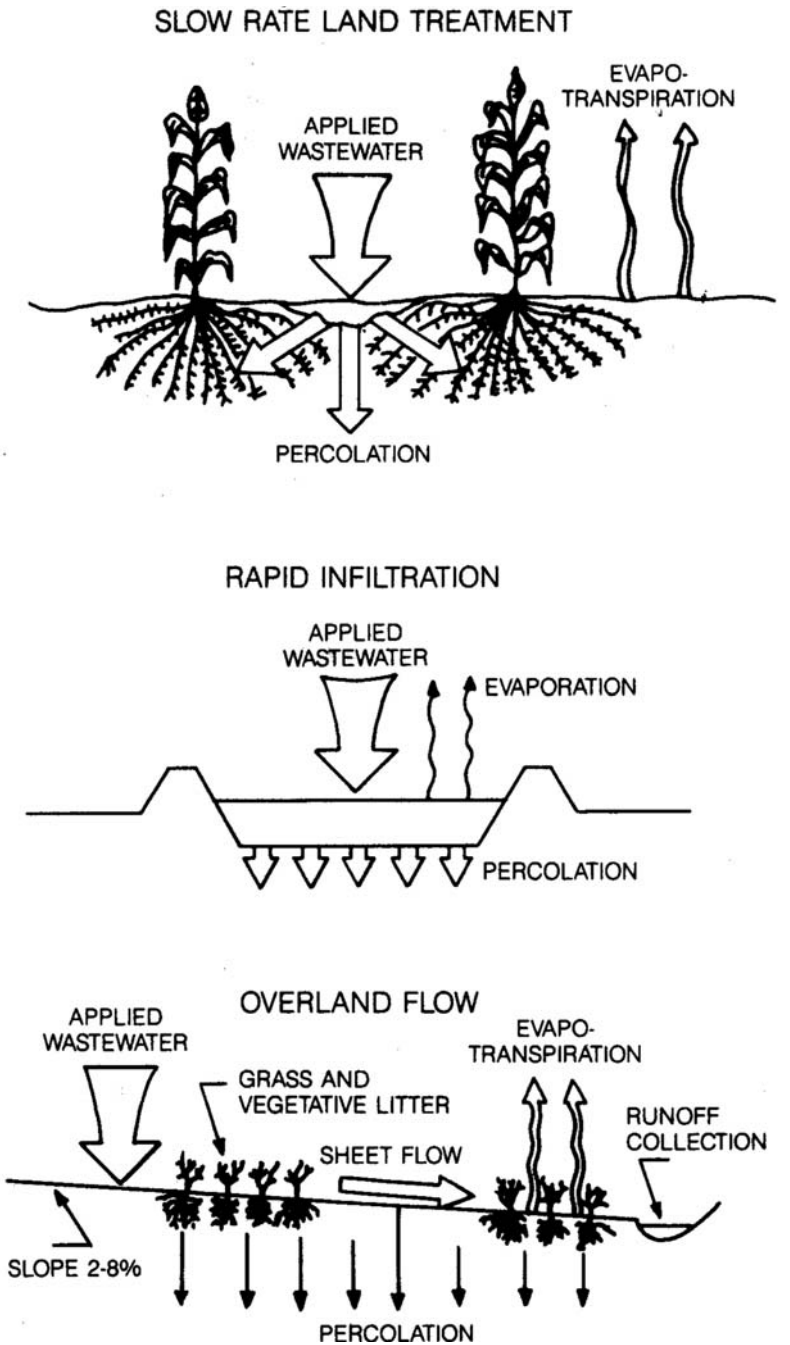


FIGURE 23.5 Schematics of the three major forms of land treatment (U.S. EPA, 1981).

and irrigation techniques such as fixed riser sprinklers, and moving systems such as center pivots systems. The vegetation uses a portion of the flow, while some of the flow reaches the groundwater. Organic wastes are removed within the top 1 to 2 cm (0.4 to 0.8 in.) of soil by filtration and adsorption, while bacterial oxidation ultimately degrades the organics.

Suspended solids are removed primarily by filtration; any inert solids become part of the soil matrix. Nitrogen is removed mainly through crop uptake and harvest. Denitrification can be a mechanism for nitrogen loss as well as ammonia volatilization and storage in the soil. Phosphorus is removed from the wastewater primarily through adsorption and chemical precipitation (Alexander, 1967; Loehr, 1979; Scarseth, 1962; and U.S. ACOE, 1983).

The rate of wastewater application for slow-rate systems is governed either by soil permeability or by the nitrogen concentration in the percolate water past the root zone. In arid regions, where wastewater is a valuable resource for irrigating cash crops, irrigation requirements may determine the application rate.

A general water balance used to compute the hydraulic loading rate is (U.S. EPA, 1981)

$$PR + LA_p = ET + SP \tag{23.1}$$

where

PR = monthly precipitation rate,
LA_p = monthly wastewater hydraulic loading rate,
ET = monthly evapotranspiration rate, and
SP = monthly soil percolation rate.

Slow-rate systems are designed for no surface runoff. The monthly calculated hydraulic loading rates are summed to determine the annual hydraulic loading rate. When there is concern about the protection of a potable groundwater aquifer, nitrogen is typically the limiting factor for determining the hydraulic loading. Nitrogen, in the form of nitrates, can be a concern in potable water because of the potential for infant methemoglobinemia, in addition to affecting receiving waters in other manners such as the potential for accelerated eutrophication. From a nitrogen balance, the allowable hydraulic loading can be computed as follows (U.S. EPA, 1981):

$$LA_n = \frac{C_p(PR - ET) + NU\,(10)}{(1-f)\,C_n - C_p} \tag{23.2}$$

where

LA_n = allowable hydraulic loading rate based on nitrogen limitations, cm/a;
C_p = percolate nitrogen concentration, 10 mg/L;
PR = precipitation, cm/a;
ET = evapotranspiration, cm/a;
NU = nitrogen uptake by crop, kg/ha·a;
f = fraction of applied nitrogen loss resulting from denitrification and volatilization; and
C_n = nitrogen concentration in applied wastewater, mg/L.

The more restrictive of the computed hydraulic loading rates is used to design the slow-rate system.

Rapid Infiltration Process. Wastewater applied to rapid infiltration processes percolates through the soil. The wastewater is applied to moderately and highly permeable soils by spreading basins or sprinklers; a vegetative surface cover is not normally used. Suspended solids and organic wastes are removed through filtration and straining action of the soil. The treated effluent is collected by drain tiles and discharged to surface water or it enters the groundwater. If required, monitoring is performed.

Rapid infiltration produces a highly nitrified effluent. Nitrogen removals generally average about 50% (U.S. ACOE, 1983). As with the slow-rate pro, phosphorus is removed by adsorption and chemical precipitation, which is a function of the physical and chemical characteristics of the soil.

The land required for a rapid infiltration system depends on the hydraulic loading rate (which is affected by the loading cycle), the hydraulic capacity of the soil, the underlying soil geology, and the degree of wastewater pretreatment. Design percolation rates are a fraction of the measured field infiltration rate and hydraulic permeability of the soil. Furthermore, nutrient removal and cold weather conditions may require adjustment of the hydraulic loading rate. In the U.S., rapid infiltration systems have been limited to annual hydraulic loadings of 120 m (400 ft) or less.

Overland Flow Process. The overland flow process is used at sites having highly impermeable soils. Wastewater is applied at the upper reaches of the grass-covered slopes, flows over the vegetated surface, and the surface runoff is collected. As the wastewater travels down the slope as a thin film, which is referred to as *sheet flow*, it is treated by physical, chemical, and biological mechanisms.

Organic contaminants and SS are removed by sedimentation, filtration, and biological oxidation. High nitrogen removal (70 to 90%) is achieved through a combina-

tion of plant uptake, denitrification, and ammonia volatilization. Phosphorus is adsorbed or chemically precipitated within the surface layers of the soil.

Overland flow design parameters have been empirically established through successive trials with various process parameters at overland flow systems. Table 23.7 presents design guidelines that have been used at existing overland flow systems for operation during the spring, summer, and fall to achieve effluent BOD_5 and suspended solids concentrations less than 20 mg/L; total nitrogen concentrations less than 10 mg/L; ammonia nitrogen levels less than 5 mg/L; and total phosphorus less than 6 mg/L (Smith and Schroeder, 1982; U.S. EPA, 1981; and Wightman et al., 1983). The overland flow process is suited for relatively impermeable surface soils or soils that have an underlying restrictive layer at depths of 0.3 to 0.6 m (1 to 2 ft). The desired slope of the process is from 2 to 8%.

PROCESS CONTROL. To operate a land treatment system properly, the operator must have a working knowledge of both farming practices and principles of wastewater treatment. Seasonal changes in system operation depend largely on changes in the nutrient and needs of the crops. The system must be monitored to determine system performance for permit requirements and to forecast accumulation of potentially toxic substances in the soils and crops. The operator must continually inspect the system for such problems as ponding, surface runoff, and mechanical failure. The operator should also inspect the system for nuisances such as insects and odors.The following methods are often used to manage and operate land treatment systems:

- The system is managed and operated by the wastewater treatment utility.
- The wastewater utility manages the system but a private party is contracted to operate the system.
- A private party is contracted to manage and operate the system.

TABLE 23.7 Overland flow design guidelines (U.S. EPA 1981).

Preapplication treatment	Hydraulic loading rate, cm/d	Application rate, $m^3/m \cdot h$	Application period, h/d	Application frequency, d/wk	Slope length, m
Screening	0.9–3	0.07–0.12	8–12	5–7	36–45
Primary sedimentation	1.4–4	0.08–0.12	8–12	5–7	30–36
Stabilization pond	1.3–3.3	0.03–0.10	8–18	5–7	45
Complete secondary biological	2.8–6.7	0.10–0.20	8–12	5–7	30–36

- A private party is contracted to manage the system, and another private party is subcontracted to operate it.

The system management and operation must cooperate. If a private party is involved in the operation or management of the land treatment system, it is important that the contractual agreements delineate the responsibilities of all the parties. Irrigation schedules that take into account farm operations such as planting, tilling, spraying, and harvesting should be developed (see Table 23.8).

Crops. The primary goal of land application systems is the treatment of wastewater. The cropping pattern used throughout the year is important for the removal of nitrogen from the waste stream and the prevention of nitrogen accumulation in the soil profile. Nitrogen requirements by crops typically correspond to evapotranspiration rates; therefore, nitrogen application based on changes in crop evapotranspiration should result in better removal of nitrogen than a constant application (Culp and Heim, 1978; U.S. ACOE, 1983; and U.S. EPA, 1981). Crops commonly used in land treatment can be divided into three groups:

- Forage crops, such as grasses and alfalfa, which remove 152 to 675 kg nitrogen (N)/ha·a (150 to 665 lb N/ac/yr);
- Field crops, such as corn, which consume 76 to 250 kg N/ha·a (75 to 246 lb N/ac/yr); and
- Forests, which remove 20 to 102 kg N/ha·a (20 to 100 lb N/ac/a).

Forage grasses are popular because they remove large amounts of nitrogen. Crops also remove phosphorus, prevent soil erosion, and keep soil porous for water infiltration.

The quantity of nitrogen removed through crop harvesting depends on the type of crop, the length of the growing season, and the availability of nitrogen. Frequent cutting of forage grasses at proper times will produce maximum yields and high nitrogen removal (U.S. ACOE, 1983). The initial cutting should be at the early heading stage of growth, with 5- to 6-week intervals between subsequent cuttings. Subsequent cutting should be at the late flowering stage of growth and again toward the end of the growing season.

Nitrogen uptake by corn occurs during a 4- to 6-week period in the summer when the crop is between the knee-high and the tasseling stages of growth (Alexander, 1967). Double-cropping corn with rye, winter wheat, or forage grasses will enhance nitrogen removal in slower corn uptake periods.

Wastewater quality analysis may indicate that fertilizers and soil amendments may be required to maintain crop productivity. The quantity of potassium consumed

TABLE 23.8 Example irrigation schedule for 1 year.[a]

	Evapotranspiration rate (ET), in./mo	Precipitation rate (PR), in./mo	Net (ET-PR), in.	Allowable hydraulic loading, in.	Leaching requirement, in.	Calculated allowable pumped water, in./mo	Inflow to lagoon, ac-ft	Average lagoon evaporation, in.	Average remaining, ac-ft	Irrigation applied, in./mo	Water pumped, in./mo	Water pumped, ac-ft	In lagoon at end of month, ac-ft
Jan	1.3	0.4	0.9	1.4	0.45	1.75	666	16	650	0.9	1.1	260	390
Feb	1.6	0.8	0.8	1.2	0.4	1.5	603	24	578	0.9	1.1	260	708
Mar	1.7	1.6	0.1	0.2	0.05	0.25	628	46	582	4.0	5.0	1 182	108
Apr	2.5	2.3	0.2	0.3	0.1	0.4	608	46	562	1.0	1.2	281	389
May	3.6	5.5	−1.9	0	0	0	656	36	620	0	0	0	1 009
Jun	5.8	3.1	2.7	4.1	1.4	5.1	645	70	575	2.4	3.0	709	875
Jul	8.8	2.3	6.5	9.7	3.2	12.1	476	76	400	4.0	5.0	1 185	90
Aug	11.2	2.3	8.9	13.3	4.4	16.6	666	96	570	2.2	2.8	660	0
Sep	9.0	5.6	3.4	5.1	1.7	6.4	626	70	556	1.6	2.0	473	83
Oct	3.9	4.4	−0.5	0	0	0	656	40	616	0	0	0	699
Nov	1.7	0.7	1.0	1.5	0.5	1.9	666	40	626	0.8	1.0	236	1 089
Dec	1.2	0.7	0.5	0.7	0.2	0.9	666	25	642	0.9	1.1	260	1 471

[a]in. $\times (2.54 \times 10^{-2})$ = m; ac-ft $\times$ 1 233 = m^3.

by the crop is approximately equivalent to its nitrogen uptake. The potassium fertilizer requirements can be determined from the following equation (U.S. ACOE, 1983):

$$K_f = 1.25(0.9 \times U - K_{ww}) \tag{23.3}$$

where:

K_f = annual amount of potassium fertilizer applied in the spring, lb/ac;
U = estimated nitrogen uptake by the crop, lb/ac; and
K_{ww} = amount of potassium applied in the wastewater, lb/ac.

Lime is important for maintaining proper soil pH. In addition, liming will decrease the solubility of metals in the soil. The amount of exchangeable sodium in the soil can be controlled through lime addition. High sodium and salinity can decrease the soil permeability.

The best growing conditions for most crops occur when the moisture in the soil is at field capacity (U.S. ACOE, 1983). Field capacity is the soil moisture content (percent moisture on a dry weight basis) in the field 2 or 3 days after saturation and after free drainage has ceased, that is, the quantity of water held in the soil by capillary action after gravitational or free water has drained from the soil. The plant will be adversely affected when the soil moisture drops to half the field capacity. Soil moisture probes or tensiometers can measure soil moisture that can be an integral part of a control system to program wastewater application to areas where water is needed.

An operator can estimate the soil moisture by obtaining a handful of soil from the root zone and squeezing it in his/her hand. The feel and appearance of the resulting soil should be compared to the descriptions in Table 23.9. Beneath each description is the amount of water needed to bring the top 0.3 m (1 ft) of soil up to field capacity.

Wastewater. The system manager needs to develop wastewater application rates and schedules. Operators need to make decisions concerning startup and shutdown schedules, the amount of water to be applied during each shift, the frequency of application, and the field or section to receive water. These decisions depend on climate, cropping pattern, rainfall, and the quantity of wastewater to treat. The application schedules must include times for wastewater storage that are affected by cropping pattern, planting, harvesting, climate, precipitation, soil moisture, and mechanical failure. The operator must have the knowledge and capability to alter the application and storage schedules to achieve the wastewater treatment objectives during special environmental conditions.

TABLE 23.9 Field estimating of soil moisture content (U.S. ACOE, 1983).

Fine texture	Medium texture	Moderately coarse texture	Coarse texture
No free water after squeezing, wet, leaves outline on hand (0.0 in.)	Same as fine texture (0.0 in.)	Same as fine texture (0.0 in.)	Same as fine texture (0.0 in.)
Soil easily squeezes out between fingers in ribbons, has slick feeling, but not completely wet (0.0–0.6 in.[a])	Forms a pliable ball, sticks readily if high in clay (0.0–0.5 in.)	Forms weak ball, breaks easily, will not stick (0.0–0.4 in.)	Sticks together slightly, may form a weak ball under pressure (0.0–0.2 in.)
Forms a ball, squeezes out between thumb and forefinger in ribbon (0.6–1.2 in.)	Forms a ball, sometimes sticks slightly with pressure (0.5–1.0 in.)	Tends to ball under pressure, but will not hold together (0.4–0.8 in.)	Appears dry, will not form a ball when squeezed (0.2–0.5 in.)
Somewhat pliable, will form a ball when squeezed (1.2–1.9 in.)	Somewhat crumbly but holds together from pressure (1.0–1.5 in.)	Appears dry, will not form a ball (0.8–1.2 in.)	Appears dry, will not form a ball (0.5–0.8 in.)
Hard, baked, cracked (1.9–2.5 in.)	Powdery, dry, sometimes slightly crusted but easily broken down into powdery condition (1.5–2.0 in.)	Dry, loose, flows through fingers (1.2–1.5 in.)	Dry, loose, single-grained, flows through fingers (0.8–1.0 in.)

[a]in. $\times (2.54 \times 10^{-2}) = $ m.

Note: The numerical values (water index) represent the amount of water that would be needed to bring the top 1 ft (ft $\times$ 0.304 8 = m^2) of the soil to field capacity.

The quality of the wastewater applied to land needs to be monitored. The primary objective of wastewater analysis for agricultural use is to forewarn the manager of potential problems. Table 23.10 presents a list of laboratory analyses to determine water quality of irrigation water. Guidelines for interpreting the water quality data are provided in Table 23.11.

DATA COLLECTION. The monitoring program provides information for the operation of the system. Land application systems are monitored to ensure that the treatment system meets the requirements of the federal and state agencies and to determine whether all components of the system are functioning properly. All land treatment systems with point source discharges have an NPDES permit that establishes performance and operational criteria for the system. Land application systems without point source discharges may not necessarily be permitted, or have a groundwater permit. The operator must be aware of his monitoring requirements, if permitted; if not permitted, the operator should gather enough data to ensure successful operation of the facility.

Wastewater. Most states are concerned about the quality of wastewater applied to the treatment site. Table 23.12 presents a typical monitoring schedule for measuring certain wastewater quality parameters. Nitrogen, phosphorus, BOD_5, and pH are typically measured for most land treatment systems. As previously mentioned, pH, nutrients, salts, and other chemicals are measured to ensure a healthy crop and proper operation of the system to achieve the system objectives. Table 23.13 presents monitoring criteria that should be considered when storage ponds are used.

Groundwater. Groundwater is typically monitored at the system boundary. Perimeter wells are located hydraulically downgradient of the site. An additional well is installed upgradient of the land treatment site to determine groundwater quality before it enters the site. Figure 23.6 illustrates a typical shallow groundwater monitoring well. A minimum of three casing volumes (3 $\times$ cross-sectional area of well casing $\times$ depth of water in casing) should be removed from the well before sampling. The depth to the water table should also be measured (see Figure 23.6).

Nitrogen concentrations in the groundwater are of major concern if the aquifer serves as a drinking water supply. Typically, land application systems can remove sufficient nitrogen to meet drinking water requirements. Because of the slow movement of groundwater, water samples typically need to be taken only once or twice a year.

Soil and Vegetation. Soil and vegetation analyses are conducted to determine the long-term accumulation of certain pollutants and to provide information for process control. Soil samples should be collected from each irrigated area at least annually.

TABLE 23.10 Additional laboratory determinations needed to evaluate the suitability of reclaimed municipal wastewater for irrigation (Pettygrove and Asano, 1985).

Nutrients (mg/L)
- Nitrate-nitrogen (NO_3–N)
- Ammonia-nitrogen (NH_3–N)
- Organic-nitrogen (Org–N)
- Potassium (K)
- Total nitrogen (Total N)
- Ortho-phosphate-phosphorus (PO_4–P)
- Total phosphorus (TP)

Residual free chlorine (Cl_2 in mg/L)
Total dissolved solids (TDS in mg/L)
Trace elements[a] (Groups I and II) (shown below)

	Typical detection limits, mg/L[b]		Recommended maximum concentration, mg/L
	AA spectro-photometer	ICAP spectro-photometer	
Group I			
Aluminum (Al)	0.03	0.02	5.0
Arsenic (As)	0.14	0.05	0.10
Barium (Ba)	0.008	0.000 5	—
Cadmium (Cd)	0.000 5	0.004	0.01
Chromium (Cr)	0.002	0.005	0.10
Copper (Cu)	0.001	0.003	1.0
Fluoride (F)	—	—	1.0
Iron (Fe)	0.003	0.003	5.0
Lead (Pb)	0.01	—	—
Lithium (Li)	0.000 5	—	2.5
Manganese (Mn)	0.001	0.001	0.2
Mercury (Hg)	0.17	—	—
Nickel (Ni)	0.004	0.01	0.2
Selenium (Se)	0.07	0.05	0.02
Silver (Ag)	0.000 9	—	—
Vanadium (V)	0.04	0.005	0.1
Zinc (Zn)	0.000 8	0.002	2.0
Group II			
Antimony (Sb)	0.03	—	—
Beryllium (Be)	—	—	0.1
Cobalt (Co)	0.006	0.006	0.05
Molybdenum (Mo)	0.03	0.008	0.01
Thallium (Tl)	0.009	—	—
Tin (Sn)	0.11	0.03	—
Titanium (Ti)	0.05	0.002	—
Tungsten (W)	1.2	0.04	—

[a]Routine checks for trace elements would not include Group II trace elements unless they were suspected of being present.
[b]Most laboratories use either the atomic absorption spectrophotometer (AA) or the inductively coupled argon plasma emission spectrophotometer (ICAP).

TABLE 23.11 Example guidelines for interpretation of water quality data for irrigation (Pettygrove and Asano, 1985)

		Degree of restriction on use		
Potential irrigation problem	**Units**	**None**	**Slight to moderate**	**Severe**
Salinity (affects crop water availability)				
Electrical conductivity, EC_W	dS/m or mmho/cm[a]	<0.7	0.7–3.0	>3.0
Total dissolved solids (TDS)	mg/L	<450	450–2 000	>2 000
Permeability (affects infiltration rate of water into the soil; evaluate using EC_W and SAR[b] together)				
SA = 0–3		and EC_W = >0.7	0.7–0.2	<0.2
= 3–6		= >1.2	1.2–0.3	<0.3
= 6–12		= >1.9	1.9–0.5	<0.5
= 12–20		= >2.9	2.9–1.3	<1.3
= 20–40		= >5.0	5.0–0.29	<2.9
Specific ion toxicity affects sensitive crops				
Sodium Na[c]	SAR			
Surface irrigation	mg/L	<3	3–9	>9
Sprinkler irrigation	mg/L	<70	>70	—
Chloride (Cl)				
Surface irrigation	mg/L	<140	140–350	>350
Sprinkler irrigation	mg/L	<100	>100	—
Boron (B)	mg/L	<0.7	0.7–3.0	>3.0
Trace elements (see Table 23.10)	mg/L			
Miscellaneous effects (affects susceptible crops)				
Nitrogen (total-N)[d]	mg/L	<5	5–30	>30
Bicarbonate (HCO_3) (overhead sprinkling only)	mg/L	<90	90–500	>500
pH		Normal range 6.5–8.4		
Residual chlorine (overhead sprinkling only)	mg/L	<1.0	1.0–5.0	>5.0

[a]Conversion = 0.001 $\mho$/cm × 1 siemens/$\mho$ × 100 cm/m = 0.1 siemens/m = 1.0 decisiemens/m = dS/m.
[b]Sodium absorption ratio.
[c]With overhead sprinkler irrigation and low humidity (%), sodium or chloride greater than 70 or 100 mg/L, respectively, has resulted in excessive leaf absorption and crop damage to sensitive crops.
[d]Total nitrogen should include nitrate-nitrogen, ammonia-nitrogen, and organic-nitrogen. Although forms of nitrogen in wastewater vary, the plant responds to the total nitrogen.

TABLE 23.12 Typical monitoring schedule for applied wastewater (U.S. ACOE, 1983).

	Size of system, mgd[3]	
Parameter	**0–0.075**	**>2.0**
Biochemical oxygen demand	1 per 3 mo	2 per week
Suspended solids	1 per 3 mo	2 per week
pH	1 per 3 mo	2 per week
Kjeldahl nitrogen	1 per 3 mo	2 per week
Ammonium nitrogen	1 per 3 mo	1 per week
Nitrate nitrogen	1 per 3 mo	1 per week
Phosphorus	1 per 6 mo	1 per week
Chloride	1 per 6 mo	1 per week
Sodium	1 per 6 mo	1 per mo
Calcium	1 per yr	1 per mo
Magnesium	1 per yr	1 per mo
Potassium	1 per yr	1 per mo

[a]Interpolate for intermediate sizes (mgd $\times$ [4.383×10^{-2}] = m^3/s).

Table 23.14 outlines a possible monitoring program. Composite soil samples should be obtained from areas of different soil types, areas receiving different hydraulic loadings, and areas planted in various crops.

A baseline characterization of the soil is required during the final stages of design, or just before startup of the system, to determine the need for fertilizers and soil amendments to enhance crop production and to establish a database for comparison with future annual soil analyses. The local county agricultural extension agent can help the system manager determine from which locations the soil samples should be collected and how many individual soil samples should be collected and composited at each location. Furthermore, the extension agent can help interpret the soil data.

Vegetation should be obtained from each crop cultivated and analyzed for the constituents listed in Table 23.15. Typically, the leafy material will be the first to show increases in metal content, thereby providing an early indication of future problems. Plant analysis may also be used to monitor nutrient deficiencies within the crop. Only the leaves or parts of the plant of the same age and relative position on the plant should be sampled. To account for plant variability, sufficient plants must be sampled. Table 23.16 presents plant parts to be sampled and the number of samples to be collected. Dead plant tissue should not be included in the tissue sample. Plant tissue analysis is not a substitute for soil analysis but is a co-analysis useful in process control and assessment of long-term problems.

TABLE 23.13 Monitoring of storage pond effluents (U.S. ACOE, 1983).

	Design flow, mgd[a]	
Parameter	**0–0.015**	**>2.00**
Biochemical oxygen demand	1 wk before application season, once every 3 mo during application season	1 wk before application season, then 2/wk during season
Suspended solids	Same as BOD	
pH	Same as BOD	
Kjeldahl nitrogen	1 wk before application season, 1 sample at midpoint of season	1 wk before application season, 1/wk during season
Ammonia nitrogen	Same as Kjeldahl nitrogen	
Nitrate nitrogen	Same as Kjeldahl nitrogen	
Phosphorus	Same as Kjeldahl nitrogen	
Chloride	1 wk before application season	1 wk before application season, 1/mo thereafter during season
Sodium	Same as chloride	
Calcium	Same as chloride	
Magnesium	Same as chloride	
Potassium	Same as chloride	
Bacteria: total coliforms or fecal coliforms	1 wk before application season, 1/mo thereafter during season	1 wk before application season, then 2/wk during season

[a]Interpolate for intermediate sizes (mgd $\times$ $[4.383 \times 10^{-2}]$ = m^3/s).

TROUBLESHOOTING. Land treatment systems may develop problems such as

- Overloading,
- Low temperatures,
- Toxic materials from industrial wastes,
- Nutrient deficiencies,
- Short-circuiting,
- Malfunctioning of irrigation equipment,
- Erosion,
- Insect propagation,

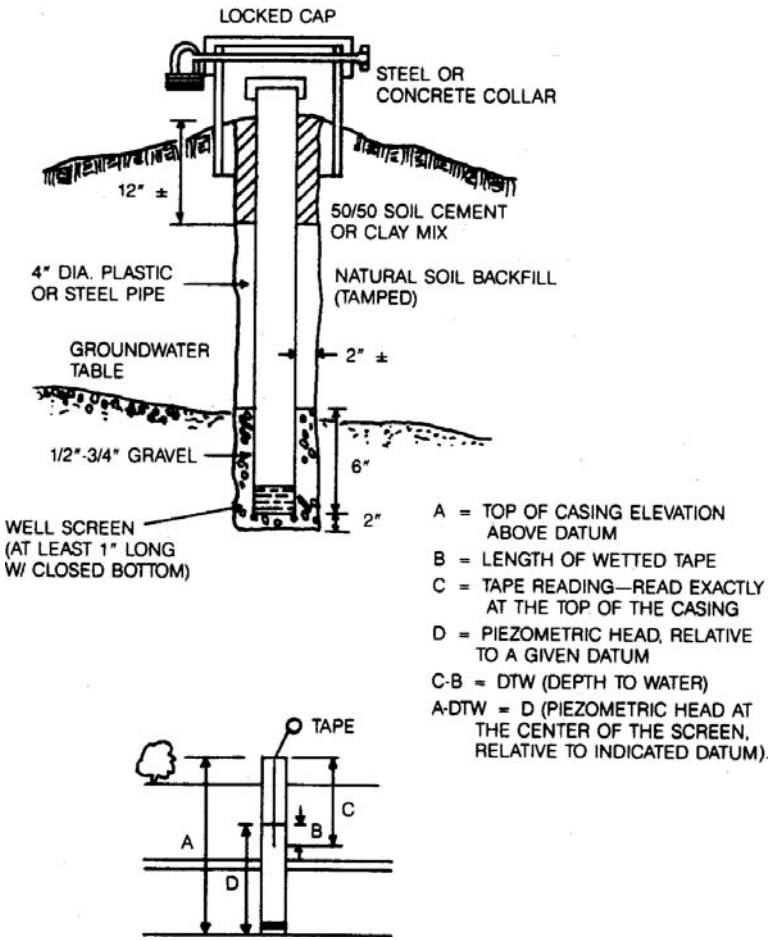


FIGURE 23.6 Typical shallow monitoring well and water-level determination (in. $\times$ $[2.54 \times 10^{-2}]$ = m) (U.S. ACOE, 1983).

- Aerosol drift, and
- Groundwater contamination.

Table 23.17 presents a troubleshooting guide that will enable the operator to identify problems and their possible solutions.

MAINTENANCE. Refer to Chapter 8 for pump maintenance and Chapter 12 for maintenance of drives, seals, and other common elements. Specific maintenance needs

TABLE 23.14 Soil monitoring on agricultural sites (U.S. ACOE, 1983).

Annual sample and test
pH (for lime needs)
Available phosphorus
Exchangeable/extractable
Potassium
Sodium
Magnesium
Calcium
Baseline and every 5 years
pH (for lime needs)
Nitrogen
Cation exchange capacity, percent organic matter
Exchangeable/extractable
Potassium
Phosphorus
Copper
Zinc
Nickel
Cadmium
Total
Boron
Copper
Zinc
Nickel
Cadmium
Sodium adsorption ratio in western states or arid climates

TABLE 23.15 Vegetation monitoring on agricultural sites (U.S. ACOE, 1983).

Component	Frequency
Total nitrogen (N) and phosphorus (P)	Annual sample if N or P removal is required by system
Nitrate (NO_3) for forage grasses and silage	At harvest if recommended by extension agent for livestock protection
Copper, zinc, nickel, and cadmium	At first harvest and every 5 years thereafter to establish trends

TABLE 23.16 Vegetation sampling—field pattern and plant part (U.S. ACOE, 1983).

Crop	Pattern	Plant part
Alfalfa	X diagonals of field, 50–100 clumps	Upper stem cutting in early flower stage
Corn	X diagonals or along row at least 50 plants into field	Center one-third of leaf, just below lower center, at full tassle
Wheat and grains	X diagonals, 200 or more leaves	First four leaf blades from top of plant
Grass and soil	X diagonals	Clippings or whole tops
Soybeans	Randon leaves from at least 5% of plants, 50 to 100 leaves	Youngest mature leaves, after pod formation
Tree fruits	X diagonals in orchard, one leaf from north, south, east, and west sides of tree	Mature leaves, shoulder height, 8–12 weeks after full bloom

for pumps and other mechanical equipment are presented in the operations and maintenance manuals provided by the engineering consulting firm for the specific site.

Air, vacuum, and pressure relief valves should be checked monthly for proper operation. If pressure gauges are used in the wastewater distribution system, it is recommended that they be drained when not in use, particularly during freezing weather.

Slow-Rate Process. Systems using sprinklers should have schedules for inspection and cleaning. All lines and pipes in seasonal operation should be drained when not in use to limit corrosion. Large center-pivot irrigation require inspection of the tires and gear boxes. Proper tire pressure must be maintained, and the gear boxes must be properly lubricated at the start of operation. Automatic drain valves at each irrigation machine should be inspected during every shutdown, particularly if freezing weather conditions are expected. Malfunctioning valves should be removed and cleaned or replaced. Passive drain valves on center-pivot rigs should be checked at least once every 3 years. If in-line strainers are used to minimize clogging of nozzles, they should be checked daily and cleaned when necessary to allow proper irrigation. Nozzles on irrigation machines and devices should be checked daily and cleaned when necessary to allow proper wastewater application to the land.

The integrity of surface runoff control structures, such as retention areas, contour plowing, or construction of berms, needs to be maintained to prevent drainage from the land application site. These surface runoff control structures should be inspected daily and reconstructed when necessary.

TABLE 23.17 Troubleshooting guide for land treatment (Culp and Heim, 1978, and U.S. ACOE, 1983).

Indicators/observations	Probable cause	Check or monitor	Solutions
Water ponding in irrigated area where ponding normally has not been used	Application rate is excessive	Application rate	Reduce rate to normal design rate
	If application rate is normal, drainage may be inadequate	Seasonal variation in groundwater level	Irrigate portions of the site where groundwater is not a problem or store wastewater until level has dropped
		Operability of any drainage wells	Repair drainage wells or increase pumping rate
		Conditions of drain tiles	Repair drain tiles
		Leaks in system	Repair pipe
Lateral aluminum distribution piping deteriorating	Effluent permitted to remain in aluminum pipe too long, causing electrochemical corrosion	Operating techniques	Drain aluminum lateral lines except when in use
	Dissimilar metals (steel valves and aluminum pipe)	Pipe and valve specifications	Coat steel valves or install cathodic or anodic protection
No flow from sprinkler nozzles	Nozzle clogged with particles from wastewater due to lack of screening at inlet side of irrigation pumps	Screen may have developed hole due to partial plugging of screen	Repair or replace screen
Wastewater is running off irrigated area	Sodium adsorption ratio of wastewater is too high and has caused clay to become impermeable	Sodium adsorption ratio (SAR) should be less than 9	Feed calcium and magnesium to adjust SAR
	Soil surface sealed by solids	Soil surface	Strip crop area
	Application rate exceeds infiltration rate of soil	Application rate	Reduce application rate until compatible with infiltration rate
	Break in distribution piping	Leaks in distribution piping	Repair breaks

TABLE 23.17 Troubleshooting guide for land treatment (Culp and Heim, 1978, and U.S. ACOE. 1983) (*continued*).

Indicators/observations	Probable cause	Check or monitor	Solutions
	Soil permeability has decreased because of continuous application of wastewater	Duration of continuous operation on the given area	Each area should be allowed to rest (2–3 days) between applications of wastewater to allow soil to drain
	Rain has saturated soil	Rainfall records	Store wastewater until soil has drained
Irrigated crop is dead	Too much (or not enough) water has been applied	Water needs of specific crop versus application rate	Reduce (or increase) application rate
	Wastewater contains excessive amounts of toxic elements	Analyze wastewater and consult with county agricultural agent	Eliminate industrial discharge of toxic materials
	Too much insecticide or weed killer applied	Application of insecticide or weed killer	Proper control of application of insecticide or weed killer by a qualified ticketed sprayer
	Inadequate drainage has flooded root zone of crop	Water ponding	Improve drainage or limit application
Growth of irrigated crop is poor	Too little nitrogen (N) or phosphorus (P) applied	N and P quantities applied; check with agricultural agent	If increased wastewater application rates are not practical, supplement wastewater N or P with commercial fertilizer
	Timing of nutrient application not consistent with crop need	Consult with county agricultural agent	Adjust application schedule to meet crop needs
Irrigation pumping station shows normal pressure but above normal flow	Broken main, lateral, riser, or gasket	Inspect distribution system for leaks	Repair leak
	Missing sprinkler head or end plug	Inspect distribution system for leaks	Repair leak
	Too many laterals on at one time	Number of laterals in service	Make appropriate valving changes
Irrigation pumping shows above pressure but below average flow	Blockage in distribution system resulting from plugged sprinklers, valves, screens, or frozen water		Locate blockage and eliminate

TABLE 23.17 Troubleshooting guide for land treatment (Culp and Heim, 1978, and U.S. ACOE. 1983) (*continued*).

Indicators/observations	Probable cause	Check or monitor	Solutions
Irrigation pumping station shows below normal flow and pressure	Pump impeller is worn	Pump impeller	Replace impeller
	Partially clogged inlet screen	Screen	Clear screen
Excessive erosion occurring	Excessive application rates	Application rate	Reduce application rate
	Inadequate crop cover	Condition of crop cover	Reseed crop
Odor complaints	Wastewater turning septic during transmission to irrigated site and odor being released as it is discharged to preliminary treatment	Sample wastewater as it leaves transmission system	Contain and treat offgases from a discharge point of transmission system by covering inlet with building and passing offgases through deodorizing system
	Odor from storage reservoirs		Improve preliminary treatment or aerate reservoirs
Center pivot irrigation rigs stuck in mud	Excessive application rates		Reduce application rates
	Improper tires or rigs		Install tires with higher flotation capabilities
	Poor drainage		Improve drainage
Nitrate concentration of groundwater in vicinity of irrigation site is increasing	Application of nitrogen is not in balance with crop needs	Check quantity applied or nitrogen being applied with needs of crops	Change crop to one with higher nitrogen needs
	Nitrogen being applied during periods when crops are dormant	Application schedules	Apply wastewater only during periods of active crop growth
	Crop is not being harvested and removed	Farming management	Harvest and remove crop

Rapid Infiltration Process. The operator must prevent the sealing of the soil surface to maintain the soil infiltration capacity. Accurate records should be kept on the infiltration capacity to determine when restoration is needed. To restore the infiltration process, the infiltration basin is allowed to dry completely and the surface organic mat is disked.

An alternative method is to completely remove the top layer of soil and replace it with a suitable soil. Because this alternative is more labor and equipment intensive, it is also more expensive. Furthermore, care must be taken to minimize the amount of vehicular traffic on the infiltration beds to limit the amount of compaction of the subsurface soil layers.

In cold climates, the surface soil should be disked each year during the late summer or fall to keep the beds from clogging during the winter. The ridges and furrows left by plowing the basin surface each fall will allow sheets of ice to rest on the ridges. Subsequent wastewater applications should be below the ice. This will insulate the wastewater and the soil surface. For this ice bridge to occur, the ice must form before the wastewater level drops below the top of the ridge. This allows the remaining water to continue to infiltrate the furrows (U.S. ACOE, 1983, and U.S. EPA, 1981).

Overland Flow Process. Maintaining the integrity of the overland flow slope to provide a sheet flow of wastewater down the length of the slope is essential to producing an acceptable effluent. Channels that may develop because of poor construction or hydraulic overloading must be filled and reseeded as soon as possible. Barren areas should be reseeded to reduce hydraulic short-circuiting. Accumulated solids at the top of the slope may need to be removed to prevent smothering of grass and development of anaerobic conditions. These solids can be disked into the soil. When driving on the slopes, high flotation tires should be used to reduce pressures and limit the formation of tire ruts. Grass cutting and harvesting should be conducted perpendicular to the slope direction.

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INTRODUCTION

There are three basic types of wastewater treatment processes: biological, chemical, and physical. Biological processes include trickling filters, rotating biological contactors, activated sludge, and anaerobic digestion. Chemical processes include heavy metal precipitation, phosphorus precipitation, acid or alkali addition for pH control, and disinfection with chlorine or hypochlorite. Physical processes include grit removal, primary and secondary clarification—sedimentation, filtration, and centrifugation.

Currently, most wastewater treatment plants (WWTPs) in the United States provide preliminary, primary, and secondary wastewater treatment. The focus is on reducing carbonaceous biochemical oxygen demand (CBOD) and total suspended solids (TSS) to meet discharge permit parameters. Preliminary treatment (Chapter 18) typically involves removing rags and large solids (via headworks screens) or chopping them into small pieces (via comminutors or grinders), and removing inorganics and grit (via grit channels or chambers). Primary treatment (Chapter 19) typically involves removing readily settleable and floatable matter, as well as larger organics, in gravity settling tanks. Secondary treatment (Chapters 20 and 21) typically involves lowering BOD and TSS concentrations via a combination of biological and settling processes. Chemicals can be used in primary or secondary clarifiers to increase solids capture. The resulting effluent can then be disinfected (Chapter 26) and discharged.

Increasingly, to further enhance receiving water quality, regulators are setting stricter limits for nitrogen, phosphorus, metals, nonbiodegradable soluble organics, BOD, TSS, fecal coliform, and other parameters. Regulators and environmentalists also are focusing on tertiary treatment, so the resulting effluent can be recycled for irrigation, industrial uses, and other applications traditionally served by potable water. Both objectives can be addressed by physical–chemical processes. Chemical addition, for example, can be used to further reduce conventional parameters, such as suspended solids, or new processes can be added to treat phosphorus and soluble, nonbiodegradable chemical oxygen demand (COD).

This chapter will mainly address the use of physical–chemical treatment to (a) enhance suspended solids reduction in primary treatment, (b) further reduce solids in advanced treatment processes, and (c) reduce phosphorus; soluble, nonbiodegradable COD; and other parameters. Solids-handling processes that incorporate elements of physical and chemical treatment are discussed extensively in other chapters of this book. (Advanced biological treatment for nitrogen and phosphorus reduction, which is becoming more common than physical–chemical removal, especially at larger WWTPs, is discussed in Chapter 22).

FUNDAMENTALS OF THE COAGULATION AND FLOCCULATION PROCESSES. In the wastewater treatment industry, coagulation involves adding inorganic chemicals (see Table 24.1), organic polymers, or a combination thereof to wastewater to promote solids or phosphorus removal. Suspended colloidal particles all carry the same surface charge (usually negative), and their mutual repulsion is enough to prevent them from settling. Coagulants destabilize these charges, reducing the repulsion between particles and promoting their settling. Coagulants also chemically react with soluble phosphorus to form an insoluble precipitate that can be removed via sedimentation or filtration.

TABLE 24.1 Inorganic chemicals commonly used for coagulation in wastewater treatment (adapted from Metcalf & Eddy, 2003).

Chemical	Formula	Molecular weight	Equivalent weight	Form
Alum	$Al_2(SO_4)_3 \cdot 18H_2O$	666.5		Liquid
	$Al_2(SO_4)_3 \cdot 14H_2O$	594.4	114	
Aluminum chloride	$AlCl_3$	133.3	44	Liquid
Calcium hydroxide (lime)	$Ca(OH)_2$	56.1 (as CaO)	40	Lump powder slurry
Ferric chloride	$FeCl_3$	162.2	91	Liquid lump
Sodium aluminate	$Na_2Al_2O_4$	163.9	100	Flake

Flocculation is similar, except that the chemicals "chain" the particles together into flocs (aggregates) that float or sink, making them easier to remove from the system. In the flocculation step, the chemically treated water is gently stirred to form large flocs of suspended solids or phosphorus precipitates, which are then removed via sedimentation and filtration. When the proper type and amount of coagulant or flocculant is added to wastewater, it can remove approximately 90% of the phosphorus and suspended solids normally present in a secondary effluent.

If treatment plant staff are considering using an organic polymer, they should work closely with their consultant and polymer supplier because many products are commercially available and their applications are often site-specific.

Coagulant typically is added to a tertiary process. However, some WWTPs add coagulant to the activated sludge tank, where it is mixed by the aeration process, and remove the resulting floc from the secondary clarifier. Others add coagulant to raw wastewater as it enters the plant and remove the resulting solids from the primary clarifier. When coagulants are added to primary clarifiers, however, care must be taken not to remove all the phosphorus, which is an essential nutrient for biological growth in secondary treatment. Also, chemical coagulation will increase the volume of sludge that must be handled (see "Sedimentation").

SEDIMENTATION. Depending on the treatment levels required, coagulated and flocculated effluent may enter a clarifier or settling basin, where gravity causes the solids to settle on the bottom. Patented high-rate clarification or ballasted flocculation systems also can remove coagulated–flocculated solids from effluents. A major selling point of these technologies is that they require less space than conventional clarifiers.

As mentioned before, chemical coagulation increases the volume of sludge that must be handled. Relatively speaking, iron salts or alum will produce less sludge than lime will. As a general rule, the amount of sludge that can be attributed solely to alum addition can be calculated (in mg/L) as 0.26 times the alum dose. This is in addition to the TSS and other solids removed via the alum.

For example, suppose a treatment plant receives 10 mgd (38 854 m^3/d) of wastewater containing 220 mg/L of TSS. Suppose that TSS removal in the primary clarifiers is 60% without alum addition and 80% with 25 mg/L of alum addition. So, without alum, the primary clarifier generates the following amount of sludge:

$$= 0.6 \times 10 \text{ mgd} \times 220 \text{ mg/L} \times 8.34 \text{ lb/gal}$$
$$= 11\,000 \text{ lb/d (4990 kg/d)}$$

With alum addition, the clarifier generates more sludge:

$$= (0.8 \times 10 \text{ mgd} \times 220 \text{ mg/L} \times 8.34 \text{ lb/gal}) + (0.26 \times 10 \text{ mgd} \times 25 \text{ mg/L} \times 8.34 \text{ lb/gal})$$
$$= 14\,678 \text{ lb/d} + 542 \text{ lb/d}$$
$$= 15\,220 \text{ lb/d (6904 kg/d)}$$

So, 542 lb/d of sludge is attributable to alum addition, and the overall sludge production increased from 11 000 to 15 220 lb/d, or about 39%.

Similarly, the amount of sludge that can be attributed solely to ferric chloride addition can be calculated (in mg/L) as 0.66 times the ferric chloride dose. At the plant mentioned in the above example (again, assuming 60% TSS removal without ferric chloride, and 80% removal with ferric chloride), a 40-mg/L ferric chloride dose would itself generate about 2200 lb/d of sludge and increase overall sludge production to 16 900 lb/d, or approximately 54%.

This extra sludge can overload digestion and dewatering units unless design engineers take these additional quantities into account when sizing the units in the solids processing train. The chemicals also can affect solids dewaterability, because chemical sludges can be difficult to dewater. In the case of alum, the added sulfate can also affect odor production through the breakdown of the sulfate ion and the formation of hydrogen sulfide. (For more information on solids-handling processes, see Chapters 27 through 33.)

FILTRATION. In filtration, effluent passes through a filtering medium—or a combination of two or three media—to remove suspended or colloidal matter. Filtration is typically a tertiary treatment step located downstream of secondary processes. Its pri-

mary goal is removing suspended solids from a secondary, coagulation–flocculation, or tertiary sedimentation process effluent. For example, filtering coagulation, flocculation, and sedimentation effluent can typically reduce suspended solids concentrations from between 3 and 5 mg/L to virtually zero and phosphorus concentrations from between 0.5 and 1 mg/L to 0.1 mg/L or less. An efficient filtration system should also be able to be cleaned (backwashed) using less than about 5% of its influent flow.

Occasionally, filtration alone without upstream coagulation and flocculation is used to further reduce suspended solids concentrations in activated sludge effluents. (This is less effective for trickling filter and rotating biological contactor effluents because their solids are less naturally flocculent.) Also, while filtration alone may technically meet recycled water standards, regulators will tend to err on the conservative side to meet the related health standards and typically mandate a treatment scheme using either

- Coagulation, flocculation, and sedimentation before filtration or
- Direct filtration, in which the sedimentation step is eliminated, alum is added in a rapid-mix environment, and a nonionic polymer is added to the filters.

Many types of media can be used for filtration. In addition to traditional granular media (typically sand and anthracite), natural or synthetic fiber or fabric, synthetic fuzzy balls and beads, and other filtration media are available. Nevertheless, most WWTPs using filtration use granular media.

Depending on the cleaning (backwashing) method used, granular media systems can be further classified as semicontinuous (conventional) or continuous filters. Semicontinuous filters have to be taken offline periodically for backwashing, while continuous filters can filter and backwash simultaneously.

In semicontinuous downflow filtration systems, wastewater passes through a 0.3- to 0.9-m-deep (10- to 36-in.-deep) granular bed composed of 0.35- to 1.5-mm (0.014- to 0.059-in.) particles. As the wastewater passes down through the filter, larger particles are captured near the surface of the filter, where the filter media are coarser, and smaller particles penetrate until captured by the finer filter media deeper in the filter. Eventually, the filter becomes plugged with material removed from the wastewater and must be cleaned by reversing the flow (backwashing). The upward backwash rate is sufficient to suspend the media particles and wash the filtered solids from the bed. Air or surface scouring of the media during backwash ensures adequate cleaning and prevents mud balls from forming. The backwash wastewater (typically less than 5% of the total influent flow, for a well-run filter), is recycled through the WWTP. To avoid hydraulic surges through the plant, backwash is often diverted to a storage tank and then recycled to the plant at a controlled rate.

Backwashing requires conventional filters to be taken offline, and the cumulative production downtime can be significant. To circumvent this problem, continuous-backwash granular media filters were developed. These proprietary filters backwash and filter simultaneously, and filter secondary effluents effectively.

Granular media filtration can be done via gravity flow in open concrete or steel structures, or under applied pressure in steel pressure vessels. Its operation and control may be readily automated.

RECARBONATION–pH ADJUSTMENT. If lime is added to an effluent as a coagulant, the effluent's pH will rise to between 10 and 11 and the carbonate (hardness) in the water will precipitate as calcium carbonate, as illustrated by the following reaction:

$$Ca(HCO_3)_2 + Ca(OH)_2 \rightarrow 2CaCO_3\downarrow + 2H_2O \quad (24.1)$$

Calcium carbonate can tenaciously encrust and bind downstream filter media, so the "softened" water must be stabilized before filtration by adding carbon dioxide or acids to it. Carbon dioxide is typically used—hence the term "recarbonation"—and the resulting chemical reaction is as follows:

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca(HCO_3)_2 \quad (24.2)$$

One reason that carbon dioxide is preferred is that its storage and handling requirements are less restrictive than those for strong acids; another is that acids tend to increase the total dissolved solids (TDS) in the final effluent.

DESCRIPTION OF PROCESSES AND PROCESS EQUIPMENT

COAGULANTS. Depending on the treatment objective, coagulants either destabilize similarly charged particles so they will settle more readily or react chemically with compounds to precipitate them. These functions are not mutually exclusive. For example, a coagulant added to enhance settling may also precipitate phosphorus—and even reduce heavy metal concentrations and improve disinfection efficiency. A list of common coagulants and some of their properties is provided in Table 24.1.

The amount of coagulant needed depends on time and wastewater characteristics. For example, the aluminum and iron salt concentrations needed for good phosphorus

removal are typically proportional to the phosphorus concentration and, to a lesser extent, the water's alkalinity. Lime requirements depend largely on the wastewater's alkalinity. Magnesium hydroxide, a gelatinous precipitate frequently formed when lime is added to hard waters containing the magnesium ion, helps remove colloidal material efficiently, but may adversely affect dewatering.

While all coagulants typically increase sludge production, aluminum and iron salts add significant quantities of dissolved solids (sulfates, chlorides, etc., as measured by the TDS parameter) to the final effluent and are not currently amenable to recovery and reuse. Also, alum and ferric chloride lower the effluent's pH and consume alkalinity (about 0.55 mg/L $CaCO_3$ per mg/L of alum and 0.93 mg/L $CaCO_3$ per mg/L of ferric chloride). In waters with low natural (background) alkalinity, utility staff may want to consider alternatives (e.g., sodium aluminate or aluminum chloride). Alum also enhances heavy metal removals, and the heavy metal concentrations in the precipitated sludge could affect biosolids management options.

If ferrous salts (instead of ferric salts) are considered, the water must have a pH of approximately 8.5 or more (not typical at WWTPs) or the salts must be used with chlorine to allow oxidation to the ferric state. Alternatives to alum include sodium aluminate, which does not consume alkalinity, or aluminum chloride.

If lime is used, it can be recovered via "recalcination", but this process consumes large amounts of energy. High-pH lime coagulation, however, can disinfect the water and precipitate certain heavy metals. As a result, the chemical sludge's heavy metals concentrations could limit the plant's biosolids management options.

Metal salts (e.g., alum and ferric chloride) are commonly used coagulants in wastewater treatment; however, the coagulant should be chosen based on anticipated performance, cost, and material handling issues. The capital costs for coagulant-addition facilities are similar, but the operations and maintenance costs depend on the wastewater characteristics and desired effluent pollutant levels. Unless there are specific concerns about solids handling and disposal, alum will often be selected over ferric chloride because it is less expensive, less corrosive, safer, and easier to handle.

Coagulant-addition equipment typically includes storage facilities (e.g., plastic tanks), feed equipment (e.g., feed pumps), and a containment area (sized to hold the contents of the largest storage tank if it failed when full). Wastewater utilities should keep adequate quantities of the chemical on hand and be aware of its special properties. For example, a 49% alum solution will begin to crystallize at approximately 0°C (32°F) and freeze at approximately 7.7°C (18°F). Likewise, a 35 to 40% solution of ferric chloride has a freezing point of −50°C (−58°F), but may start to crystallize at approximately 0°C (32°F). So, the storage and feed equipment may require heat tracing. Utilities should keep onsite at least as much coagulant as (a) 1 month's average daily

use, (b) 3 to 4 days of peak daily use, or (c) 150% of a typical delivery volume [typically, 28 to 30 m^3 (7500 to 8000 gal) because most tank trucks hold between 17 and 19 m^3 (4500 and 5000 gal)], whichever is largest. They should also allow adequate ordering and delivery times, including allowances for extended weekends, holidays, or unforeseen circumstances.

Most coagulant feed systems use positive-displacement pumps (e.g., diaphragm metering and progressing cavity pumps), although other variants (e.g., gear pumps and peristaltic hose pumps) can be used. Large plants may require centrifugal pumps or large progressing cavity pumps. If dry chemicals are used, dry feeders (screw, rotary, gravimetric, etc.), dissolver tanks, mixing tanks, or solution storage tanks may be required. If supplemental alkalinity is needed (not common at wastewater utilities), lime or caustic can be added. This will increase costs and handling requirements, and utility staff may find sodium aluminate or aluminum chloride to be more cost-effective.

The coagulant system's controls tend to be relatively simple: either manual, flow-paced, pH-based, or adjustable based on historical and anticipated diurnal loadings.

In addition to metal salts, polymers or polyelectrolytes may be added to promote coagulation and flocculation. A large variety of polymers is commercially available; they may be natural or synthetic, and liquid or dry. Synthetic polymers may be further classified as cationic, anionic, or non-ionic based on the type of charge (or lack thereof) on the polymer chain. Polymers may be used alone or, more commonly, with a metal salt. In either case, the polymer feed rate is low: typically less than 5 mg/L and often less than 1 mg/L. The equipment involved is similar to that used for metal salt, albeit smaller. Totes are commonly used for liquid polymer.

COAGULANT MIXING. Coagulants may be added to the flow stream in several ways, depending on the application point and mixing device used (Figures 24.1 through 24.4). For example, coagulants may be added to basins via mechanical mixers; injected into pipelines via in-line diffusers, static mixers, or modulating valves; or into open channels either directly or through an open-channel diffuser. Open channels typically have turbulent flow downstream of a Parshall flume, a similar flow-measurement device, or a hydraulic control point (e.g., a weir). If an open channel lacks turbulent flow, it can be simulated by adding in-channel mixing vanes, an air sparger, or an in-channel rapid-mixing device below the chemical-feed diffuser.

Sufficient mixing energy, mixing control, and detention time are critical to ensure that the coagulant is used efficiently and functions effectively. Mixing energy typically should range from 4.26 to 17.02 $kW/m^3 \cdot s$ (0.25 to 1 hp/mgd) of flow. Mixing controls should be able to vary the mixing energy so coagulant can be used more efficiently. Basins equipped with variable-speed flash mixers are popular because they can control

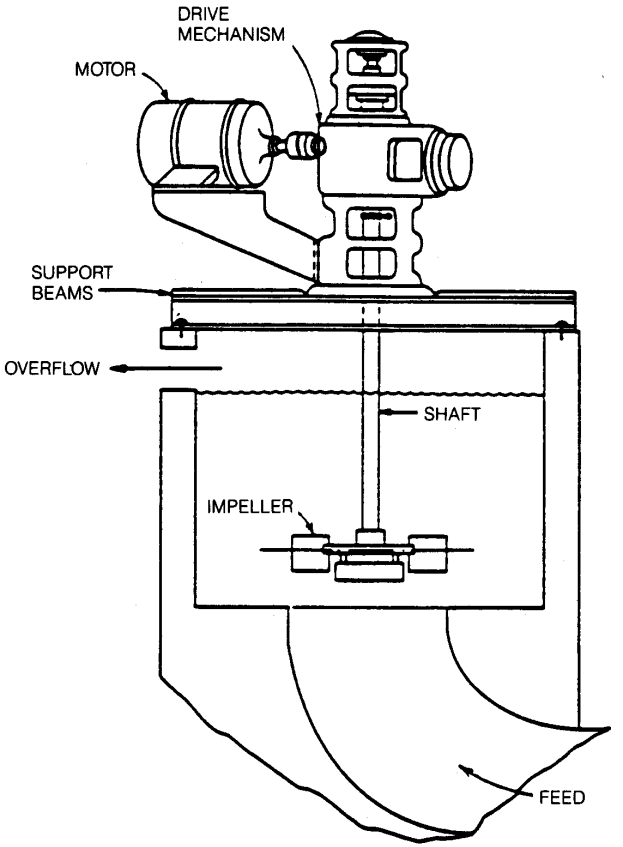


FIGURE 24.1 In-basin mechanical rapid-mixing device.

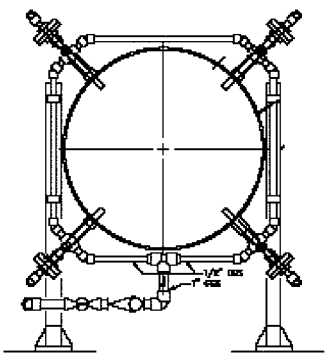


FIGURE 24.2 In-line diffusers.

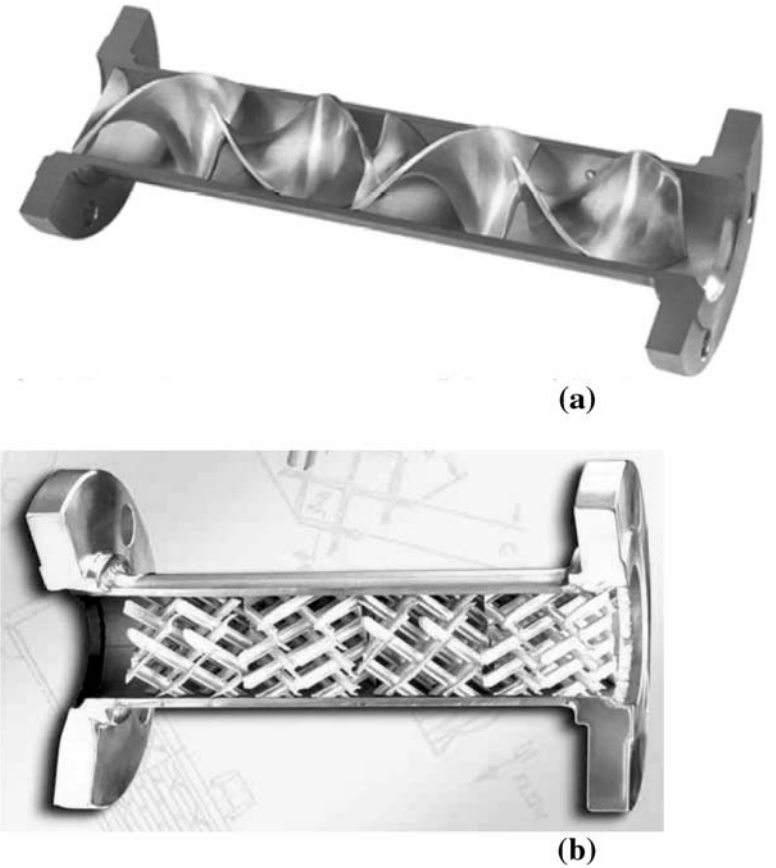
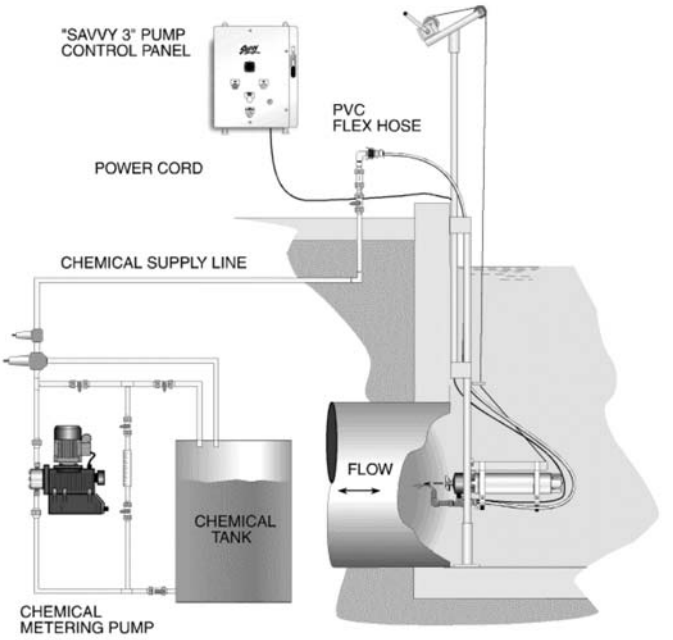
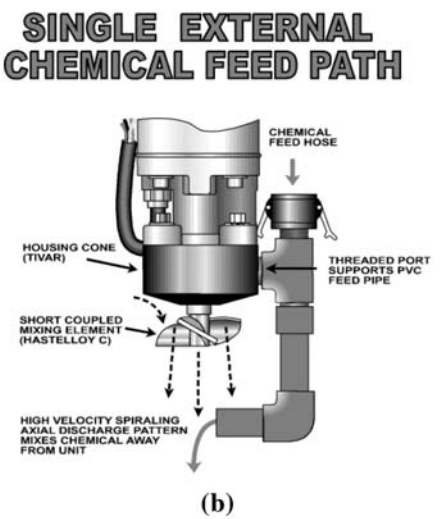


FIGURE 24.3 (a) In-line helical element static mixer (cutaway) and (b) in-line blade element static mixer (cutaway).

the mixing energy. On the other hand, using open channels for coagulant addition can be ineffective because turbulent mixing cannot be controlled. This can be compensated for by overfeeding the coagulant, but this solution is unnecessarily expensive. If the plant hydraulic profile requires that coagulant be added in an open channel (commonly encountered in plant retrofits), jet mixing devices (Figure 24.4) could be used to create the required turbulence, depending on hydraulic characteristics. Some plants also take advantage of the turbulence in a pump's volute to rapidly mix coagulants into the effluent flow. If this approach is used, utility staff should verify that the pump volute is compatible with the chemical being added, to avoid corrosion at the injection point.



(a)



(b)

FIGURE 24.4 (a) In-channel rapid-mixing device (schematic) and (b) close-up of in-line rapid-mixing device (discharge end).

Because coagulant chemical reactions are rapid, detention times are less critical than mixing energy and mixing control. However, time should be factored in the process. For example, rapid-mix basins typically have a detention time of 15 to 60 seconds to allow coagulants to disperse.

Analytical Tools to Determine Mixing Efficiency. Poor mixing performance is typically the result of low mixing energy input, hydraulic short-circuiting, or other factors. Traditional tools (e.g., dye or tracer studies) or new analytical techniques [e.g., computational fluid dynamics (CFD), digital particle image velocimetry (DPIV), laser Doppler anemometry (LDA), and laser induced fluorescence (LIF)] may be used to study and resolve these issues. Of these, the most common technique seems to be CFD or its specific subspecialty: computational fluid mixing (CFM).

Computational Fluid Mixing. Efficient use of coagulants can result in significant cost savings. The drive to reduce chemical costs led wastewater treatment professionals to use CFD techniques to optimize the mixing process. They even created a CFD subgroup specialization: CFM. This tool can be applied to both existing installations and new designs. For existing installations, site-specific CFD–CFM models can be developed that analyze mixing patterns for various chemicals (based on their physical and chemical properties), and the spatial distribution of chemicals and mixing energy across a rapid-mix basin. The models can then be used to choose a coagulant, determine injection rates, compute optimal mixing energy levels, and relocate or design retrofit accessories (e.g., baffles and baffle plates) to further optimize coagulant usage.

Site-specific CFD–CFM modeling was popularized in general industry in the 1990s and is becoming common in the water and wastewater treatment industry, especially at larger plants. The software and services needed to develop cost-effective models are available from most large and mid-sized consulting engineering firms, as well as independent CFD–CFM software vendors. For example, a project team consisting of a vendor and a mid-size engineering firm recently estimated that it would cost about $50,000 to develop a CFD–CFM optimization model for a 49 210-m^3/d (13-mgd) California Title 22 recycled water facility (this estimate includes the software license). Because the facility's nonoptimized cost for various coagulants and flocculants was more than $350,000 a year, the anticipated payback for the model was reasonable.

FLOCCULATION. Flocculation increases the collisions of coagulated solids and promotes chemical bridging between particles so they agglomerate to form settleable or filterable flocs. Whether done in separate basins before sedimentation or within the sedimentation tank (e.g., flocculating or high-rate clarifiers), flocculation involves prolonged

and gentle agitation of coagulated particles to form larger, denser particles. Mixing intensities are low: Velocity gradients of less than 60 s^{-1} are typical. The flocs should never be subjected to mixing more intense than that used for *initial* flocculation or else the floc will break up.

During flocculation, the coagulated effluent is stirred slowly via air or mechanically driven paddles causing the solid particles to agglomerate, become heavy, and settle on the tank floor. Flocculation basins are often baffled or may be two or three basins in series; their total detention times typically range from 10 to 45 minutes. As the effluent moves through the process, the stirring becomes gentler.

Flocculation can be thought of as a simple reaction:

$$\text{Dispersed solids} + \text{Preformed flocs} \Leftrightarrow \text{Flocs} \tag{24.3}$$

As in most chemical reactions, both forward and reverse reactions occur. In this case, the forward reaction is aggregation and the reverse reaction is floc breakup. Equilibrium is reached when the aggregation rate equals the breakup rate. This equilibrium is a function primarily of the mixing intensity; lower mixing intensities favor the forward reaction, but there has to be enough mixing to facilitate the collisions necessary to form settleable floc.

The time required for flocculation depends on the wastewater or effluent characteristics. For example, the South Tahoe (California) Public Utility District lime-coagulated, activated sludge effluent flocculates in 5 minutes in an air-agitated basin; good flocculation is obtained even without agitation. However, the lime-coagulated, trickling-filter effluent at the Orange County (California) Water District's Water Factory 21 is difficult to flocculate; 20 to 30 minutes of careful mixing is needed to form a good settling floc. Wastewater treatment professionals have developed a jar-test procedure to determine the appropriate flocculation time for activated sludge effluent; it may be used with other flocculation systems as well (Wahlberg et al., 1994).

Several flocculation basins in series will perform better than one large basin with the same total volume because they provide better mixing and can use different mixing energies. The following types of mechanical mixers are used for flocculation (Figure 24.5):

- Paddle- or reel-type devices;
- Reciprocating units (walking-beam flocculator, in which the paddles move in a vertical, up-and-down pattern);
- Slow-speed, flat-blade turbines; and
- Slow-speed, axial-flow propellers or turbines.

SEDIMENTATION. Sedimentation separates solids from liquids via gravity. The settling basins (or clarifiers or sedimentation tanks) typically contain mechanically

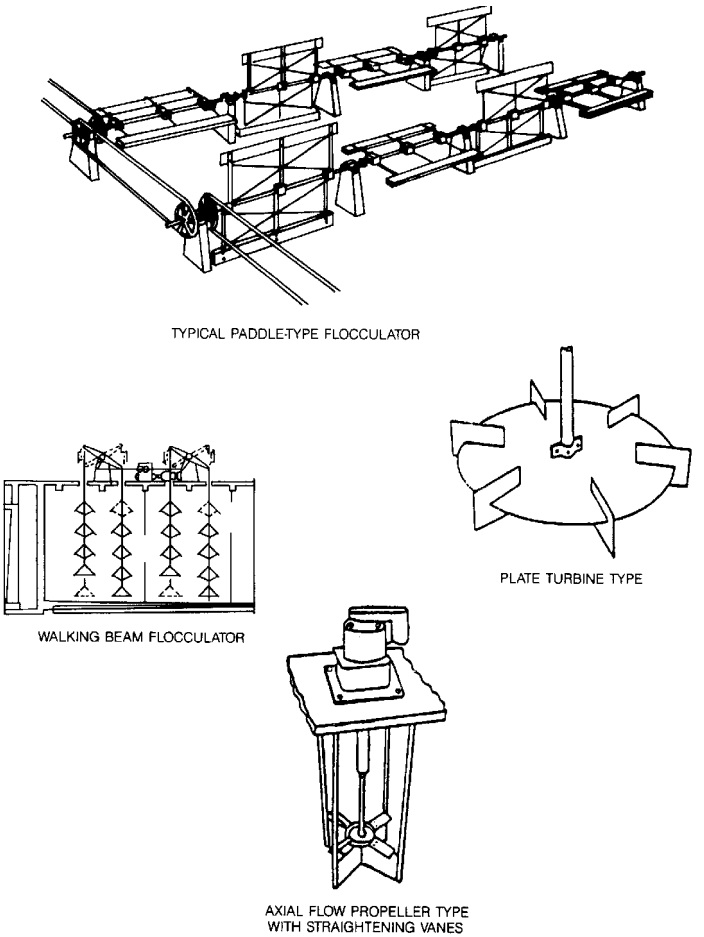


FIGURE 24.5 Typical flocculation mixers.

driven scrapers that continuously move the settled sludge to a hopper, from which it is pumped or removed via hydrostatic pressure. The tanks may be either rectangular or circular horizontal-flow tanks. The degree of treatment obtained depends largely on the upstream processes (i.e., the type and quantity of chemicals used, mixing times, and the degree of care in process monitoring and control). A commonly used parameter for controlling sedimentation is the surface overflow rate (Table 24.2).

Utilities that tried to use upflow, sludge blanket-type settling tanks for sedimentation reported difficulty in maintaining a sludge blanket. The units operated successfully, however, when the surface overflow rate was lowered to that typical of conven-

TABLE 24.2 Surface loading rates for clarifiers treating common chemically treated effluents (Metcalf & Eddy, 2003).

	Overflow rate			
	gpd/sq ft		$m^3/m^2 \cdot d$	
Suspension	**Typical range**	**Peak flow**	**Typical range**	**Peak flow**
Alum floc*	700–1400	1200	30–70	80
Iron floc*	700–1400	1200	30–70	80
Lime floc*	750–1500	1500	35–80	90
Untreated wastewater	600–1200	1200	30–70	80

*Includes settleable suspended solids in untreated wastewater and colloidal or other suspended solids in floc.

tional settling tanks and the sludge blanket was significantly reduced or eliminated (essentially converting them to conventional radial-flow basins). The unstable sludge blankets are thought to be primarily caused by variations in the influent's properties. Upflow tanks work better in water treatment, where the influent is relatively uniform and can be pumped into the clarifiers at a more or less constant flowrate.

Patented high-rate clarification systems use both gravity and "densifying" solids-contact or ballasted-media flocculation technologies to clarify coagulated and flocculated effluents. A major selling point of these technologies is that their high surface overflow rates enable them to have smaller footprints than conventional clarifiers.

In a solids-contact unit's reactor zone, influent combines with reactants and preformed solids from the presettling–thickening zone, flowing up through a draft tube where a specially designed turbine initiates flocculation (Figure 24.6). As the mixture resettles, its density increases. The internal recirculation rate is up to ten times that of the influent flow, producing optimum floc density. The flocculated effluent enters the presettling–thickening zone over a submerged weir. The solids then sink to the bottom of the vessel, where a slow-moving rake helps make them thicker and more dense. This maintains solids homogeneity, while releasing more entrained water. Thickened sludge is periodically blown down from the bottom of the thickener and typically pumped to a final dewatering mechanism. In the clarification zone, supernatant flows upward through settling tubes and is polished. The settling tubes allow rise rates of up to $0.068\ m^3/m^2 \cdot s$ (10 gpm/sq ft) for most metal salt coagulation processes—often higher for lime addition processes. The clarified water is uniformly collected in effluent launders above the tubes.

The ballasted media system (Figure 24.7) uses a technique that consists of fixing the flocs (suspended solids) onto microsand with the aid of a coagulant and a polymer.

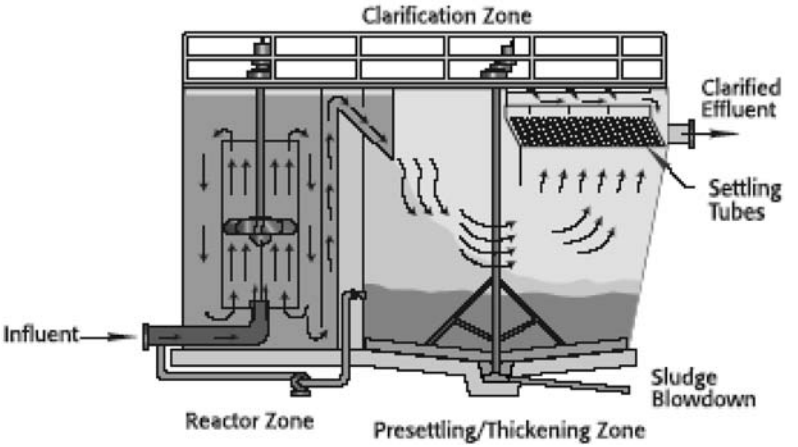


FIGURE 24.6 High-rate solids contact clarifier.

It is reputed to reduce mixing time fivefold compared to classical flocculation, and to increase the rise rate tenfold compared with conventional tube settling. Lamellar settlers, in turn, provide a large clarification surface area in a small tank volume.

Influent first enters a flash mixing zone, which destabilizes the colloids. Here, wastewater is rapidly mixed with coagulant for about 1 minute. The wastewater then

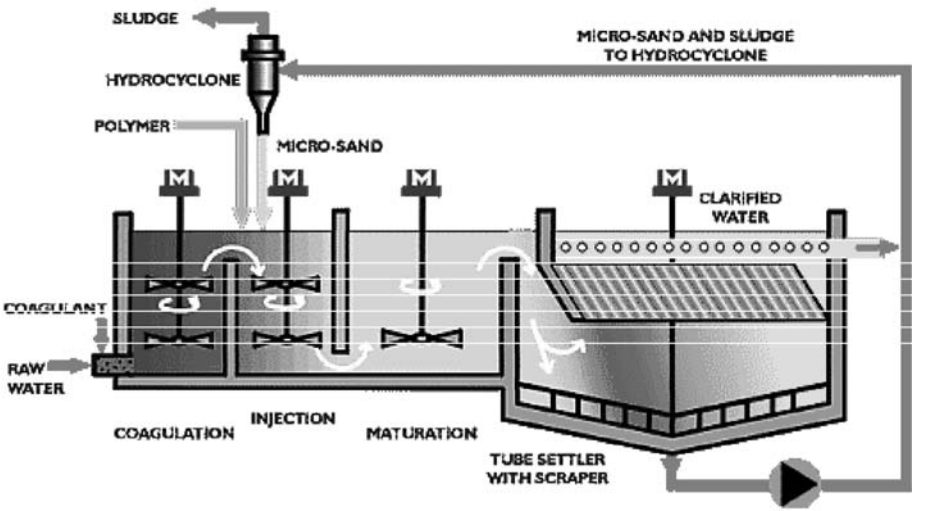


FIGURE 24.7 Ballasted media, high-rate clarification system.

enters the injection tank, where microsand and polymer are added and rapidly mixed for about 1 minute. Then, the water enters a maturation zone, where it is gently mixed for about 4 minutes. This allows the microsand ballasted flocs to grow bigger, so they can trap random flocs and settle faster in the sedimentation tank. The polymer works like a glue to affix the flocs to the microsand.

The water then enters the settling tank, where the microsand ballasted flocs settle immediately. The water flows up through settling tubes to collection troughs at the surface and exits the process.

The microsand ballasted sludge is pumped from the bottom of the settling tank to a hydrocyclone, where the microsand is cleaned from the sludge via centrifugal force. The sludge is continuously removed for treatment, and the microsand is re-injected into the system (it is continuously recycled).

RECARBONATION–pH ADJUSTMENT. During lime coagulation, the water's pH is often raised to between 10 and 11. At these pH values, the water is unstable and calcium carbonate will readily precipitate. This tenacious precipitate tends to encrust any downstream filters or carbon particles. To avoid this difficulty, the water is stabilized by lowering the pH to less than 8.8. In large WWTPs, pH reduction typically involves injecting carbon dioxide (CO_2) gas into the water (recarbonation). The carbon dioxide may be obtained from the stack gases of onsite incinerators, purchased as liquid carbon dioxide, or formed via fuel burning. An option for plants using a high-purity oxygen (HPO) activated sludge process would be to use the carbon dioxide-rich offgas from the HPO process, supplemented (as required) with an outside source of carbon dioxide. Some plants use sulfuric acid injection, which adds sulfates to the water.

Recarbonation may be done in one or two stages. In the single-stage process, enough carbon dioxide is injected to lower the pH to the desired value in one step. It also dissolves the calcium in lime, so the plant effluent will have a calcium concentration. In two-stage recarbonation, enough carbon dioxide is added in the first stage to lower the pH to between 9.5 and 10. The resulting calcium carbonate precipitate is allowed to settle, thereby removing calcium from the water and making it available for lime recovery. Then, more carbon dioxide is injected until the pH drops to the desired value.

FILTRATION. Filtering wastewater is difficult. The wastewater's solids content varies and could be high if upstream processes are improperly operated. Variable wastewater flow also causes operating difficulties. For example, rapid sand-filter media are used widely in water treatment but not in wastewater treatment because of poor performance when filtering flows with high suspended solids concentrations.

Dual- and triple-media (multimedia) filters are more effective for wastewater treatment. Filters with alternative media or designs (e.g., traveling bridge and continuous backwash filters) have also been used and are becoming more popular in wastewater treatment.

The gravity and pressure filter structures (Figures 24.8 and 24.9) often used for water treatment are readily adaptable to wastewater filtration. Wastewater is more difficult to filter than well or surface water because the solids are sticky from biological activity and more highly concentrated. In typical shallow-bed sand or diatomite water treatment filters, wastewater tends to quickly "blind" the filter surface. Nevertheless, some shallow-bed single-media filters—designed specifically for wastewater applications—have been successful.

Dual-media and multimedia filters allow more of the filter depth to be used to capture solids, making wastewater filtration practical.

A multimedia filter is a coarse-to-fine filter; its pore space gradually shrinks as the water moves toward the output point (Figure 24.10). The number of media grains also typically increases, although the grain size is not uniform because the filtration media have three specific gravities (coal, 1.4; sand, 2.65; and garnet, 4.5). This structure enables removed solids to be stored throughout the depth of the bed rather than only at the surface, greatly extending the length of filter runs between backwashes.

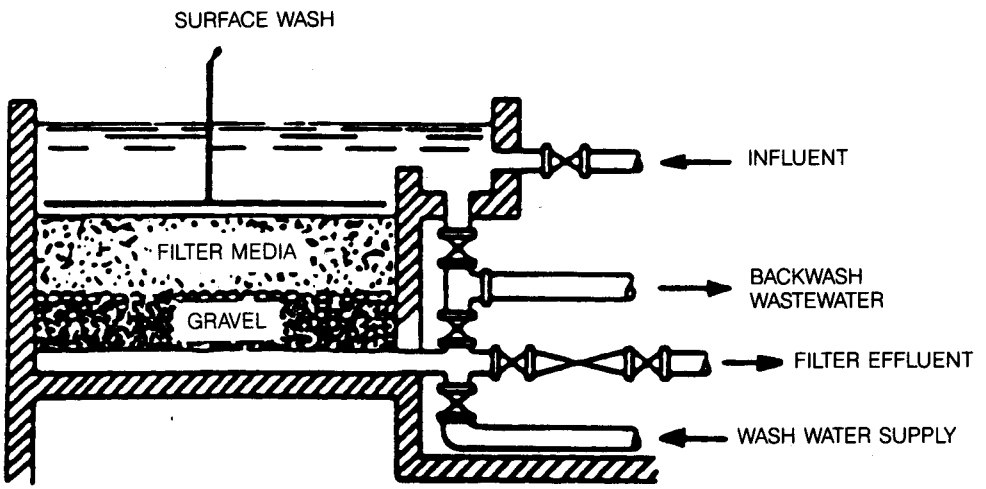


FIGURE 24.8 Cross-section of a typical gravity filter.

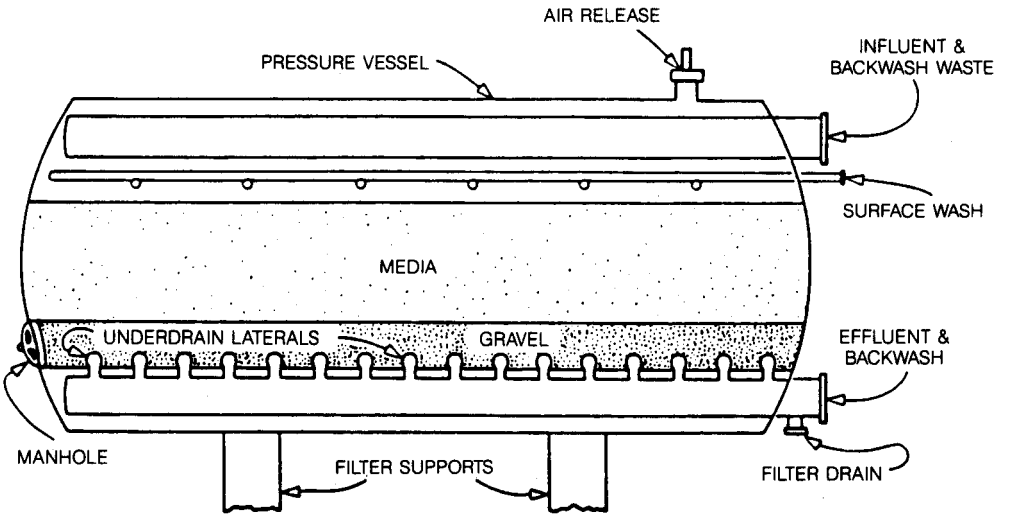


FIGURE 24.9 Typical pressure filter.

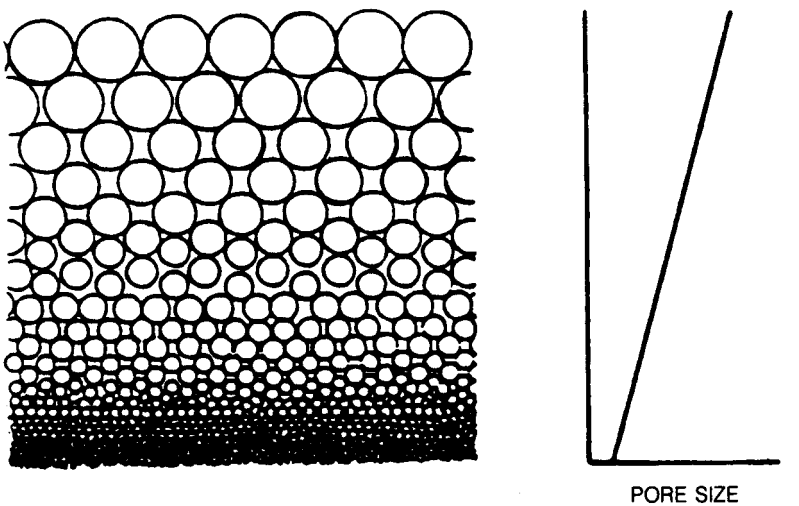
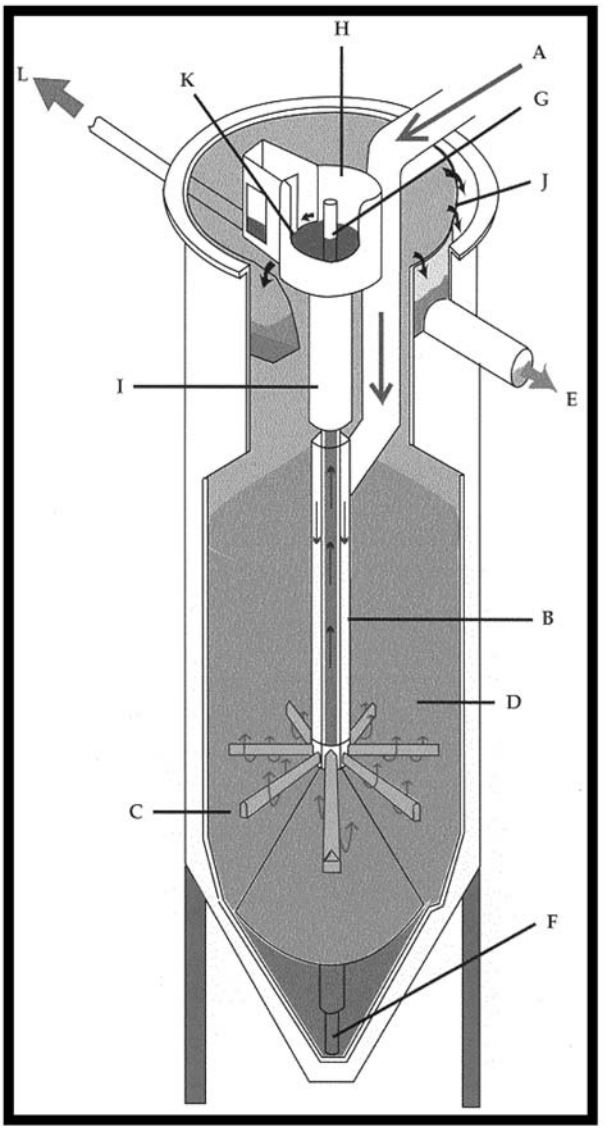


FIGURE 24.10 Schematic cross-section of an ideal filter, uniformly graded from coarse to fine from top to bottom.



A- Feed
B- Feed assembly
C- Inlet distributor
D- Sand bed
E- Filtrate
F- Airlift pipe
G- Airlift discharge
H- Reject compartment
I- Washer section
J- Filtrate weir
K- Reject weir
L- Reject line

FIGURE 24.11 Schematic of a continuous backwash, upflow filter.

Alternative filter configurations currently gaining popularity include continuous backwash filters, cloth media filters, and synthetic media filters (Figures 24.11, 24.12, and 24.13). Other designs (and design variations) are also becoming common.

In the continuous backwash, upflow filter (Figure 24.11), influent flows from the feed line (A), through the feed assembly (B), and enters the inlet distributor (C) in the

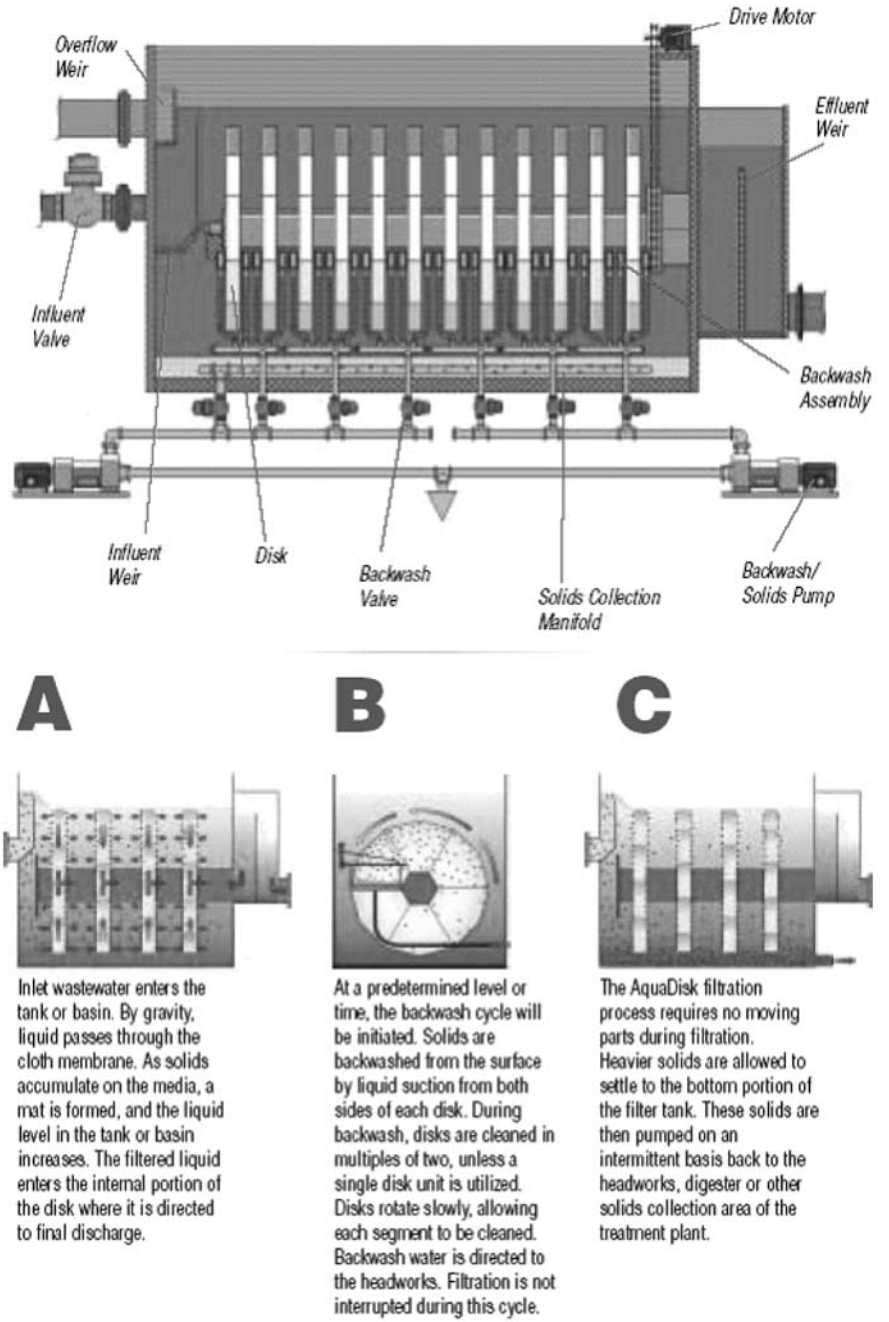


FIGURE 24.12 Schematic of a cloth media filter and its operating cycles.

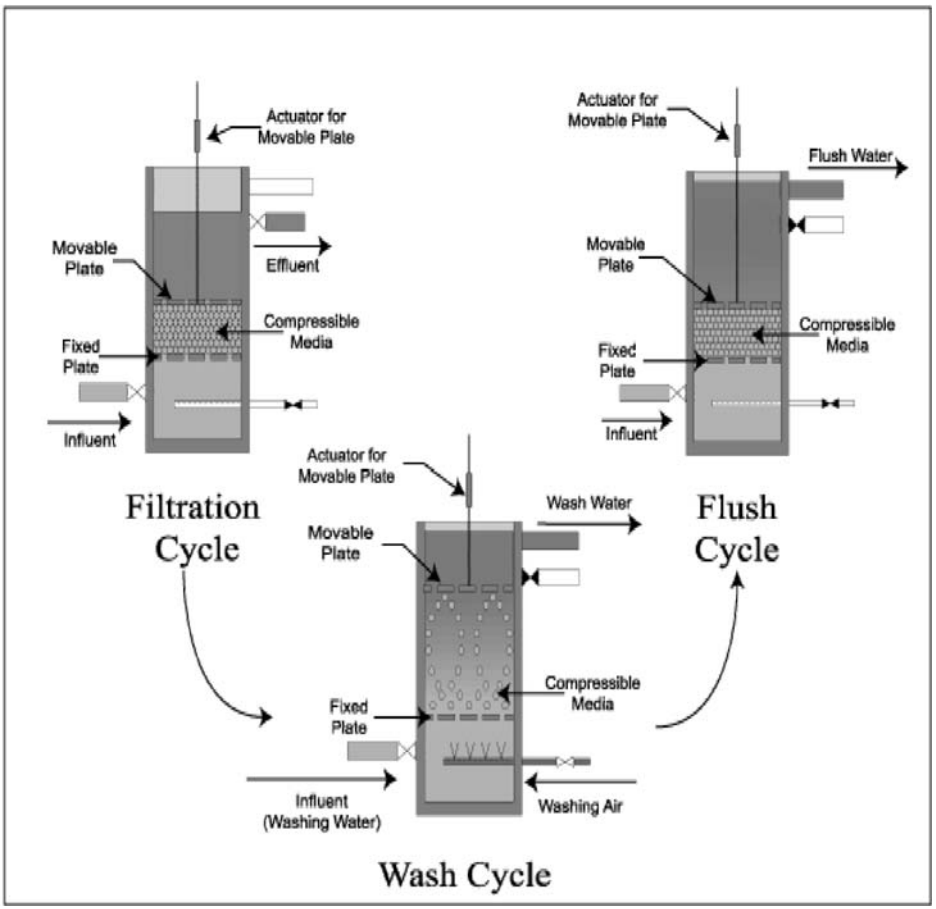


FIGURE 24.13 Schematic of operating cycles for a compressible-media, upflow filter.

lower section of the unit. It then flows upward through the sand bed (D). Simultaneously, the sand bed and the accumulated solids are drawn downward into the airlift pipe (F) at the center of the filter. A small volume of compressed air is introduced at the bottom of the airlift. The air rises, draws the sand into the airlift, and scours the sand of trapped particles.

When it reaches the top of the airlift (G), the dirty slurry spills over into the central reject compartment (H). The sand is returned to the sand bed through the washer/separator (I). As the sand falls through the washer, which consists of several concentric stages, a small amount of filtered water passes upward, washing away the dirt, while al-

lowing the heavier, coarser sand to fall through to the bed. By setting the reject weir (K) lower than the filtrate weir (J), a steady stream of washwater is assured. The continuous reject exits near the top of the filter (L), while the filtered water exits through the filtrate line (E). So, the sand bed is cleaned while producing both filtrate and reject. The process is continuous; it does not need to be taken out of service for backwashing.

PROCESS CONTROL SYSTEMS

The most important process control systems during phosphorus and enhanced suspended solids removal are those involving the chemical dose and filter operations.

DETERMINING CHEMICAL DOSE. Determining the proper chemical dose for enhanced solids removal is different than calculating one for phosphorus reduction. When alum or ferric chloride are added to wastewater, the resulting metallic hydroxide floc can entrap suspended solids and settles slowly, physically sweeping out suspended solids. The "correct" coagulant dose for enhanced suspended solids removal varies as the wastewater characteristics vary and should be determined based on extensive jar testing and bench-scale or pilot-scale tests.

Phosphorus removal relies on chemical reactions to form sparingly soluble orthophosphates that can be removed via precipitation with primary or secondary (waste activated) sludge, or separately in chemical clarifiers following secondary treatment. So, utility staff can estimate a preliminary range of chemical doses based on a wastewater's phosphorus content. However, they should conduct jar tests to compare design dose values to the doses actually required to reduce phosphorus in that specific wastewater.

Phosphorus Reduction. If lime is used for phosphorus removal, it is typically added to the primary clarification step or a tertiary treatment unit. The lime dose required to achieve a given turbidity, effluent phosphate concentration, or pH depends primarily on the wastewater's alkalinity (Figure 24.14). When used for phosphorus removal, the lime dose is essentially independent of the influent phosphorus concentration. Lime also is used frequently for pH control in systems using aluminum or ferric coagulants to remove phosphorus. When the pH reaches 9.5 via lime addition, orthophosphate converts to an insoluble form. Operating at a pH between 10 and 11 is sometimes necessary, especially if ammonia must be stripped. Typical lime doses range from 250 to 450 mg/L, but sometimes more lime is needed to form a readily settleable precipitate.

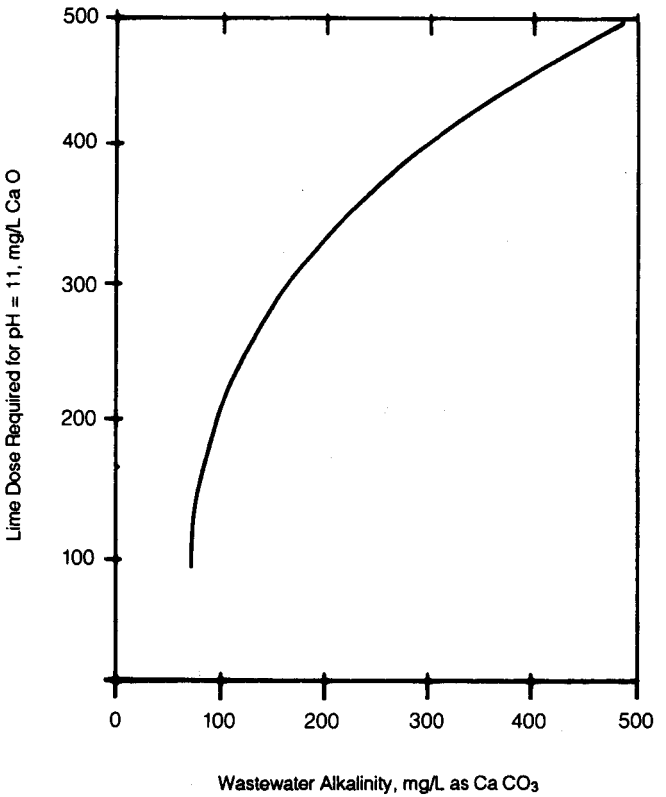


FIGURE 24.14 The relationship between lime dose and wastewater alkalinity.

If the coagulant is an aluminum salt (e.g., alum), the dose needed for phosphorus removal depends on the wastewater's phosphorus content. To achieve 85 to 90% phosphorus removal, aluminum : phosphorus mole ratios of approximately 2 : 1 are typical (Metcalf & Eddy, 2003). Assuming a typical concentration of 10 mg/L of phosphorus, a dose of 192 mg/L of alum can be calculated as follows [formula weight of alum, $Al_2(SO_4)_3 \cdot 14H_2O = 594.4$]:

$$\left(\frac{10 \text{ mg P}}{\text{L}}\right)\left(\frac{2 \text{ mmol P}}{31 \text{ mg P}}\right)\left(\frac{2 \text{ mmol Al}}{1 \text{ mmol P}}\right)\left(\frac{1 \text{ mmol alum}}{2 \text{ mmol Al}}\right)\left(\frac{594.4 \text{ mg alum}}{\text{mmol alum}}\right) \quad (24.4)$$

$$= 192 \text{ mg alum/L}$$

If using commercial-grade alum (48 to 49%), which contains about 5.4 lb of dry alum per gallon of solution (0.65 kg/L), the amount needed per million gallons of wastewater is

$$\frac{(1\text{ mil. gal})(192\text{ mg/L})(8.34\text{ lb/mil. gal})}{(5.4\text{ lb/gal})} \tag{24.5}$$

$$= 297\text{ gal of alum solution (1124 L per cubic meter of flow)}$$

Chemical overdosing can hurt the process as much as underdosing, so the in-plant chemical dosage rate should be set significantly lower than the theoretical dose and then systematically increased until optimum performance is attained.

Like aluminum salts, iron salt doses depend on the phosphorus content. Operating experience has shown that efficient phosphorus removal with iron salts requires 1.8 mg/L of iron per 1 mg/L of phosphorus (Metcalf & Eddy, 2003), plus at least 10 mg/L of iron for hydroxide formation. On this basis, 85 to 90% phosphorus reductions typically require 15 to 30 mg/L of iron (ranging from 45 to 90 mg/L as ferric chloride) per 1 mg/L of phosphorus.

Heavy Metal Removal. Many of the common heavy metals form insoluble hydroxides at pH 11, so lime coagulation reduces these metal concentrations. Except for mercury, cadmium, and selenium, lime coagulation removes 90% or more of most heavy metals. Filtration can even remove more heavy metals by removing residual particulate matter. Alum will also enhance heavy metal removals. The heavy metals removed from wastewater accumulate in the sludge and may limit the sludge management options.

Bacteria and Virus Removal. Alum coagulation can remove 95 to 99% of viruses, and ferric chloride coagulation removes 92 to 94% when combined with sedimentation and filtration. In both cases, good virus removal depends on good floc formation, and 99% virus removal can be achieved if alum or ferric chloride is coupled with effective filtration. However, viruses are extremely small and will break through filters at the first sign of turbidity breakthrough, indicated by filter effluent turbidity increases of 0.5 nephelometric turbidity units (NTU) or fewer. Viruses are not deactivated by physical–chemical processes, so their chemical sludges require more treatment or storage.

Lime coagulation effectively inactivates viruses at high pH. The inactivation rate increases rapidly as pH increases from 10.1 to 10.8 and then to 11.1.

Chemical coagulation and flocculation, sedimentation, and filtration substantially reduce the numbers of bacteria and viruses. Their effluent has low turbidity, ensuring effective bacterial and viral kills if subsequently disinfected.

Suspended Solids Reduction. When a coagulant is used to precipitate phosphates and reduce suspended solids, it can be safely assumed that the coagulant doses that produce good phosphorus removal will typically produce good solids removal, especially if polymers are used to flocculate fine, precipitated matter. This can be confirmed by jar testing, where the supernatant (liquid above the settled sludge/precipitate) is analyzed for turbidity or suspended solids.

CONTROLLING CHEMICAL DOSE. In a physical–chemical WWTP, the best-designed equipment cannot substitute for proper control of chemical coagulation. Insufficient coagulant doses will produce an excessively turbid effluent. Excessive doses may have the same result, as will inadequate or excessive mixing. Excessive turbidity increases the probability of microorganisms escaping subsequent disinfection because of turbidity's shielding effect. Successful treatment depends on proper coagulation (i.e., proper chemical doses and adequate mixing).

Achieving proper coagulation has challenged operators for many years, and a wide variety of control techniques has been developed. Most involve laboratory or bench-scale tests, the results of which operators then scale up to full-scale plant operations. For example, the most widely used technique is the jar test. In its simplest form, this test involves collecting an effluent sample, transporting it to the laboratory, and then dividing it among several beakers. Each beaker receives a different coagulant dose, and the contents are subjected to various mixing regimes (primarily through varied mixer speeds) in a ganged multiple-paddle mixing device. After an appropriate period, stirring is stopped, and the floc is allowed to settle. (The tests may be run multiple times to gauge the effects of different mixing periods.) Operators then determine the optimum coagulant dose based on the clarity of the supernatant after settling. Operators often visually inspect the supernatant to select the best dose, but measuring filtered supernatant turbidity in a laboratory turbidimeter provides a more objective means of selecting the optimum dose. Experience has shown that the jar test is effective, but there are issues with scale-up. Therefore, optimum dosages are often determined in pilot- or full-scale facilities.

Modern WWTP designs enable operators to control automatically the amount of coagulant feed in proportion to plant flow. However, coagulant demand may depend on additional variables. Data from jar tests preceding plant design may indicate a useful correlation between a parameter that can be monitored automatically and the required coagulant dose. For example, the required lime dose may correlate well with pH. If so, it can be controlled automatically via a pH monitor on the settling tank effluent. Alum or ferric chloride doses may correlate well with the raw wastewater's phosphorus content, so the WWTP design may incorporate some means of automatically

controlling coagulant doses based on some measure of phosphorus concentration. If the WWTP lacks such controls or if an existing automatic system malfunctions, then the coagulant dose must be controlled via manual tests (e.g., jar tests).

The jar test has limitations. For example, the optimum coagulant dose indicated in a jar-test beaker may not necessarily provide optimum results on a WWTP scale because the two mixing efficiencies probably differ. Also, there is an inherent time lag involved; by the time that the optimum chemical dose has been determined, the water involved has already passed by. This time lag can be shortened if the operator is alert to changing conditions that require dose adjustments.

Because temperature plays an important role in coagulation, the wastewater samples for jar tests must be collected and analyzed only after all other preparations are made to reduce the possible effect of room temperature on the samples. Valid results demand that WWTP conditions be closely simulated. Dosing solutions or suspensions are prepared from the stock materials actually used in plant treatment. The distilled water used to prepare lime suspensions is boiled for 15 minutes to expel the carbon dioxide and then cooled to room temperature before the lime is added (AWWA, 2002).

The required frequency for jar tests will vary widely from one locale to another. Some wastewater streams may vary little in coagulant demand from day to day or from hour to hour. Others may vary markedly during the day because of the wastewater's major diurnal variations. High turbidity in the chemical settling-tank effluent reliably indicates improper chemical dosing. After checking to be sure that some mechanical failure of the chemical feed system is not at fault, operators must quickly use the jar test to determine the change in coagulant dose required. Even with a dose correction, some time will elapse before a noticeable improvement occurs, because the settling tank is already filled with improperly coagulated wastewater. If the filter system is equipped with provisions for adding filter aids, the improperly coagulated settling tank effluent may receive compensating coagulant doses before filtration. This may avoid impairing the WWTP's effluent quality despite possible shortened filter runs.

In terms of system instrumentation and controls, an ideal, automated control system for chemical phosphorus removal would adjust the metal salt, polymer, and supplemental alkalinity doses to maximize phosphorus removal and minimize costs with changing wastewater characteristics. However, such systems do not seem to have a consistent history in the industry. Therefore, a common process control system is to manually set and adjust the dose rates based on observed performance. This typically results in the dose being set higher than needed to account for fluctuations in phosphorus loading without violating permit limits at peak conditions. Other methods incorporate a related parameter (e.g., flow, pH, or turbidity) or adjust the dose based on historical and anticipated diurnal loadings, to provide a degree of automated or quasi-automated control.

RECYCLING/WASTING CHEMICAL SLUDGE. More solids are generated at WWTPs when chemical addition is practiced. Unless some form of solids contact or floc blanket clarification is desired, chemical sludge is typically removed or wasted out of the system. However, some WWTPs with separate mixing, flocculation, and settling basins recycle settled sludge to either the mixing or flocculation basins to enhance floc formation. The previously precipitated particles in the return sludge may form a nucleus for more rapid agglomeration of colloidal particles in the wastewater. Also, the mass-action effect of the higher solids concentrations in the flocculation chamber may benefit floc formation. However, if the organic solids in the sludge are unusually high, recycle may impair floc formation. In WWTPs using lime coagulation and two-stage recarbonation, the best source of recycle sludge is the material that settles after first-stage recarbonation because it is almost pure calcium carbonate and has a low organic content.

While metal salt addition will increase the nonvolatile fraction of the mixed-liquor suspended solids (MLSS) in an activated sludge plant (requiring higher MLSS values to maintain treatment levels), the major effects of sludge wasting from chemical treatment are typically felt more in the downstream solids-handling processes. In addition to the higher amounts of solids to be handled, chemical sludges are also difficult to thicken and dewater (the reasons why are not yet fully understood). Also, the properties of these sludges and the degree of difficulty in handling them will not be the same from one facility to the next. While alum sludges are typically more difficult to thicken and dewater than ferric chloride sludges, the site-specific nature of sludge merits pilot- or full-scale testing of its effects on solids-handling facilities.

OPTIMIZING FILTER RUN TIME. ***Effluent Quality and Headloss.*** Filter operation depends on the flowrate through the filter, which in turn depends on the headloss through the filter. So, effective filtration control should involve continuous monitoring of headlosss and influent and effluent turbidity. Also, better influent quality (i.e., better upstream secondary process operations) should slow headloss buildup, thereby increasing run times and decreasing backwash needs.

Filter Aids. Modern filtration systems include feed equipment for filter aids (typically polymers). Polymers are high-molecular-weight, water-soluble organic chemicals that can be used as coagulants, settling aids, or filtration aids. They may be cationic, anionic, or non-ionic. When used as a filtration aid, a polymer dose of less than 1.0 mg/L typically can increase the strength of the chemical floc and control the depth of floc penetration into the filter. For best results, the polymer should be added directly to the filter influent. However, if polymers are used as settling aids, filtration aids may be un-

necessary. Also, polymers cannot compensate cost-effectively for improper chemical coagulation or poorly performing secondary processes.

When determining the proper polymer dose, a common test procedure is to add an initial dose (typically approximately 1.0 mg/L), observe the effects, and then lower or increase the dose in increments of 0.25 to 0.5 mg/L, as appropriate, until a desired operating range is obtained.

Effects of Polymers. If the polymer dose is too low (Figure 24.15a) the floc will be fragile and shear; penetration of the filter will result. This terminates the filter run prematurely because of a breakthrough of effluent turbidity. If the polymer dose is too high (Figure 24.15b), the floc becomes too strong for penetration of the filter, causing a rapid buildup of headloss in the upper portion the filter. The excessive headloss prematurely terminates the filter run. The optimum polymer dose (Figure 24.15c) allows the filter to reach terminal headloss just as its effluent turbidity begins increasing. It prevents premature termination of the filter run because of excessive headloss or turbidity breakthrough, thereby reducing the amount of filter washwater to be recycled through the WWTP.

Polymer Handling. Polymers can be delivered to WWTPs in either liquid or powder form. Although dry polymers have some handling issues, may not dissolve easily, and require special dissolution, mixing, and feeding equipment, their use can lower overall costs more than liquid polymers can. Because many polymers are biodegradable, they can only be stored in dilute solution for a few days before losing strength. Polymer feed equipment includes some type of positive-displacement pump (e.g., diaphragm pumps and progressing cavity pumps). Handling issues can increase costs. For example, the pump head of diaphragm pumps can be plugged by "fish-eyes" in the polymer, caused by unwanted moisture in the dry polymer storage facility or improper wetting when the dry polymer is converted to a liquid. Also, some treatment plants contract with their polymer suppliers to recycle their polymer totes (to save money). If the bins are not cleaned or are cleaned incompletely before refilling, a "skin" will form inside the bins that may break off into the polymer and plug pumps. While this problem can be minimized by adding strainers upstream of the pumps, unwanted moisture could enter the feed system when the strainers are cleaned.

When using polymers, utility staff should remain open to change. Liquid polymer is best delivered in bulk and kept onsite in storage tanks. Utility staff should conduct periodic polymer trials to ensure that they are still using the most cost-effective product. If a utility decides to switch polymers, the storage tanks must be thoroughly cleaned and dried before the new product is delivered (assuming it is a solution or emulsion) because mixing polymers can lead to undesirable results,

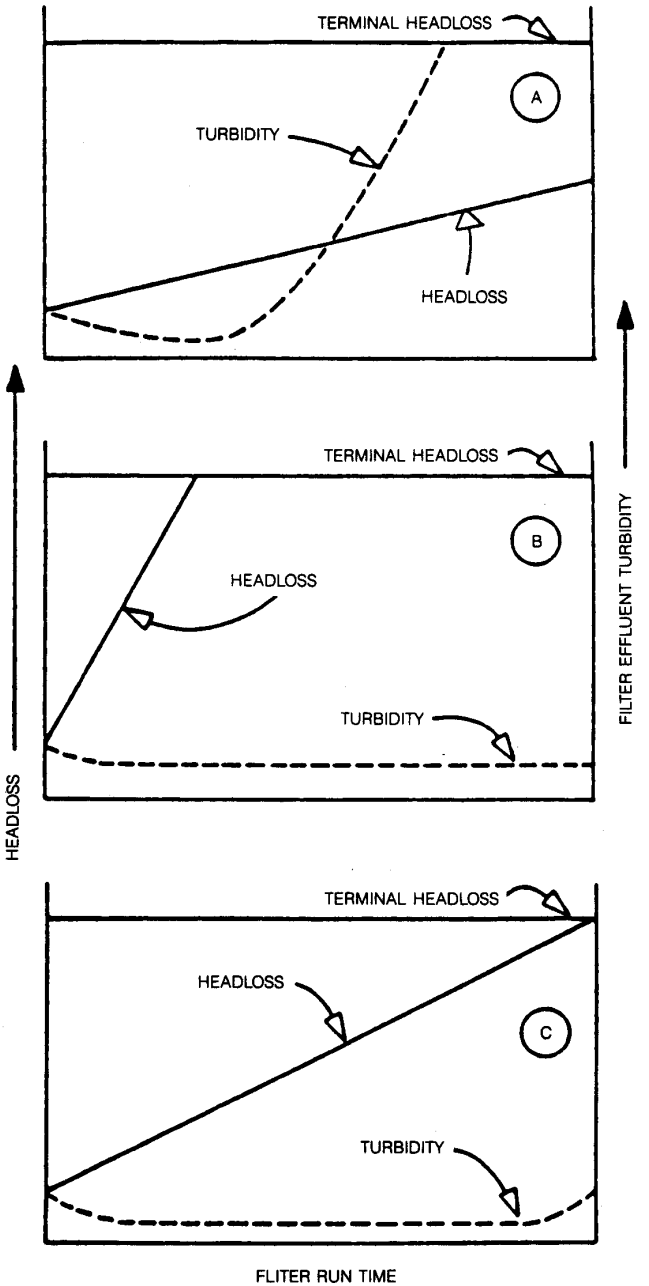


FIGURE 24.15 Effects of polymers as filtration aids: (a) inadequate polymer dose, (b) excessive polymer dose, and (c) optimal polymer dose.

including polymerization of the product, which would necessitate manual cleaning of the tank.

BACKWASHING FILTERS. Successful filter operations depend on clean filter media. If the media are not cleaned adequately, biological organisms could accumulate and eventually plug the filter. Adequate backwashing, along with surface wash or air–water backwash, can eliminate plugging.

Media Expansion and Suspension. Wastewater treatment professionals used to believe that the filter media had to expand by 50% for cleaning to be effective. However, optimum scouring of the media particles occurs when media suspension begins, because the total shearing force against the media grains equals the weight of the media in water. The shearing force remains constant, no matter how much more the media expansion and wash rates increase. So, a wash rate corresponding to 25% expansion of the coal layer is adequate for a dual-media filter.

How much filter media expand depends on the backwash rate, which in turn depends on the water temperature and the filter media's size and specific gravity. (There is an indirect relationship between temperature and water viscosity.) The backwash water needed may be as much as 8 to 10% of the filter influent flowrate, although a well-operated filter should use less than 5% of its influent flow for backwashing. A rise in water temperature from 10°C to 20°C (50°F to 68°F) requires the wash rate to increase about 30% to maintain a given expansion of silica sand. So, operators must observe changes in wastewater temperature and adjust the backwash rates accordingly.

Backwash Duration. For most conventional filters, the optimum backwash duration depends on the filter's use, but typically ranges from 5 to 8 minutes. Highly treated backwash water (e.g., filter effluent or chemically coagulated and settled wastewater) will always have low suspended solids concentrations. Operators should carefully monitor the backwash flow indicator to maintain the desired backwash rate.

Surface Washing. For conventional filters, an effective surface wash ensures that clumps of media and floc do not survive the backwash as mud balls. The term *surface wash* in this context is a misnomer because the lateral currents established actually circulate the bed's entire contents. A typical surface-wash apparatus consists of a revolving pipe with a number of nozzles suspended by a bearing at the pipe's center. These units, positioned 2.5 to 5.1 cm (1 to 2 in.) above the normal surface of the filter, inject washwater through the nozzles [at less than 340 tp 690 kPa (50 to 100 psi) of pressure] causing the pipe to rotate. The water supply requirements for these devices vary, but typically range from 0.5 to 0.7 $L/m^2 \cdot s$ (0.75 to 1.0 gpm/sq ft).

Typically, surface wash starts approximately 60 seconds before the main backwash pumps are turned on and stops 60 seconds before the end of backwash to allow the bed to reclassify. The nozzles, directed downward approximately 30 degrees from the horizontal, cause agitation throughout the bed depth. The surface washwater must be high quality to avoid plugging the nozzles. A strainer with 2.4-mm (0.09-in.) perforations is often used in the surface wash line as precaution.

In pressure-filter systems, an external indicator shows whether the surface wash arm is actually rotating during backwash. Operators ensure that the surface wash system is functioning properly during each backwash. Deep filters sometimes have a rotating agitator in the bed that is similar to the surface wash arms. These subsurface agitators have the nozzles staggered from 15 degrees above horizontal to 15 degrees below.

Air–water backwash techniques are an alternative to mechanical surface wash. It involves injecting air through the filter underdrain system. The rising air bubbles break up mud balls in the filter. In dual- or multimedia beds using coal, the backwash water and the air cannot be applied at the same time because the air tends to float the coal out of the filter.

DATA COLLECTION

Data collection and analysis for regulatory reporting, process monitoring, safety, and historical data collection are discussed briefly below. (For more information on data collection and analysis, see Chapter 17.)

SAMPLES—TYPES AND ANALYSIS. Sample types can be broadly categorized by the manner or method in which they are collected (e.g., manually by an operator using dippers, weighted bottles, hand-operated pumps, sludge judges, etc. or automatically via automated sampling equipment and related instrumentation, controls, and accessories). Analysis methods also may be classified as manual or automatic depending on the tool(s), techniques, or methodology used. In fact, pH, temperature, turbidity and other parameters can now be reliably measured via online instrumentation, and samples only need to be collected to double-check or calibrate the online instruments. More parameters (e.g., dissolved oxygen, suspended solids, and ammonia) are being monitored online as online instrumentation becomes ever more reliable, providing real-time information from newer and often competing technologies. Physical–chemical treatment monitoring will involve both manual and automatic sampling and analysis, depending on the nature and the purpose of the samples and the parameters being analyzed.

In addition to manual and automatic, samples can also be characterized as grab or composite based on how often they are collected.

Grab Samples. A *grab sample* is a discrete sample that is collected manually. They typically are taken when operators need to know process stream characteristics at a specific time. Grab samples can characterize process stream variations over time, as well as allow rapid analysis of unstable parameters.

Composite Samples. A *composite sample* is one sample consisting of a combination of grab samples collected during a specific period (typically, 24 hours). It can be obtained either manually or via automatic sampling equipment and typically provides information on the flow's average characteristics. Composite samples may be either time or flow-proportioned composites. In time composites, several fixed-volume samples are collected at specific time intervals and then combined. In flow-proportioned composites either the volume or sampling frequency of the grab samples varies so the composite better mirrors the changes in flowrates during the sampling period.

[For more information on composite sampling refer to *Wastewater Sampling for Process and Quality Control* (WEF, 1996).]

QUALITY ASSURANCE PLAN. A good sampling program with detailed protocols merits a good quality assurance plan (QAP)—also called QA/QC plan, or quality assurance project plan (QAPP). A good QAP will typically

1. Provide the list of parameters to be tested and the sampling methods to be used.
2. Present a detailed sampling plan.
3. Specify the types and sizes of samples.
4. Describe the sampling and chain-of-custody protocols.
5. Describe the sample-storage and -preservation procedures.
6. Specify and describe the analytical protocols to be used.

PERMIT REPORTING. All WWTPs operating under a National Pollutant Discharge Elimination System (NPDES) permit must conduct a sampling and analysis program to ensure compliance with their permit requirements. The permits typically specify the parameters to be tested; the sampling location, type, frequency, and analyses to be performed; the sampling protocols (or references thereto) to be used; and the frequency of reporting analytical results to the permitting authority. Failure to conduct the permitted program can result in adverse action from the permitting agency.

The typical permit limits that apply to physical–chemical treatment include turbidity, pH, ammonia-nitrogen, total phosphorus, and bacteriological quality.

PROCESS CONTROL REPORTING. In addition to the permit-related sampling and analyses, utilities also need to do sampling and analysis for process evaluation and control. An effective process monitoring and reporting program will provide information on each process's loading and performance, and data that allow operators to anticipate operational adjustments.

The parameters used to monitor and control physical–chemical treatment processes can include suspended solids, alkalinity, conductivity, turbidity, pH, ammonia-nitrogen, total phosphorus, and chemical feed rates.

PLANNED MAINTENANCE PROGRAM

Following is a brief discussion of maintenance programs. For more information on maintenance, including types (e.g., preventive and corrective), the need to emphasize preventive maintenance, and maintenance management programs, see Chapters 6 and 12.

WHY IS A PROGRAM REQUIRED? Increasingly, maintenance managers are viewed as asset managers responsible for the entire lifecycle value of a piece of equipment rather than on solely keeping it functional. A planned maintenance program (PMP) optimizes the effectiveness of maintenance management via systematic methods and procedures. Its goal is to keep equipment and facilities functioning safely, efficiently, and cost-effectively, so operations staff can meet treatment targets at a minimum operating cost.

A planned maintenance program will typically incorporate a maintenance management system, which can be manual, hosted on one PC, or a computerized maintenance management system (CMMS) with multiple, networked workstations. All maintenance management systems should address the following categories:

- Equipment records (description and history),
- Work planning and scheduling,
- Storeroom and inventory,
- Budget and costs tracking, and
- Staffing and organization

EQUIPMENT LISTING. A good maintenance program should include an equipment-record system with a comprehensive equipment numbering system in

which each item in the plant has been assigned a unique identifier. A simple means of doing this is to assign a block of 1000 numbers to each process area or structure within the plant. Then, each equipment item within each area can be assigned an individual number within its 1000 block. This numbering structure will also allow subareas to be set up within a main 1000 block.

For example, let's assume that the physical–chemical treatment area at a treatment plant is assigned the 6000 block. Let's also assume that this area has the following subareas: coagulation, flocculation, sedimentation, filtration, and disinfection. The physical–chemical treatment area can then be organized so numbers in the 6000 to 6199 range relate to equipment in the coagulation subarea, 6200 to 6399 relate to the flocculation area, and so on. This method will leave enough numbers unassigned to accommodate any equipment added to that area or subarea in the future.

FREQUENCY OF CHECKS. Maintenance checks can be run hourly, daily, every shift, weekly, monthly, quarterly, semiannually, or annually. How often an item should be checked depends on various factors (e.g., age, type, and criticality of service or use; service life; and the level of preventive and predictive maintenance desired or performed). The frequency of checks also depends on the manufacturer's required and recommended practices, especially when the item is in its warranty period. Other factors to be considered include scheduling work to minimize idle time, reduce peak workloads, and maximize maintenance personnel's capabilities.

CONVENTIONAL PROCESSES

SEDIMENTATION. ***Fundamentals of the Process.*** Sedimentation is the process of separating suspended particles from water via gravity in large basins or tanks, typically under quiescent conditions. The terms *sedimentation*, *settling*, and *clarification* are typically used interchangeably. Wastewater treatment professionals tend to use *clarification*.

Description of Process and Process Equipment. Settling basins (or clarifiers or sedimentation tanks) allow solids to be separated from wastewater or chemically treated effluent via gravity. These basins typically contain mechanically driven scrapers that continuously move the settled sludge to a hopper, from which it is pumped or removed by hydrostatic pressure.

Both rectangular and circular horizontal-flow sedimentation tanks have been used to separate chemical sludges, as have clarifiers with large flocculating center wells, and upflow sludge blanket clarifiers. When treating coagulated wastewater, however,

upflow sludge blanket clarifiers have difficulty maintaining a uniform sludge blanket and preventing solids carryover into the effluent. Variations (surges) in influent flow can make the sludge blankets in solids contact units unstable, so solids contact units are typically considered where uniform inflow is anticipated or where the units are preceded by upstream storage or equalization.

Recent developments include patented high-rate clarification systems that use densifying solids contact or ballasted media flocculation (in addition to gravity) to clarify coagulated and flocculated effluents.

Process Control Systems. Process control systems for chemical sedimentation units focus on the surface loading or overflow rate, detention time in the basins, and the solids loading rate [the rate of solids feed divided by the clarifier's cross-sectional area, expressed as $kg/m^2 \cdot d$ (lb/d/sq ft)]. Because these parameters are typically set during design and physically limited by the unit's size provided, operators will only have indirect control over these parameters. Some indirect control measures might include using in-plant tankage or equalization basins; system storage in collection systems; careful pump operations to minimize influent surges; and flow distribution among multiple clarifiers. Adding chemicals to settling tanks will also increase sludge generation. For example, when chemicals are added to primary clarifiers for enhanced primary treatment, the additional solids generated will necessitate higher sludge withdrawal rates to prevent other operating problems in the clarifiers.

Normal Process Control. The sedimentation process is key to overall WWTP performance. If the settling tank effluent contains high suspended-solids concentrations, it will reduce the efficiency of downstream unit processes and perhaps even cause a severe upset, resulting in a complete WWTP shutdown. The important variables when operating a sedimentation process are upstream coagulation and flocculation, the surface overflow rate, and the sludge withdrawal rate.

The surface overflow rate depends on the wastewater flow and the volume of recycle flows (e.g., filter backwash water and sludge processing streams). Operators typically cannot control the inflow, but they can control the timing of the recycle flows.

The amount of sludge withdrawn from the basins must be sufficient to avoid overloading the collection arms, prevent floc carryover, and avoid septic conditions. However, excessive withdrawals will result in a thin sludge (less than 1% solids), which can hurt downstream solids processing. Excessively thick sludge can also have adverse effects, including organics solubilization and sludge blanket subject to washout during hydraulic transients. The downstream thickening process may dictate the desired concentrations for sludge withdrawals.

Some other issues to be aware of include

1. Short-circuiting and hydraulic instabilities because of variable influent characteristics or poor influent distribution;
2. Density currents or thermal stratification, resulting in dead spaces at the surface of the clarifier (when the influent is colder than the tank contents) or at the bottom (when the influent is warmer than the tank contents); and
3. Wind effects, in which wind blowing across the water surface may set up circulation cells, reducing net volume and detention time in the tank.

These issues are site-specific, often difficult to spot, and once spotted, may be hard to analyze. Dyes or tracers are a simple, practical method for assessing the hydraulic performance of sedimentation basins. Tracer studies can also be used to determine the success of any corrective measures. Theoretical analysis techniques [e.g., computational fluid dynamics (CFD)] may also be useful in simulating, analyzing, and resolving such conditions.

Furthermore, operators should be aware that they may not be able to resolve these issues operationally. Depending on how often they occur, retrofits to the tanks (ranging from strategically placed baffles to tank covers) may be required to resolve them. Failure to address poor solids removal in the sedimentation process can increase downstream solids processing costs (primarily due to withdrawing excessively thin sludges).

Data Collection. The pH and turbidity of the chemical settling tank influent and effluent should be monitored and recorded continuously. Settleability tests on the flocculator effluent (clarifier influent) should be run daily. For phosphorus removal, composite samples of the settling tank influent and effluent should be tested for phosphorus concentration. The solids concentrations in the sludge pumped from the chemical clarifier should be measured daily, based on grab samples. The sludge blanket depth also can provide valuable operating data.

Planned Maintenance Program. Planned maintenance programs for chemical settling tanks are not significantly different from those for conventional primary or secondary clarifiers, so programs for conventional units can be used as a guide (see Chapters 19 and 20). However, chemical sludges may have different handling characteristics than conventional primary and secondary sludges. Also, sludges produced by different chemicals will have differing properties. For example, the physical characteristics of alum sludge will be different than those of lime sludge. If lime is used as a coagulant, then calcium carbonate deposits may need to be routinely removed from the rapid

mixer shaft and paddles and all lime sludge transporting devices may need routine cleaning. The major mechanical equipment to maintain includes polymer mixing equipment; chemical feeders; rapid mixer motors, gear drives, and shaft bearings; flocculator drive motors, speed reducers, and shaft bearings; settling tank scraper drive motors and speed reducers; sludge pumps; and vibrators on lime storage bins.

Troubleshooting. Other than issues related to the sludge handling characteristics, troubleshooting for chemical settling tanks is not significantly different than that for conventional primary settling tanks, so guides for conventional units can be used as a starting point (see Chapter 19). The single biggest troubleshooting issue for chemical settling tanks is usually high effluent turbidity. Probable causes and potential solutions are listed below:

1. Inadequate sludge removal—adding chemicals to settling tanks increases sludge generation, so sludge withdrawal rates must be higher than those for an equivalent conventional settling tank.
2. Poor floc formation—this could be caused by incorrect chemical dose (run a jar test to determine the appropriate dose); interrupted chemical feed (check that the chemical feeders are operating and the chemical supply is not exhausted); or chemical dispersion is inadequate (adjust rapid mixer speed).
3. Floc forming but breaking up before settling—Check for excessive turbulence in flocculation zone (check and adjust flocculation mixer speed if necessary) or turbulence at the clarifier inlet or within the clarifier (solutions range from reducing flowrate into unit to installing stilling baffles at strategic locations). Another solution might be using a polymer with the inorganic coagulant to strengthen the floc, if this has not already been done.

FILTRATION. ***Fundamentals of the Process.*** Filtration involves passing flow through a filtering medium or a combination of two or three media to remove suspended or colloidal matter. Although the term *filtering* implies a straining mechanism, several other mechanisms occur simultaneously in the filter media and affect the process's efficiency. These mechanisms include sedimentation (settling) on the filter media, flocculation within the media's pore spaces, and physical and chemical adsorption onto the filter media.

Description of Process and Process Equipment. Filters can be divided into semicontinuous and continuous. Semicontinuous (conventional) filters have to be taken offline periodically for backwashing, while filtering and backwash occur simultaneously in

continuous filters. Continuous filters may be upflow or downflow, with a single medium and deep beds, while semicontinuous filters tend to be downflow and may have shallower single-, dual-, or multi-media beds.

Process Control Systems. All filters have common elements that enable them to perform the functions discussed below.

Flowrate Control. There currently are three principal methods to control flowrates through conventional downflow filters:

1. Constant rate with fixed head,
2. Constant rate with variable head, and
3. Variable rate with fixed or variable head.

In the first method, the flowrate is kept constant by an effluent rate control valve. The valve is nearly closed at the beginning of a filter run and opens slowly as the filter becomes clogged. The run terminates when the valve is fully open.

In the second method, a constant rate is achieved via some type of influent control [e.g., an influent weir box with a starting (driving) water surface elevation above a design terminal headloss]. The filter run is terminated when the filter headloss buildup reaches the design terminal headloss.

In the third method, the flowrate is allowed to decline as the headloss builds up. Declining rate systems may be influent- or effluent-controlled.

Filter Aids. Chemical addition is especially important when secondary treatment is followed directly by filtration. If filtration is preceded by distinct coagulation, flocculation, and settling steps, then the filters may not need any chemicals. However, most filter designs typically provide for chemical addition (usually alum and some type of polymer).

Filter Backwash. The typical backwash methods for conventional granular media filters include

1. Water backwash with surface and subsurface washers (surface washers are typically used in single-medium filters; subsurface washers—installed at the expected depth of the expanded interface—may be necessary in dual- or multi-media filters).

2. Water backwash with an auxiliary air scour where the air is applied for 3 to 4 minutes before the backwash cycle begins (typically used in dual- and multimedia filters or as an alternative to mechanical surface washers).
3. Simultaneous air–water backwash (typically used in single-medium unstratified filter beds; less common in dual- or multimedia filter beds because the air tends to float coal out of the filter).

Filter Appurtenances. Typical filter appurtenances include the underdrain system and washwater troughs. In conventional downflow filters, the underdrain system supports the filter media and distributes the backwash water. They range from graded gravel beds to plastic and steel nozzles inserted into precast channels, poured in concrete, or affixed on steel plates.

Washwater troughs are typically located at the top of the filter to collect backwash water and convey it to the filter drain. The rectangular troughs are constructed of fiberglass, sheet metal, or concrete and topped with weir plates. Media separator baffles may be placed on the underside of the troughs to minimize loss of filter media.

Process Monitoring and Control. Filter instrumentation can range from passive systems for monitoring headloss and influent and effluent turbidity, to fully automated operations. At the passive monitoring level (typically for smaller facilities) effluent turbidity and headloss values may be monitored manually. Operators take filter units offline and initiate and complete backwashes. At the other end of the range, fully automated filters will include instrumentation and control logic that can take filter units offline, backwash them, and put them back into service with little, if any, operator input. These systems typically include motorized valves, flow meters, differential pressure meters, and turbidity meters, all feeding information or receiving operating commands from a central control unit with a microprocessor-based device (e.g., a programmable logic controller).

Normal Process Control. The following sections describe process control for each step of conventional, semicontinuous downflow filtration, with only occasional references to continuous backwash upflow filtration. Most of the other filter types use proprietary designs and technology, and operators will be better served by referring directly to the particular manufacturer's directions.

Filling the Filter. When starting up a filter for the first time or filling one that has been drained, special precautions are required to avoid serious damage to the filter. First,

the filter must be filled with water. For a conventional filter, operators should slowly pump water up through the filter underdrain system from the backwash supply (essentially, a slow backwash). For a continuous backwash upflow filter, filling it from the bottom expels air that would otherwise be trapped in the media. If the filter media are dry, the filter must be filled and allowed to soak for 8 hours before backwashing is attempted. If the filter has been filled from the top, it should not be backwashed—even if a filter cycle has since occurred. Water moving down through a filter will not remove trapped air, which can completely overturn the gravel during backwashing, creating gravel mounds or allowing fine media to be lost from the bed during subsequent filter cycles. In severe cases, the filter media and the gravel may have to be replaced. If the filter has been filled from the top, it should be drained completely, and then operators should initiate a slow backwash.

Whenever a filter drains below the level of the top of the media or a dry filter is being filled, the bottom-filling procedure must be strictly followed to avoid severe damage to the filter media and support gravel.

Filter Aids. A key element in optimizing filter performance is using an appropriate amount of filter aid (e.g., polymer or alum). The filter aid improves filtration in several ways:

- Strengthening the floc,
- Controlling the depth of floc penetration into the beds,
- Improving the clarity of the filtered water, and
- Increasing the permissible flowrate through the bed.

The amount of filter aid needed increases as water temperature decreases, flowrates increase through the filters, and applied turbidities increase. The optimum dosage causes the maximum desired filter headloss to be reached just as turbidity breakthrough is impending. If lime is the primary coagulant, using alum (5 to 20 mg/L) as a filter aid (supplementing polymer) may reduce filter effluent turbidity.

The filter aid coats the grains of the filter media. When a new filter enters service, three or four filter runs may be needed to properly coat the grains. Conversely, three or four filter backwashes may be required to reduce the coating if a filter aid dose is reduced. Operators should proceed with caution when reducing filter aid doses because the residual effects of previous coats on the bed may delay the full response to the reduced dose. Controlling the filter aid dose becomes a relatively simple task once operators learn to interpret the turbidity and headloss recordings.

Turbidity Monitoring. Continuously monitoring the effluent turbidity of each filter helps operators maintain the proper application rate of filter aid to each filter unit. Also, if the effluent turbidity exceeds the maximum predetermined allowable value, the filter should be automatically taken out of service and backwashed.

Filter Backwashing. High headloss through a filter bed typically indicates the need for backwashing, so headloss through each filter bed must be monitored. After each backwash, operators should note in the daily log the initial headloss at a predetermined flowrate. At a given flowrate, the headloss through a clean filter should be the same [between 0.3 and 0.6 m (1 and 2 ft)]. If the initial headloss gradually increases, it may indicate that the backwash is too short to clean the filter media thoroughly and should be lengthened. It could also be caused by an inoperative surface wash arm.

Sudden changes in filter flow should be avoided because hydraulic surges tend to cause particles to penetrate the bed. Changes in flow should be gradual, not abrupt. As the filter rate decreases, the length of the filter runs will increase significantly.

Recycle of Backwash Flows. Because all filter backwash wastewater is recycled and reprocessed, utilities sometimes calculate the percentage of WWTP throughput that is recycled as backwash to indicate the system's efficiency. If, for example, four filters were in operation, each with a flowrate of 170 L/s (2695 gpm), and a 7-minute backwash/filter/day was required at a flowrate of 500 L/s/filter (7926 gpm/filter), then the percentage of backwash water would be calculated as follows:

Volume of backwash water

$$= (500\text{L/s} \times 10^{-3}\ \text{m}^3/\text{L}) \times (7\ \text{min} \times 60\ \text{s/min}) \times 4\ \text{filters}$$
$$= 840\ \text{m}^3\ (221\ 904\ \text{gal})$$

Filter throughput

$$= (1440 - 7)\ \text{min/day} \times 60\ \text{s/min} \times 170\ \text{L/s} \times 10^{-3}\ \text{m}^3/\text{L} \times 4\ \text{filters}$$
$$= 58\ 466\ \text{m}^3\ (15.45 \times 10^6\ \text{gal})$$

Percentage backwash water

$$= \frac{840\ \text{m}^3}{58\ 466\ \text{m}^3} \times 100\%$$

$$= 1.44\%$$

Typically, if the backwash water percentage is more than 5%, the system's performance is questionable. Questionable performance may stem from any of the following causes:

- Excessive solids carryover from the settling tank or recarbonation basins,
- Excessive filter aid doses with reduced filter runs,
- An inoperative filter surface wash system or a surface wash that is too short for the backwash cycle, or
- Excessive backwash duration.

However, smaller WWTPs, those with high diurnal flow variations, and those without equalization storage capability may require backwash water percentages as large as 8 to 10%.

Most WWTPs collect filter backwash wastewater in a storage tank so it can be recycled through the treatment processes at a controlled rate. The backwash holding tank also may receive other waste flows to equalize the rates at which these flows are returned to the treatment processes. Also, some of the tank contents may be returned to the rapid mix unit to reduce chemicals and improve coagulation.

Data Collection. The primary control parameters for filtration are effluent turbidity and filter headloss. They typically are continuously monitored via automated instruments. Effluent turbidity, an indirect measure of suspended solids, is the best filter control parameter because it can be measured rapidly and automatically. Turbidity can be correlated to suspended solids as follows:

$$TSS = (TSS_f)\,(T) \tag{24.6}$$

Where

TSS = Total suspended solids (mg/L),
TSS_f = Factor to convert turbidity readings to total suspended solids, and
T = Turbidity (NTU).

Settled secondary effluent

$$\text{TSS (mg/L)} = (2.0 \text{ to } 2.4) \times \text{Turbidity (NTU)} \tag{24.7}$$

Filter effluent

$$\text{TSS (mg/L)} = (1.3 \text{ to } 1.5) \times \text{Turbidity (NTU)} \tag{24.8}$$

If upstream processes include lime coagulation and recarbonation, the filter's influent pH must be determined.

Planned Maintenance Program. Everyday, operators should ensure that each rotary surface wash arm rotates freely by watching them operate. They should check the calibration of effluent turbidimeters at least once per week. Flow and headloss instrumentation should be checked and calibrated according to the manufacturer's recommendations. The major mechanical equipment that requires maintenance includes backwash pumps, surface wash pumps, filter pumps (influent or effluent pumps may be part of the system), filter aid feed pumps, valves, and automatic valve operators.

Troubleshooting. The troubleshooting chart in Table 24.3 describes symptoms, probable causes, and potential solutions.

RECARBONATION. ***Fundamentals of the Process.*** Recarbonation is the process of adding carbon dioxide to water after it has been treated with lime. Lime coagulation raises the pH to between 10 and 11, making the water unstable and precipitating calcium carbonate, which tends to encrust any downstream filters or carbon particles. Adding carbon dioxide lowers the pH to less than 8.8 and reconstitutes the bicarbonates.

Description of Process and Process Equipment. At large WWTPs, recarbonation typically involves injecting carbon dioxide (CO_2) gas into the water. The process may have one or two stages. In the one-stage process, enough carbon dioxide is injected to lower the pH from between 10 and 11 to the desired value in one step (Figure 24.16). This dissolves the calcium in the lime, so the plant effluent will have a calcium concentration. In two-stage recarbonation, enough carbon dioxide is added in the first stage to lower the pH to between 9.5 and 10. The resulting calcium carbonate precipitate is allowed to settle, thereby removing calcium from the water and making it available for lime recovery. Then, more carbon dioxide is injected until the pH drops to the desired value.

Recarbonation equipment typically includes a carbon dioxide source and storage and feed systems. Carbon dioxide sources include stack gases of onsite furnaces, boilers, or incinerators; CO_2 purchased and stored in liquid form; or CO_2 formed when fuels burn. Commercially supplied liquid CO_2 is gaining popularity because of its steadily decreasing costs and relatively simple storage and feed equipment. Gas feed systems typically include a simple pressure gauge and a manually or automatically controlled valve at the feed point. A pH meter continuously monitors the pH changes and may be used for automated control of the feed valve.

TABLE 24.3 Filtration troubleshooting chart.

Indication	Probable cause	Potential solution
Short filter runs because of high headloss	Surface clogging	Check surface wash operation; lengthen surface wash cycle.
		Reduce solids applied to filter by improving upstream treatment.
		Replace sand media with dual media; filter gas bound by release of nitrogen bubbles; bump filters with short backwash.
	Filter cleaning inadequate	Increase backwash duration and rate.
Excessive effluent turbidity	Filter needs backwashing	Backwash filter; repair or install surface wash.
	Improper upstream coagulation	Run jar tests; adjust coagulant dose.
	Improper filter aid dose	Adjust filter aid dose.
	Coagulation system failure	Check chemical supply and chemical feeder operations.
Excessive amounts of backwash water required (more than 5% of throughput)	Influent solids concentrations are too high	Improve upstream treatment (coagulation and settling).
	Filter aid dose too high	Reduce filter aid dose.
	Surface wash system has failed	Repair surface wash system.
	Inadequate surface wash	Increase duration of surface wash.
	Excessive backwash duration	Reduce backwash cycle duration.
Mudballs on filter surface	Inadequate backwash and surface wash	Increase backwash rate and duration of surface wash cycle.
Gravel on upper layers of filter	Air entering gravel underdrains during backwash	Start backwash pump against a closed valve and release air via a pressure-relief valve in the backwash line.
		Install a pressure-relief valve at the high point in washwater line and add pressurized water to the line to keep it full of water and expel air.

TABLE 24.3 Filtration troubleshooting chart (*continued*).

Indication	Probable cause	Potential solution
	Backwash water pressure too high	Change source of backwash supply or install pressure control valve.
Media is washing out of filters during backwash	Backwash rate too high	Reduce backwash rate.
	Washwater troughs not level	Adjust washwater troughs.
	Surface wash cycle too long	Reduce surface wash duration so it ends at least 1 minute before backwash is complete.
	Uneven distribution of backwash water	Clean filter underdrains.
Filter cleaning is a problem in warm weather	Higher temperatures reduce viscosity of backwash	Increase backwash rate during warm weather.
Filters difficult to clean after being offline	Microbial growths in filter	Add 5 to 15 mg/L of chlorine to filter influent before taking offline.

Recarbonation basins, if used, are typically similar to rectangular sedimentation basins with CO_2 diffusers arranged in the appropriate locations (for two-stage systems, typically at the influent and effluent ends, with an intermediate sludge settling zone).

Process Control Systems. The operation and control of recarbonation systems is relatively straightforward. Feed valves may be automatically controlled based on the pH measurement (using the last recarbonation stage as the control). Feed valves may also be manually controlled. In two-stage systems, the CO_2 split between the two stages is fairly constant once established for a given flow and desired pH. In this case, the valves between the two stages may not need to be readjusted frequently, and the final pH control point may be used to adjust the overall feed rate. Typically, the system will work satisfactorily with continuous, automatic pH monitoring and manual feed-rate adjustments.

Normal Process Control. If the pH of the recarbonation basin water is controlled to provide equilibrium with respect to calcium carbonate, the water will neither cause corrosion nor form scale, a desirable situation. In two-stage recarbonation systems,

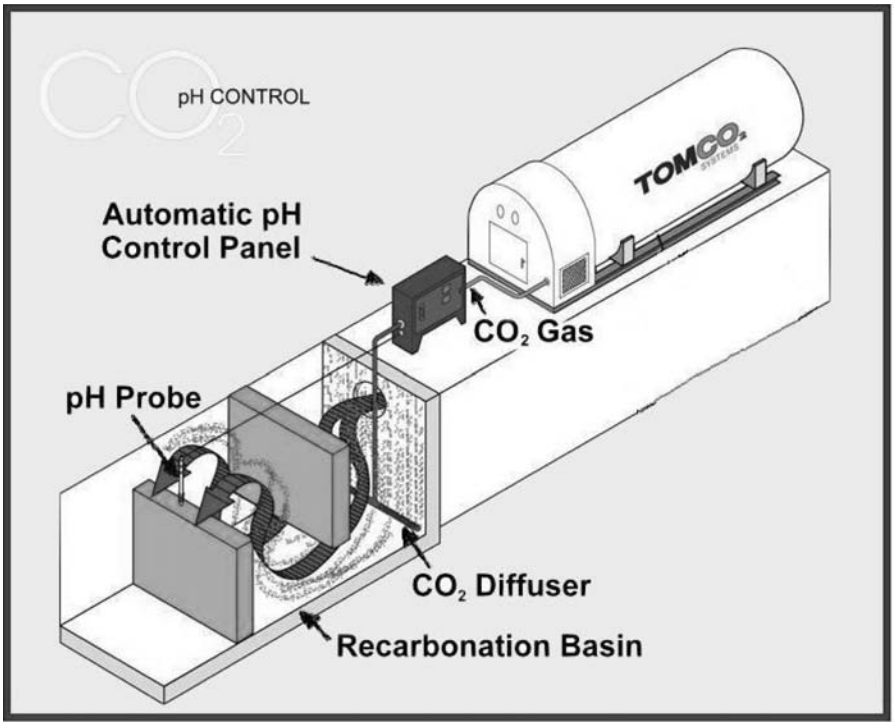


FIGURE 24.16 Typical single-stage recarbonation using gas feed system.

efficient settling of the calcium carbonate floc may require the addition of polymers or coagulants.

The amount of carbon dioxide applied may be controlled by trial and error based on pH measurements and manual valve adjustments. The first adjustment provides enough carbon dioxide flow to reduce the pH to between 7 and 8. The second adjustment splits that flow between the two stages so the pH will be 10 at approximately the midpoint of the intermediate settling basin. Once these two adjustments are made, few (if any) refinements will be needed. The pH is measured at the midpoint rather than at the entrance of the settling basin because at average wastewater temperatures, all carbon dioxide gas bubbles will enter solution and react completely with hydroxide to form calcium carbonate in approximately 15 minutes.

Data Collection. The most important parameter in recarbonation is pH, which is typically monitored continuously via online pH meters. Grab samples should be

TABLE 24.4 Tests for recarbonation and lime recalcining.

Sampling location	Daily grab samples	Weekly grab samples
Recarbonation		
Single-stage (effluent)	pH	—
Two-stage (first stage)	—	pH
Two-stage (effluent)	pH	—
Lime recalcining		
Thickener influent	TS[a]	Ca, Mg, P
Thickener effluent (sludge)	TS	Ca, Mg, P
Thickener effluent (supernatant)	TS	Ca, Mg, P
Centrifuge cake	TS	Ca, Mg, P
Centrifuge centrate	TS	Ca, Mg, P
Recalcined lime	TS	Ca, Mg, P

[a]Total solids.

collected once a shift or daily to validate the results of the online system. Table 24.4 shows other necessary tests.

At most WWTPs, proper monitoring and control of the solids-handling and lime-recalcining processes will require one operator's full-time attention.

Planned Maintenance Program. A recarbonation maintenance program should be based on those for simple chemical gas (or solution) feed systems, as well as those for thickeners, centrifuges, incinerators, and furnaces. Utility staff should consult the maintenance programs for these processes before setting up a planned program for the recarbonation process.

Troubleshooting. The troubleshooting chart in Table 24.5 describes symptoms, probable causes, and potential solutions for the lime-recalcining process.

ADVANCED PROCESSES

SOLUBLE CHEMICAL OXYGEN DEMAND REMOVAL. Despite secondary treatment, coagulation–flocculation, sedimentation, and filtration, some soluble organic materials may persist in the effluent. These persistent materials, often called *refractory organics*, produce color and contribute to the secondary effluent's COD. These COD values often range from 30 to 60 mg/L.

The most practical method of removing refractory organics from water is activated carbon adsorption (Table 24.6).

TABLE 24.5 Troubleshooting chart for lime recalcining.

Indication	Probable cause	Potential solution
Recalcined lime contains less than 70% CaO	Furnace temperatures too low	Increase temperatures to 1850 °F[a] on fired hearths.
Large clinkers forming in furnace	Inadequate air	Increase air flow to provide 70 to 100% excess air.
Offensive odor in recalcining area	Insufficient combustion air	Increase air flow to provide 70 to 100% excess air.
Recalcined lime tends to agglomerate into soft particles at least 0.25 in.[b] in diameter (rather than having desired flourlike appearance)	Furnace temperatures too low	Increase temperature to 1850 °F[a] on fired hearths.
Recalcined lime is dense and has poor reactivity	Furnace temperatures too high	Reduce temperatures to 1850 °F[a] on fired hearths.

[a]$(°F - 32) \times 0.5556 = °C$.
[b]in. $\times$ (25.40) = mm.

TABLE 24.6 Organic compounds amenable to removal by granular activated carbon (U.S. EPA, 2000).[a]

Class	Example(s)
Aromatic solvents	Benzene, toluene, xylene
Polynuclear aromatics	Naphthalene, biphenyl
Chlorinated aromatics	Chlorobenzene, PCBs, endrin, toxaphene, DDT
Phenolics	Phenol, cresol, resorcinol, nitrophenols, chlorophenols, alkyl phenols
Aromatic amines and high-molecular-weight aliphatic amines	Aniline, toluene, diamine
Surfactants	Alkyl benzene sulfonates
Soluble organic dyes	Methylene blue, textiles, dyes
Fuels	Gasoline, kerosene, oil
Chlorinated solvents	Carbon tetrachloride, percholoroethylene
Aliphatic and aromatic acids	Tar acids, benzoic acids
Pesticides/herbicides	2,4-D, atrazine, simazine, aldicarb, alachlor, carbofuran

[a]DDT = dichloro-diphenyl-trichloroethane; GAC = granular activated carbon; and PCBs = polychlorinated biphenyls.

Fundamentals of the Process. Carbon activation is a manufacturing process that produces many pores within the carbon particles. The greater surface area provided by the "walls" of the pores makes the activated carbon extremely effective in removing organics.

When the carbon's adsorption capacity has been exhausted, the carbon can be regenerated by heating it in a furnace until the adsorbed organics are driven off and pass through an afterburner to prevent air pollution. The furnace's oxygen levels are minimized to avoid burning the carbon. Small WWTPs that cannot afford an onsite regeneration furnace may ship spent carbon to a central regeneration facility for processing or to a suitable landfill.

The degree of treatment preceding carbon adsorption depends on the desired final effluent quality. For example, if a high-quality effluent is desired, secondary treatment, coagulation–sedimentation, filtration, carbon adsorption, and disinfection can, if properly designed and operated, produce a colorless, odorless effluent free of bacteria and viruses, with a BOD of less than 1 mg/L and a COD of less than 20 mg/L.

Description of Process and Process Equipment. Activated carbon has an extremely large surface area per unit weight (on the order of 1000 m^2/g), making it an extremely efficient adsorptive material. Large organic, nonpolar molecules are hydrophobic and so will adsorb to any solid. Many short-chained, biodegradable organic molecules (e.g., sugars and methanol) cannot adsorb readily, but they probably will not exist in secondary effluents.

Powdered carbon (crushed carbon that is finer than 300 mesh) has been used to remove organics from wastewater by mixing the powder with wastewater and then coagulating and settling the particulate. Sometimes the powdered carbon is added to the aeration tank of an activated sludge WWTP and then settled with the mixed liquor in the secondary clarifier. Sometimes separate clarification and coagulation steps are added. Powdered activated carbon is corrosive and can be explosive, so it must be properly stored and transported.

In granular activated carbon treatment, wastewater passes through beds (resembling pressure or gravity filters) or 6- to 7.75-m (20- to 25-ft) columns full of carbon. Typical contact times are 20 to 40 minutes for domestic wastewaters.

The precise effect of wastewater turbidity or suspended solids on granular activated carbon has not been determined, but the buildup of suspended or colloidal materials (e.g., ash) may restrict pore openings and, therefore, the effective surface area of the carbon, degrading its adsorptive capacity. Such hazards can be minimized by treating only highly treated, low-turbidity wastewater (e.g., filter effluent).

The rate of organics adsorption in municipal wastewater typically increases as the pH decreases. Adsorption is poor when the pH is more than 9.0.

The carbon used for wastewater treatment must be physically strong enough to withstand the repeated handling required during regeneration and backwashing. Regeneration requires that the saturated carbon be moved, typically in a water slurry, from the carbon contactor system to the regeneration system. Currently, the best carbons are made from select grades of coal. These hard, dense carbons can be conveyed in water slurry without appreciable deterioration.

Most carbon contact columns are either upflow or downflow and either open concrete or enclosed steel vessels (Figure 24.17). The upflow (countercurrent) approach uses carbon more efficiently and avoids plugging by particulates. Activated carbon will remove oxygen from the air in a contacting vessel, so operators must carefully check a carbon contactor's oxygen content before entering it.

Process Control Systems. Process control for activated carbon systems focuses on mimizing the amount of carbon withdrawn for regeneration and lost during regeneration.

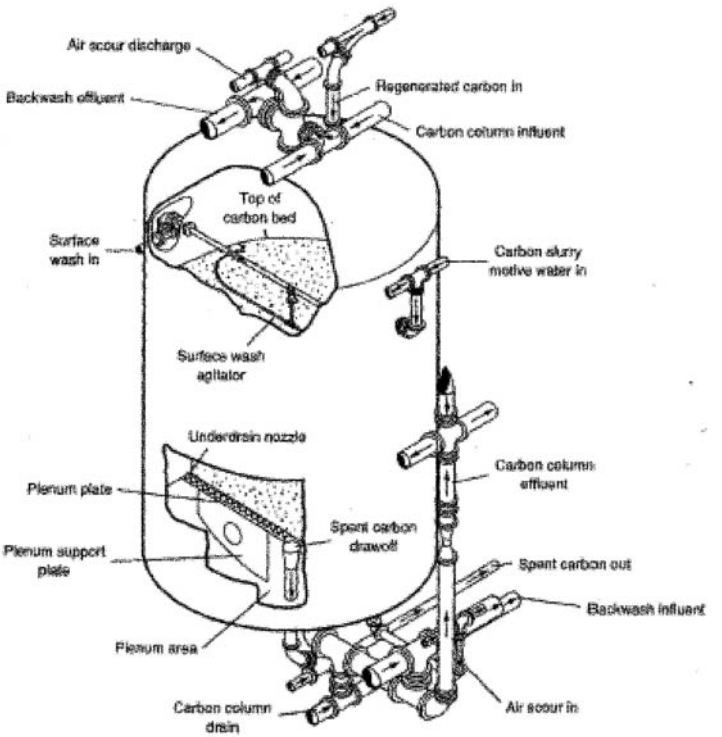


FIGURE 24.17 Downflow carbon contactor (Metcalf & Eddy, 2003).

Consistently treating high-quality water reduces the required regeneration frequency. So, careful operator attention on screening, coagulation, settling, and filtration will pay dividends in the carbon adsorption process.

When using upflow carbon columns, operators should avoid withdrawing an excessive amount of carbon for regeneration. When the effluent BOD or COD reaches the maximum allowable concentration for permit compliance, typically approximately 10% of the carbon is saturated and should be withdrawn for regeneration. Withdrawing more will result in unnecessarily regenerating partially spent carbon. Carbon's weight (apparent density) increases as it adsorbs organics, so monitoring the apparent density will indicate when operators have begun to withdraw partially spent carbon. The apparent density of carbon is its weight per unit volume (expressed as grams per cubic centimeter). The apparent density test procedure is defined on page B-23 of the U.S. Environmental Protection Agency (U.S. EPA) manual, *Process Design Manual: Carbon Adsorption* (U.S. EPA, 1973).

Carbon loss during regeneration in a multiple-hearth furnace can be significant. One major cause is carbon burnt (over-regenerated) during startup, shutdown, or other operations. Continuous furnace operation avoids startup and shutdown losses; operating as long as possible during a regeneration can reduce losses. Regeneration furnaces are routinely controlled via tests of the carbon's apparent density, supplemented periodically by tests of iodine number, adsorption isotherms, or activity of the regenerated carbon (U.S. EPA, 1973).

The apparent density of regenerated carbon should match that of virgin carbon. If the apparent density is too high, typically the furnace feed rate is too high or the temperature is too low. If the apparent density is too low, typically the feed rate is insufficient or the temperature is too high (over-regenerating some carbon).

Progressive decreases in the regenerated carbon's iodine numbers indicate that the regenerating temperature is too low and that the adsorbates being carbonized remain in the pores. The carbon temperature during regeneration must be at least 820 °C (1500 °F) to prevent partial deterioration. If partial deterioration occurs, the furnace temperatures must be raised as high as 950 to 980 °C (1750 to 1800 °F) to correct the problem. The iodine number may not be fully restored, however, until after several successive regenerations.

Steam added to the lower hearths of the furnace may improve carbon regeneration because it distributes temperatures more uniformly throughout the furnace, reduces the regenerated carbon's apparent density, and increases the regenerated carbon's iodine number. Typically, approximately 1000 g steam/kg carbon (1 lb steam/lb dry carbon) is used.

Over-regeneration may indicate a system malfunction if it cannot be corrected by adjusting the temperature, carbon feed rate, steam feed rate, or furnace drive speed.

Utility staff should analyze the gases in the malfunctioning furnace and in the gas outlet to determine if air is leaking from the feed entry, product discharge pipe, hearth doors, or bottom shaft seal. They also should check for indications of changes in the fuel:air ratio devices. If leaks are not found, the fuel:air ratio should be adjusted to produce more carbon monoxide (CO) at the burners (but no more than 4% total).

Normal Process Control. As carbon adsorbs organic materials from wastewater, it eventually becomes saturated (exhausted) and organic substances break through the process. The effluent COD concentration indicates the need to remove exhausted carbon for regeneration. Utility staff can determine the long-term efficiency of the carbon adsorption and regeneration processes by calculating the amount of COD removed per pound of carbon regenerated (lb $\times$ 0.4536 = kg). A large decrease in this value through several regeneration cycles indicates that the carbon is becoming fouled and is losing its efficiency. System operations must then be changed.

Utility staff could also calculate the pounds of carbon withdrawn per volume of wastewater treated (carbon dosage) (lb/mil. gal $\times$ 0.1198 = g/m^3). If this value is increasing, then the process needs adjustments or carbon efficiency is permanently lost. Adjustments may include improving upstream processes to reduce particulate clogging of the carbon pores or changes in carbon regeneration.

In the carbon columns, contact time significantly affects effluent quality. Using the portion of the column volume occupied by carbon, contact time is calculated as follows:

$$\text{Contact time (min)} = \frac{\text{Carbon volume (gal)}}{\text{Flowrate (gpm)}} \tag{24.9}$$

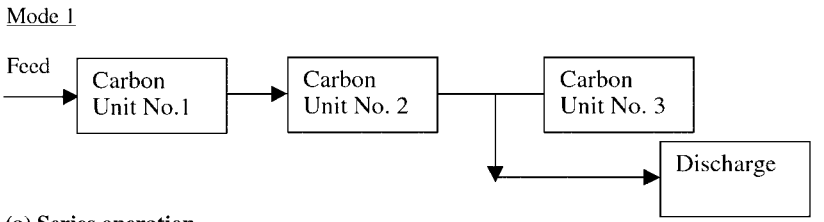
Note: gal $\times$ (3.785×10^{-3}) = m^3; gpm $\times$ (6.308×10^{-5}) = m^3/s.

Longer contact times may reduce effluent COD, color, and perhaps carbon dose. If contact times become too long, however, they could encourage undesirable anaerobic conditions in the carbon columns.

The COD removals in the carbon columns may vary day to day from 40 to 75%. The absolute value of the effluent COD (in milligrams per liter) is, therefore, a better measure of process efficiency.

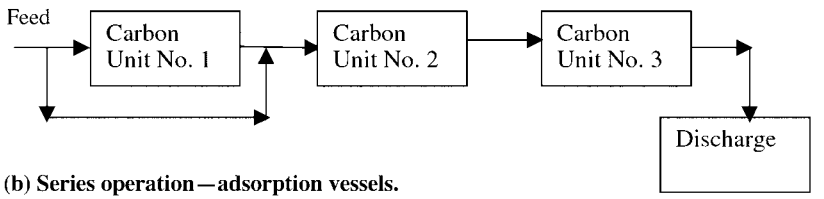
One approach for minimizing costs and regeneration cycles would be to operate three carbon adsorption vessels in series (two active and one on standby). While requiring more process monitoring and more filters, it may minimize the regeneration frequency and improve overall efficiency. This approach assumes that the carbon has

considerable reserve adsorptive capacity once a low-level breakthrough has occurred. By operating in series, the first vessel continues to remove organics even though its discharge exceeds the limit, and the second polishes that discharge. Once the second vessel experiences breakthrough, it is valved into the primary position, a third vessel is valved in to provide the polishing step, and the first vessel is taken offline to regenerate (Figure 24.18). In addition to maximizing carbon's adsorptive capacity, it may



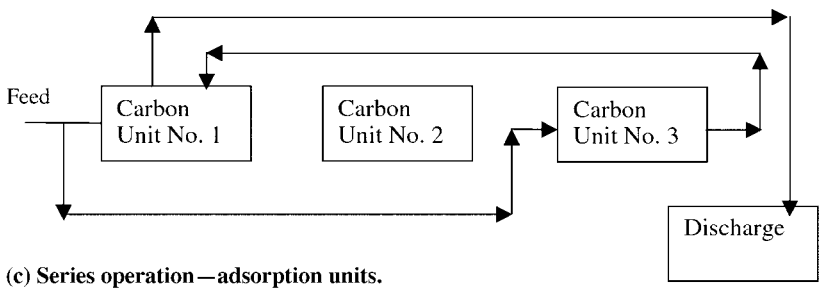
(a) Series operation.

Mode 2
Operate in mode 1 until breakthrough from unit no. 2 approaches discharge limit, then switch to mode 2 and regenerate/replace carbon in unit no. 1.



(b) Series operation—adsorption vessels.

Mode 3
Operate in mode 2 until break through from unit no. 3 approaches discharge limit, then switch to mode 3 and regenerate/replace carbon in unit no. 2.



(c) Series operation—adsorption units.

FIGURE 24.18 Carbon adsorption vessel schematics.

facilitate regeneration, giving operators time to maintain the units without risking organic breakthrough to the final effluent.

Data Collection. Data collection and control test requirements reflect local regulatory requirements (Table 24.7). The apparent density test (U.S. EPA, 1973) is essential to proper operation of the regeneration system. Routine steady-state process monitoring calls for apparent density tests once per hour when the furnace is in operation. When the regeneration system variables are changing, the test frequency is adjusted accordingly. The iodine number and ash content are determined once per day when the regeneration system is operating.

Planned Maintenance Program. The major maintenance items include carbon slurry pumps, carbon conveyors, and the carbon regeneration furnace. They should be maintained according to the manufacturer's recommendations.

Troubleshooting. The troubleshooting chart in Table 24.8 describes symptoms, probable causes and potential solutions for carbon adsorption systems.

NITROGEN REMOVAL (INCLUDES AMMONIA STRIPPING). The following three physical–chemical processes have been used to remove nitrogen from wastewater:

- Breakpoint chlorination,
- Ion exchange, and
- Ammonia stripping.

Biological nitrification and denitrification for nitrogen reduction, which is becoming more commonplace, is discussed in Chapter 22. Other nitrogen removal processes are not described because they are seldom used for wastewater treatment.

Fundamentals of the Process. *Breakpoint Chlorination.* Ammonia reacts with chlorine to form chloramines. In the presence of more chlorine, chloramines oxidize to nitrogen gas, which then escapes the liquid stream. The overall reaction can be described as follows:

$$2NH_3 + 3HOCl \Rightarrow N_2 \uparrow + 3H_2O + 3HCl \qquad (24.10)$$

where hypochlorous acid (HOCl) is formed in the hydrolysis reaction when chlorine (Cl_2) is added to water.

Ion Exchange. Ion exchange involves replacing specific ions in an insoluble material with those of another species in solution. To reduce ammonia levels, wastewater is

TABLE 24.7 Carbon adsorption tests.

Influent	Effluent	All columns
TOC[a]	TOC COD[b]	TOC COD Odor Color

[a]Total organic carbon.
[b]Chemical oxygen demand.

TABLE 24.8 Troubleshooting chart for soluble chemical oxygen demand removal processes.

Indication	Probable cause	Potential solution
Carbon adsorption		
Excessive headloss in carbon beds	Biological growths in columns	Backwash carbon beds more frequently.
	High influent turbidity	Improve upstream treatment (coagulation, settling, and filtration).
	Carbon breaking up during regeneration	Remove carbon and wash fine carbon particles from system; if necessary, replace carbon with a different type.
	Inlet or outlet screens plugged	Backflush screens.
Decrease in carbon efficiency	Improper regeneration	Adjust carbon regeneration process (see below).
Hydrogen sulfide being generated in carbon beds (may corrode metal and concrete)	Anaerobic biological activity in carbon beds	Reduce detention time by reducing number of beds in service or amount of carbon in bed.
		Apply 5 to 10 mg/L of chlorine to carbon bed influent.
		Backwash carbon more frequently.
Carbon regeneration		
Carbon transport lines plugged	Piping too small	Install at least 2-in.[b]-diameter pipes.
	Inadequate dilution water	Add more dilution water to decrease carbon slurry concentration.
Excessive carbon loss (more than 5%)	Operating schedule of furnace	Store enough carbon to permit more continuous furnace operations.

TABLE 24.8 Troubleshooting chart for soluble chemical oxygen demand removal processes (*continued*).

Indication	Probable cause	Potential solution
Apparent density (AD) of regenerated carbon greater than that of virgin carbon	Insufficient heat	Increase furnace temperature by 50 °F[a] increments until virgin carbon AD is achieved.
		If temperature is in correct range, decrease carbon feed rate.
		Increase steam feed rate if less than 1 lb/lb[c] of carbon.
		Increase furnace drive speed.
Apparent density of regenerated carbon less than virgin carbon	Too much heat being applied to carbon	Decrease furnace temperatures by 50 °F[a] increments until virgin carbon AD is achieved.
		If temperature is in correct range, increase carbon feed rate.
		Decrease steam feed rate.
		Decrease furnace drive speed.
		If above adjustments do not solve the problem, check for air leaks at feed entry, discharge pipe, hearth doors, or bottom shaft seal.
		Change fuel : air ratio to produce more CO at burners, but not more than 4% CO.
		Replace refectories and observe proper heating and cooling procedures in the future.

[a] $(°F - 32) \times 0.5556 = °C$.
[b] in. $\times$ (25.40) = mm.
[c] lb/lb $\times$ 1000 = g/kg.

passed through an ion exchange resin with more affinity for the ammonium ion than for other cations typically present in the wastewater. Naturally occurring compounds called *zeolites* can be used to remove ammonium ions. The zeolite clinoptilolite has been found to be the most cost-effective resin for removing the ammonium (NH_4^+) ion from wastewater. Synthetic ion-exchange resins are also available—some with considerably higher removal capacities—but typically have not been used in wastewater treatment.

Ammonia Stripping. In most wastewaters, ammonia-nitrogen exists as ammonium ions in equilibrium with un-ionized gaseous ammonia as follows:

$$NH_4^+ \Leftrightarrow NH_3 + H^+ \tag{24.11}$$

If the wastewater's pH is raised above 7, the equilibrium of this reaction shifts so the ammonium ion is converted to ammonia. At pH 7, nearly all ammonia-nitrogen is in the form of ammonium ions; at pH 12, almost all is in the form of dissolved ammonia gas, which can be removed via air stripping.

Description of Process and Process Equipment. *Breakpoint Chlorination.* Based on eq 24.10, the theoretical mass of chlorine needed to oxidize the mass of ammonia present is calculated to be 7.6 mg/L of chlorine per 1 mg/L of ammonia-nitrogen. In practice, this ratio will range from 8 mg/L of chlorine for lime-settled and filtered secondary effluent, to 10 mg/L for raw wastewater (WEF, 1998). So, a typical secondary effluent ammonia concentration of 20 mg/L may require approximately 235 kg of chlorine/ML (2000 lb/mil. gal) of treated effluent—a dose 40 to 50 times greater than that typically used for disinfection. With such large chlorine requirements, breakpoint chlorination often fails to compete economically with other nitrogen removal processes.

Also, the large amounts of chlorine lower the water's pH, so large amounts of alkalinity must be added to maintain a near-neutral pH of 7, which is also where the breakpoint reaction requires the shortest contact times. About 30 mg/L of alkalinity must be present for every 1 mg/L of ammonia-nitrogen present to maintain the proper pH range. Theoretically, 14.3 mg/L of alkalinity is required to neutralize the hydrochloric acid formed by oxidizing 1 mg/L of ammonia-nitrogen. To keep the pH higher than 6.3, at least twice that amount of alkalinity is needed. Unless the water is highly alkaline or lime treatment precedes chlorination, alkali addition facilities should be provided. If sodium hypochlorite is used instead of chlorine, the alkalinity requirement is reduced by 75% (WEF, 1998).

The components of a breakpoint chlorination system include a rapid-mix facility, a contact basin, and chlorination and alkali feed equipment. The chlorine and alkali are added in the same rapid-mix facility.

The large chlorine doses raise concerns about undesirable chlorination byproducts in the effluent and their effect on the receiving water. Upstream nitrification can effectively reduce the chlorine dose required for breakpoint chlorination by reducing the ammonia-nitrogen concentration. Also, dechlorination may be required along with the breakpoint chlorination to meet discharge permit limits.

Ion Exchange. Clinoptilolite can be used to remove ammonium from wastewater via ion exchange. Typically, wastewater passes downward through a 1.2- to 1.5-m (4- to 5-ft) bed of clinoptilolite (20 × 50 mesh particles). When the effluent ammonia-nitrogen concentration begins to increase, indicating bed exhaustion, the clinoptilolite is regenerated by taking the bed offline and passing lime [$Ca(OH)_2$] through the exchange bed. The ammonium stripped from the resin during regeneration is then converted to ammonia gas and removed from the regenerant via air stripping. The lime slurry regenerant's stripping tower handles only a small portion of the total plant throughput, so only a small tower will be needed, and heating it during cold weather may be practical.

Ammonia Stripping. If the ammonia-nitrogen in wastewater is converted to dissolved ammonia gas, it may be liberated from solution by passing the wastewater over a stripping tower. To optimize removal, the wastewater's pH must be raised to between 10.8 and 11.5 (depending on liquid temperature) to ensure that the ammonia is in gas form. Basically, a stripping tower consists of a tower, packing material (over which the wastewater is passed to maximize air–liquid contact), support plates(s) for the packing, a distribution system for the wastewater, and an air supply source (e.g., a fan). As illustrated in Figure 24.19, stripping towers may be either countercurrent (air inlet at base), or crossflow (air inlet along the entire depth of fill). After stripping, effluent pH is adjusted via recarbonation or acid addition.

According to the *Design of Municipal Wastewater Treatment Plants* (WEF, 1998), no ammonia-stripping facilities are known to be routinely in use at U.S. WWTPs. Existing installations have been abandoned because of difficulty meeting year-round standards, air emissions constraints, and maintenance difficulties. Nevertheless, stripping is briefly summarized here because it may be considered in regions with moderate climates or in combination with high lime phosphorus removal.

Process Control Systems. *Breakpoint Chlorination.* Automatic control of the process is important. Chlorine doses should be linked to influent ammonia-nitrogen concentrations. Alkaline doses also should be reliably measured and paced. If the chlorine and alkali are not paced together, the whole process could be upset.

Ion Exchange. Like conventional filters, ion exchange vessels have a media bed supported by an underdrain system, as well as effluent and washwater troughs. Automated process control systems will include facilities to monitor influent and effluent ammonia, take the unit offline to initiate backwashing, and high-pH regeneration.

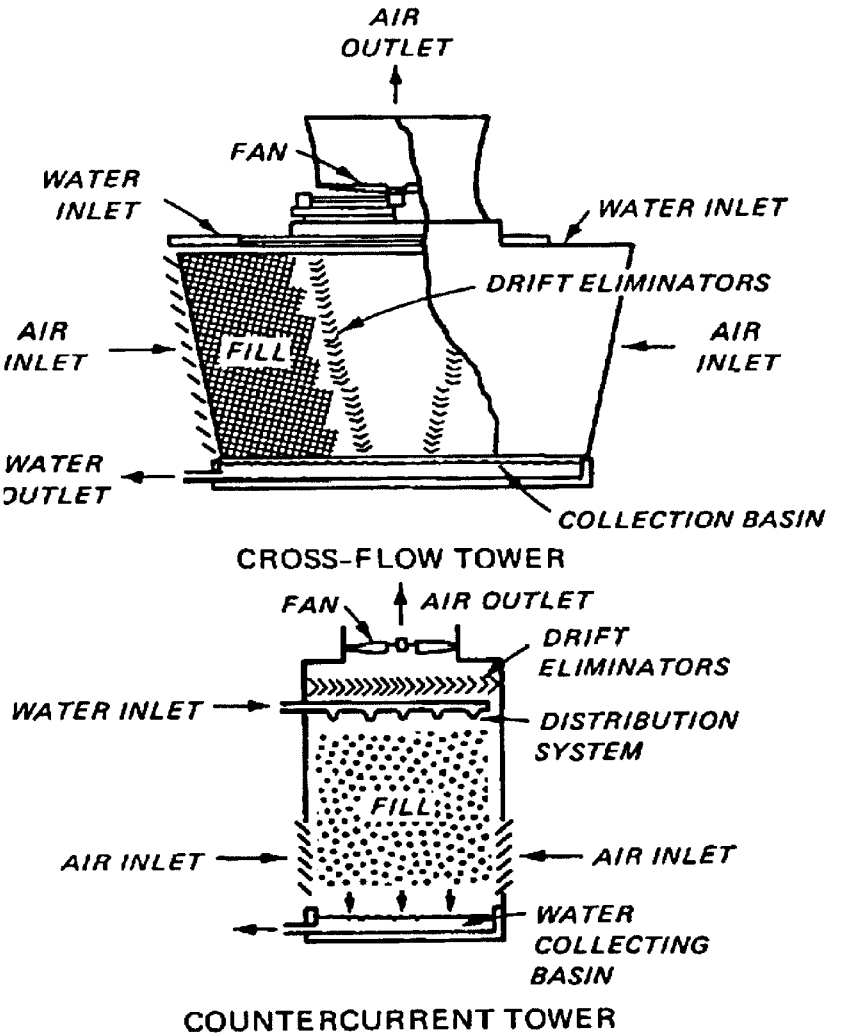


FIGURE 24.19 Schematics of air-stripping towers.

Ammonia Stripping. Process control systems for ammonia stripping should ensure that

- The wastewater's pH is maintained around pH 11 to keep the ammonia-nitrogen in dissolved ammonia gas form, and
- There is enough air flow to keep the stripped liquid in droplet form to maximize the air–water interface, which is critical to the stripping process.

Ammonia stripping is most compatible with physical–chemical processes that increase the pH (e.g., high-lime coagulation). Even so, supplemental alkali may be needed to maintain the pH. Automatic control of alkali feed can be based on the stripped liquid's pH, as monitored in the water collecting basin or a following stage.

Normal Process Control. *Breakpoint Chlorination.* Normal process control involves matching the chlorine and influent ammonia-nitrogen levels, and maintaining pH in the required range. If the pH drops momentarily, nitrogen trichloride, a malodorous gas, is formed, and lowering the pH will not correct the problem. If the pH goes above 8, the breakpoint reaction will occur, albeit very slowly.

Ion Exchange. Normal process control for zeolite ion exchange includes monitoring influent quality, monitoring effluent quality, maintaining a high-pH regenerant, and maintaining bed backwashing frequency and duration to minimize scaling in the zeolite beds and related process equipment. The influent may need to be prefiltered to avoid fouling the zeolite. Lime slurry makeup feed will be needed to maintain the strength of the regenerant solution. Backwash facilities will be needed to control carbonate deposits in the zeolite beds and related equipment.

Ammonia Stripping. Normal process controls for ammonia stripping should ensure that

- The wastewater's pH remains above 11 and
- Large volumes of air flow through the stripper to maximize ammonia removal.

Data Collection. *Breakpoint Chlorination.* Normal data collection is similar to that for most chlorination systems, with an emphasis on pH. Monitoring influent and effluent nitrogen levels is important to determine removal efficiency and demonstrate compliance with permit limits.

Ion Exchange. Data collection requirements for ion exchange depend on local regulatory requirements for ammonia removal. Online monitoring of regenerant pH will also be required, along with periodic grab samples to validate the online pH measurement.

Ammonia Stripping. Data collection requirements for ammonia stripping depend on local regulatory requirements for ammonia removal. Also, pH monitoring, typically via online monitoring with periodic grab samples to validate the online measurement, may be required.

Planned Maintenance Program. *Breakpoint Chlorination.* Because the equipment used for breakpoint chlorination is similar to chlorination and other chemical feed systems, its maintenance program should be based on those for such systems.

Ion Exchange. Planned maintenance for ion exchange beds mostly involves such equipment as fans, centrifugal pumps, and chemical feed equipment (see other chapters of this book for maintenance guidance). Flow, pH, and ammonia monitoring devices should be checked routinely and calibrated periodically based on the manufacturer's recommendations.

Ammonia Stripping. Planned maintenance for ammonia strippers mostly involves such equipment as blowers, fans, centrifugal pumps, and chemical feed equipment (see other chapters of this book for maintenance guidance). Also, the ammonia stripper's packing may need periodic cleaning if scale buildup is a major issue.

Troubleshooting. *Breakpoint Chlorination.* Most troubleshooting issues related to chlorination (see Chapter 26) may also apply to breakpoint chlorination. In addition, the alkaline feed unit should be closely monitored. The chlorine, alkali, and wastewater should be completely mixed to avoid low-pH areas, where nitrogen trichloride can be produced.

Ion Exchange. Below are some ion-exchange issues to be aware of, and possible solutions:

- Regeneration with lime slurry alone can be a slow process. The regeneration rate can be increased by adding salt (sodium chloride) to the regenerant solution.
- The high-pH regenerant can cause calcium carbonate deposits to form in the zeolite exchange bed, the stripping tower, and the piping and appurtenances. Violent backwashing may be required to remove these deposits, although this should be balanced with the need to minimize media loss during backwashing.

Ammonia Stripping. Below are some ammonia-stripping issues to be aware of, and possible solutions:

- Scaling. Tower packing is susceptible to calcium carbonate deposits. Countercurrent towers are less prone to this problem. Also, the packing media should be selected so operators can access the media and clean scaling deposits.

- Poor to no cold-weather operations. Air temperatures are critical to operations. The strippers might have to be enclosed if ice forms within the towers when air temperatures are below 0 °C (32 °F).
- Air flows. Required air–water ratios can range from 2200:1 to 3800:1 (WEF, 1998).

PHOSPHORUS AND ENHANCED SUSPENDED SOLIDS REMOVAL.

To reduce the eutrophication rate in receiving waters, many dischargers are required to reduce effluent phosphorus concentrations. (Phosphorus is often the growth-limiting nutrient for algae in fresh surface water.) Although biological nutrient-removal processes can significantly reduce phosphorus concentrations, chemical phosphorus-removal systems remain common. Some plants may use a combination of biological and chemical processes (e.g., the Phostrip process) to achieve an effluent total phosphorus concentration of less than 1 mg/L.

Enhanced suspended solids removal processes are essentially identical to chemical phosphorus removal systems. These processes typically include coagulation, flocculation, sedimentation, and filtration.

Fundamentals of the Process. The most common coagulants are lime, alum, and ferric chloride.

Chemical Coagulation for Enhanced Solids Removal. When alum is added to water, it reacts with bicarbonate alkalinity to form insoluble aluminum hydroxide, which is a gelatinous floc that sweeps out suspended particles as it settles in a sedimentation basin or is removed via filtration.

$$3Ca(HCO_3)_2 + Al_2(SO_4)_3 \cdot 14H_2O \Rightarrow 2Al(OH)_3 + 3CaSO_4 + 6CO_2 + 14H_2O \qquad (24.12)$$

Similarly, ferric chloride forms insoluble ferric hydroxide, which traps suspended solids and removes them as it settles in sedimentation basins or is removed by filters.

$$2FeCl_3 + 3Ca(HCO_3)_2 \Rightarrow 2Fe(OH)_3 + 3CaCl_2 + 6CO_2 \qquad (24.13)$$

Chemical Coagulation for Phosphorus Removal. Lime reacts with orthophosphate in wastewater to precipitate hydroxyapatite as follows:

$$5Ca^{2+} + 4OH^- + 3HPO_4^- \Rightarrow Ca_5OH(PO_4)_3 + 3H_2O \qquad (24.14)$$

Lime-addition facilities for phosphorus removal are expensive, so they are less common than alum or ferric chloride addition.

The generalized phosphorus-removal reactions involving alum and ferric chloride are as follows:

$$Al^{3+} + H_nPO_4^{-3+n} \Leftrightarrow AlPO_4 + nH^+ \quad (24.15)$$

and

$$Fe^{3+} + H_nPO_4^{-3+n} \Leftrightarrow FePO_4 + nH^+ \quad (24.16)$$

Again, the resulting precipitates may be removed via settling in a sedimentation basin, with effluent filtration as a possible polishing step.

Metal salts (e.g., alum and ferric chloride) will typically consume alkalinity and lower pH if sufficient alkalinity is not naturally present in the water. Supplemental alkalinity (e.g., sodium hydroxide) may be required to keep the pH in the 5 to 7 range to meet biological treatment requirements. More alkalinity may be needed to meet effluent pH limits. As a general rule, approximately 0.5 mg/L of alkalinity is required to react with each 1 mg/L of alum, and approximately 1.0 mg/L of alkalinity is required to react with each 1 mg/L of ferric chloride.

Description of Process and Process Equipment. Various precipitation schemes exist for chemical phosphorus removal (Figure 24.20). In pre-precipitation, chemicals are added to the primary influent, and the resulting precipitates are removed with the primary sludge. In co-precipitation (simultaneous precipitation), chemicals are added to the primary effluent, the mixed liquor (in the aeration basin of an activated sludge process), or before secondary clarification, and the resulting precipitates are removed with the waste activated sludge. In post-precipitation, chemicals are added to the secondary clarifier effluent, and the resulting precipitates are removed in additional clarifiers or via filtration.

Chemical phosphorus removal equipment primarily includes units for storing and feeding the selected chemicals.

Process Control Systems. Process control systems typically focus on the ability to maintain adequate coagulant doses. Ideally, an automated control system would dose the chemicals in response to variations in flows and phosphorus loading. In practice, chemical dosing systems are flow paced (based on influent) if influent phosphorus levels are relatively constant, or they anticipate peak phosphorus loads to avoid permit violations. If jar testing is used to determine chemical doses, the emphasis should be on determining a range of doses that will accommodate the expected variations in flows and phosphorus loading.

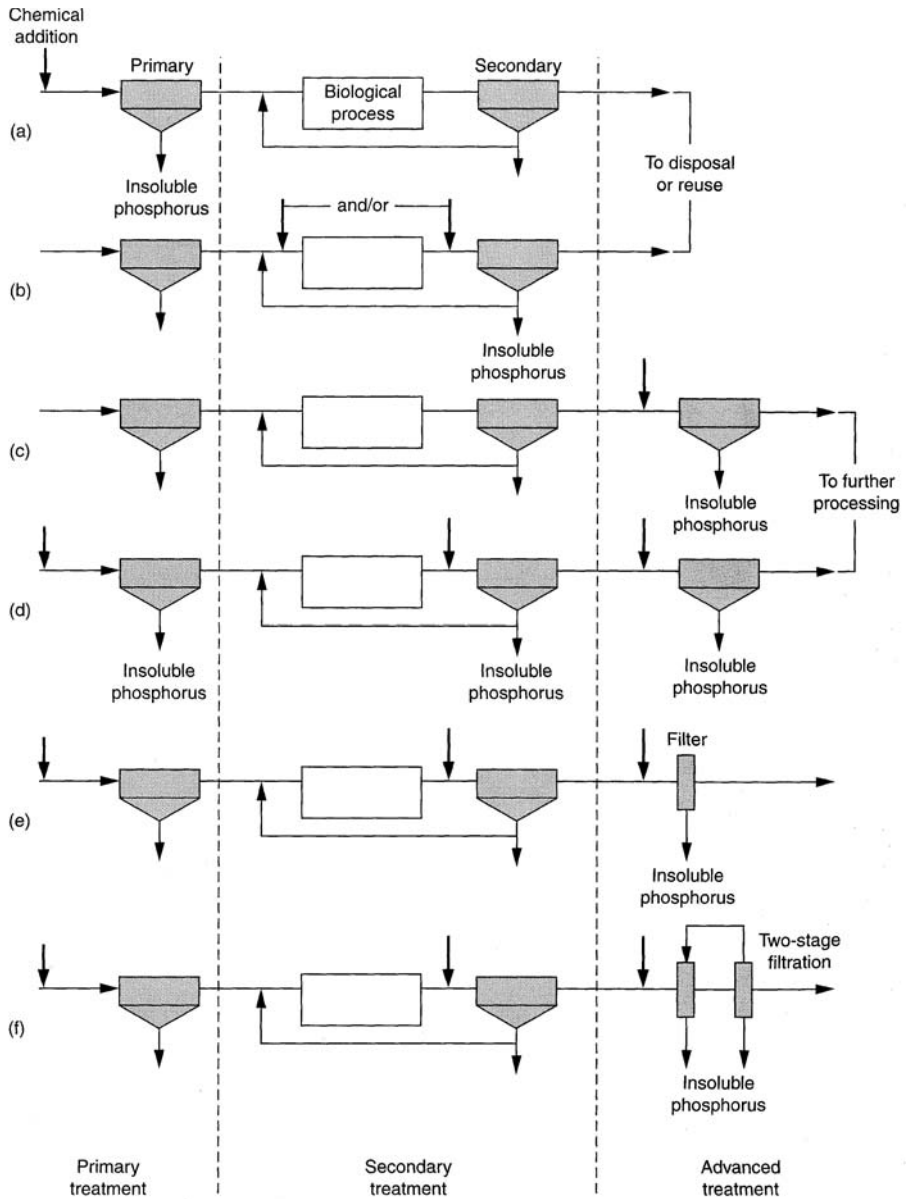


FIGURE 24.20 Possible chemical-addition points for phosphorus removal: (a) before primary sedimentation, (b) before and/or after biological treatment, (c) after secondary treatment, and (d–f) at several locations (known as "split treatment") (Metcalf & Eddy, 2003).

Wastewater pH can be measured using online pH measurement systems. A simple feedback loop using the online pH values can then be used to dose caustic or other forms of supplemental alkalinity to replace that consumed by metal salt addition.

Normal Process Control. A common process control practice is to set the doses of coagulant, polymer, and supplemental alkalinity based on historical operating data. In practice, the feed rates are set higher than anticipated to account for variations in the phosphorus load and avoid permit violations at peak conditions. A typical, though not necessarily recommended, mode of operation is to overdose coagulants at average influent concentrations so adequate coagulant concentrations are available at peak influent phosphorus loads.

Data Collection. Data collection and analysis requirements for chemical phosphorus removal will reflect local regulatory requirements for phosphorus removal. Also, pH monitoring, typically online monitoring with periodic grab samples to validate the online measurement, may be required to monitor the process and provide feedback control for any supplemental alkali.

Planned Maintenance Program. Planned maintenance for chemical phosphorus removal mostly involves typical maintenance procedures for such equipment as chemical storage tanks, mixing equipment, centrifugal pumps, and chemical feed equipment, which are discussed in other chapters of this book. Flow, pH, and phosphorus monitoring devices should be checked routinely and calibrated periodically based on the manufacturer's recommendations.

Troubleshooting. Chemical phosphorus removal processes typically include coagulation, flocculation, sedimentation (precipitation), and (possibly) filtration. Troubleshooting guidelines for these processes are provided throughout this chapter.

Regardless of the chemical dosing point or whether alum or ferric chloride is the primary coagulant, provisions should exist for adding polymer (generally an anionic polymer) to help flocculate solids. If flocculation is inadequate, pin floc can develop and result in phosphorus carryover from the primary or secondary clarifier.

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Chapter 25

Process Performance Improvements

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INTRODUCTION, PURPOSE, BACKGROUND, AND CHAPTER ORGANIZATION

INTRODUCTION. Wastewater treatment plants (WWTPs) represent significant capital investments and operational costs for municipalities and industries. Increasingly stringent discharge standards, and the demands for higher treatment capacity caused by population growth, are resulting in demands for further expansion of existing facilities. In many instances, the most cost-effective approach to facility upgrade is not expansion, but process performance improvement. Even if some treatment units must be upgraded and/or expanded, the magnitude of the upgrade/expansion can be optimized with process performance improvements.

A process performance improvement project may be driven by the following:

- Limited plant capacity—Implementation of plant performance evaluation methodologies have, in many cases, shown plant capacities greater than their nominal (design) capacity. In these cases, evaluation of the actual capacity may avoid or delay plant expansion. In other cases, remedial measures (process performance improvements) can be identified during the analysis, resulting in more cost-effective capacity improvements.
- New effluent requirements—Plants facing new effluent requirements may achieve them without plant expansion through the use of a long list of methodologies for process performance improvement (e.g., bioaugmentation, online monitoring and advanced process control, addition of media for attached growth, introduction of baffles to improve clarifier or bioreactor performance, and chemical addition for settling enhancement, among many others).

- Cost-saving opportunities—A large fraction of a plant's operating costs are related to energy consumption and chemical use. Process performance improvements have shown to reduce these costs with excellent payback periods. Online control of chemical addition, pacing it to effluent quality targets, and automatic dissolved oxygen control in aeration basins are good examples of commonly used performance improvements that generate cost savings while improving effluent quality.

PURPOSE. The purpose of this chapter is to present evaluation technologies to determine actual unit process capacities and to assess process bottlenecks, introducing process performance improvement options. The chapter focuses on a set of methodologies that have been successfully used to evaluate and achieve process performance improvements in WWTPs. Specific plant testing and evaluation methodologies that can be used to define plant capacity and assess plant optimization approaches are described.

BACKGROUND. Considerable experience exists in process performance improvement at existing municipal WWTPs in North America. One evaluation and optimization approach that has been demonstrated in the United States and Canada is the Composite Correction Program (CCP). The CCP was developed by the U.S. Environmental Protection Agency (U.S. EPA) to identify and resolve factors that limit the performance of municipal WWTPs. The CCP uses a two-step program to identify the unique combination of factors contributing to noncompliance with effluent criteria and to implement on-site technical assistance and training to bring the plant back into compliance (Ontario Ministry of the Environment et al., 1995). The background, rationale, approach, and costs of conducting CCPs and other similar optimization programs are well-documented (Ontario Ministry of the Environment et al., 1995).

In addition to CCP, numerous process performance evaluation technologies have been successfully used to assess the actual capacity of WWTPs, evaluate their performance, and investigate means of optimizing WWTP processes (Ontario Ministry of the Environment, 1996). The following are some of the most commonly applied technologies:

- Online monitoring—use of a computer and online instrumentation to measure and record "real time" data and identify dynamic interactions between various treatment components.
- Aeration efficiency analysis—measurement of "dirty water" and "clean water" oxygen transfer efficiencies for aeration systems.
- Stress testing—evaluation of unit process ultimate capacity by inducing high loads (both hydraulic and organic) and measuring system performance.

- Clarifier flow pattern analysis—dye tracer analysis to determine flow patterns and short-circuiting within a clarifier.
- Hydraulics analysis—evaluation of overall plant hydraulics by field measurements and hydraulic modeling.
- Digester residence time distribution and mixing evaluation—tracer analysis of digesters to identify mixing efficiencies, short-circuiting patterns, and digester dead spaces.

CHAPTER ORGANIZATION. This chapter first discusses the steps of process performance improvement. An important relevant topic, flow meter accuracy, is also discussed. Next, tools used to define the process performance of the existing facility are presented. These include hydraulic capacity analysis, tracer testing, and aeration system analysis. A section then follows on chemical addition. Chemical selection steps are detailed along with examples of process performance improvements. Next, a section on bioaugmentation is presented. Appendixes are included to fully explain flow meters; an aeration system analysis is presented along with a tracer case history.

STEPS OF PROCESS PERFORMANCE IMPROVEMENT

Figure 25.1 presents a simplified outline of the steps involved in process performance improvement. Figure 25.2 represents a more detailed diagram showing 18 tasks associated with process performance improvement.

Objective
Resources required to achieve the Objective
Schedule
Capabilities of existing facility
    Process Layout
    Data Collection
    Data Analysis
    Process Capacity Diagram
Reassess objective
    Modify resources
        Budget
        Schedule
        Data collection
        Data Analysis
Perform additional work to further define plant capability
Develop Projects to attain desired results

FIGURE 25.1 Simplified outline of the steps involved in process performance improvement.

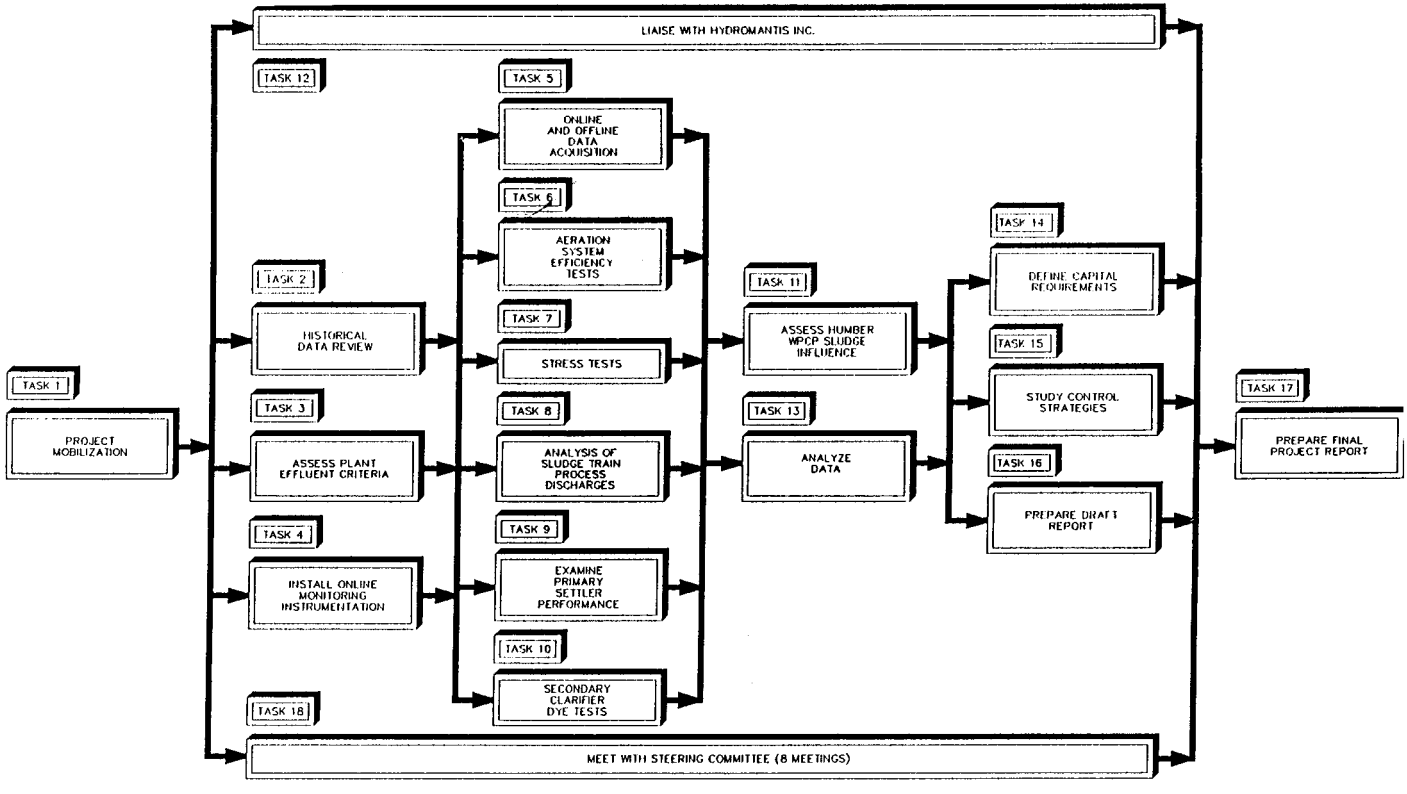


FIGURE 25.2 Typical task flows.

It is important to note that before implementing and even proposing process performance improvements, an evaluation of process performance should be carried out at the facility. In fact, the majority of work in a process performance improvement project is establishing performance baselines. In other words, what are the capabilities of your existing facility?

OBJECTIVES. The objectives of a process performance improvement project must be clearly established by proponents of the work to set realistic project targets, budgets, and schedules, and to ensure that the required work can be completed effectively. If a formal objective and work plan cannot be developed by the proponent alone, then advice should be obtained from the regulatory authority or other funding agency to ensure that project evaluation, implementation conditions, and conclusions will be acceptable to the parties involved. The scope of the investigation should be clearly identified prior to project bidding, quotation, or initiation based on the owner's or regulator's needs.

RESOURCES—LABOR AND EQUIPMENT. In general, the process performance evaluation team will include the plant owner and the process performance improvement provider. Often, the regulatory agency and funding partners are part of an overall project steering committee. Actual tests require the support of plant operators, technologists, and engineers to complete the field work, assess the results, and document the findings. The use of temporary online field instrumentation requires continuing technical support to maintain its calibration and accuracy.

A trained and experienced field technologist is generally required on a full-time basis for process performance evaluation activities. These activities may extend from a few days for a single short-term test to several months for a complete plant process performance evaluation involving online instrumentation and stress testing in different seasons. The duration of the test work has a significant bearing on the level of effort expended and the cost.

Installation of field equipment may require additional staff to assist the field technologist as well as in-kind assistance from plant staff, including operators and maintenance staff. Additional plant support may be required during testing, such as

- General staff assistance during test for installation and start-up,
- Plant process adjustments during a test, and
- Laboratory analytical and daily sampling.

With online instrumentation, trained staff who are familiar with the instrumentation are essential to ensure that adequate results are obtained. In many cases, plant staff

will not posses the resources themselves to provide this service on a sustained basis; external assistance will be needed.

SCHEDULE. The schedule is a function of the objective. For example, a project may have been initiated by regulators who have specified a timeframe for completion. A schedule must also factor in staff and consultant availability, lead time for the procurement and installation of specialized equipment, and the time required to acquire other specialized services (i.e., laboratory, maintenance, and hydraulic modeling).

Proper scheduling is required to phase process tests and to meet the needs of the operations and laboratory staff in the plant. An overall approach with all the parties concerned, including the plant operating staff, should be agreed upon during project initiation.

Many project tasks will be phased to allow for examination of plants on a step-by-step basis. For example, it is common practice to complete a review of plant design, historical performance, and operational data early in a project to obtain a good understanding of plant operating conditions.

CAPABILITIES OF EXISTING FACILITY. As mentioned previously, understanding the capability of the existing facility must come before contemplating process performance improvements. To understand your facility, a process layout should be constructed and historical data collected. Collected data will require analysis. Later in this chapter, several tools will be presented to assist in defining the existing process capabilities.

Process Layout. Plant information collected must be sufficiently detailed to develop an accurate process flow schematic that identifies the following:

- Unit processes, including number, configuration, and operational flexibility;
- Current sampling locations;
- Location of existing instrumentation (e.g., flow meters and dissolved oxygen meters);
- Internal recycle streams (e.g., digester supernatant); and
- Points of chemical addition (e.g., chlorine for effluent disinfection and metals salts/lime for phosphorus removal).

Key equipment such as mechanical surface aerators, aeration blowers, and pumps must be itemized. Comprehensive performance evaluation checklists (U.S. EPA, 2002) may assist with collection of the required process flow and equipment details.

Data Collection and Analysis. Historical data review is an essential component of a process performance improvement project. It provides the opportunity to become familiar with the operation and performance of the wastewater treatment facility. The general objectives of the historical data review are to

- Determine historical unit process loading condition and performance,
- Identify factors that may limit plant performance, and
- Provide information for planning other process performance improvement tasks.

Data Collection Methodology. Following the kick-off of a project, historical plant performance and operational data should be collected. Previous reports and planning information may also be collected to provide supporting information on plant performance as well as possible expansion requirements. Historical data are generally transferred to an electronic format to facilitate the statistical analysis of the data, including graphical presentation in terms of probability distributions, time trends, or scatter diagrams.

To identify plant flow increases/decreases and possible seasonal flow variations, average and maximum daily plant flow records for a 10-year period are reviewed in conjunction with rainfall data, if available. Long-term historical flow records are especially pertinent if the plant is approaching its rated hydraulic capacity or if severe flow impacts have been identified. Historical plant performance data, including influent, primary effluent, and final effluent concentration data, are reviewed for a 5-year period to identify recent trends in influent wastewater characteristics and to assess recent performance history and compare it to effluent objectives and/or expansion needs. Available operations data for a 1- to 2-year period are collected and analyzed to provide a complete understanding of the plant performance and condition. Detailed operational information is also used to determine unit process loading rates, operational parameters (i.e., food-to-microorganism [F:M] ratio and solids retention time [SRT]), and a solids mass balance.

Data Analysis and Process Loadings. Using historical data, loading rates and operational parameters for each unit process are determined and compared to typical design and performance criteria. An example of common unit process loading and operational parameters determined in a historical data review of a conventional activated sludge plant is presented in Table 25.1. Available literature should be consulted to obtain reference values for the specific analysis parameters of the unit processes at similar types of facilities (Metcalf & Eddy, 1991).

TABLE 25.1 Common unit process loading and operational parameters.

Unit Process Parameters	Typical Units[a]
Influent	
Minimum plant flow	mgd
Average plant flow	mgd
Maximum day	mgd
Plant bypass flow	mgd
Per capita flowrate	gpd/cap
Parameter concentrations	mg/L
Parameter loading rates	lb/d
Aerated grit tank	
Detention time	minutes
Air supply	cfm
Surface and tank floor velocity	ft/sec
Quantity of grit removed	cu ft or cu yd
Primary clarification	
Surface overflow rate	gpd/sq ft
Parameter removals	percent
Weir overflow rate	gpd/lin ft
Tank depth	ft
Aeration	
Hydraulic retention time	hours
SRT	days
Organic loading rate	lb/d/cu ft
F:M ratio	days
Return sludge rate	percent
Power input of aeration	hp/cu ft
Mixed-liquor suspended solids/ mixed-liquor volatile suspended solids concentration	mg/L
Biological yield	lb volatile suspended solids/lb biochemical oxygen demand removed
Chemical addition for phosphorus removal	
Addition rate	lb/d
Dosage rate	mg/L
Secondary clarification	
Surface overflow rate	gpd/sq ft
Solids loading rate	lb/d/sq ft
Sludge volume index	mL/g
Tank depth	ft
Weir loading rate	gpd/lin ft
Return activated sludge/waste activated sludge flowrates	mgd

TABLE 25.1 Common unit process loading and operational parameters (*continued*).

Unit Process Parameters	Typical Units[a]
Final effluent	
Parameter concentrations	mg/L
Parameter loading rates	lb/d
Parameter removals	percent
Dissolved air flotation	
Solids loading rate	lb/d/sq ft
Hydraulic loading rate	gpd/sq ft
Air:solids ratio	cu ft/lb
Chemical addition	lb/d
Recycle ratio	percent
Anaerobic digestion	
Hydraulic retention time	days
Volatile solids loading rate	lb/d/cu ft
Temperature	°F
pH	pH units
Volatile acid concentration	mg/L
Alkalinity	mg/L as $CaCO_3$
Power input	horsepower
Solids concentration	percent
Volatile solids destruction	percent
Sludge production mass per unit flow	lb/mgd
Gas production rate	cu ft/d
Effluent disinfection	
Chlorine dosage rate	mg/L
Chlorine residual concentration	mg/L
Contact time at peak flow	minutes
Fecal coliform or *E. coli* concentration	number/100 mL

[a]See *Conversion Factors* chapter for equivalent SI units.

Data analysis and process loadings must include the impact of solids train recycles. Such streams may limit aeration capacity and prevent primary clarifiers from performing as expected (Newbigging et al., 1995; Nolasco et al., 1994a).

Solids recycle streams at a WWTP may include

- Supernatant from anaerobic digesters,
- Decant or supernatant from sludge conditioning and/or incineration processes,
- Centrate from centrifuges,
- Filtrate from filter presses,
- Subnatant from dissolved air flotation units, and
- Waste activated sludge that is co-thickened in the primary clarifiers.

Solids recycle streams can increase the organic loading to the liquid train by 5 to 50%, depending on the type and number of solids treatment processes used.

Solids mass balances across unit processes (e.g., clarifiers) and for the activated sludge process should be completed as part of the unit process analysis.

Solids mass balances (accumulation = solids in − solids out) account for solids within the treatment process and generally will not close exactly. A discrepancy of less than approximately 10 to 15% is considered acceptable. Discrepancies of more than 10 to 15% should be an indication that further assessment is required to resolve the cause of the inconsistency. Although it is possible to complete mass balances for other parameters (e.g., phosphorus), only solids information is typically available for each process stream.

An example of a solids mass balance for a secondary clarifier is provided as follows:

$$\text{Accumulation} = \text{Solids in} - \text{Solids out} \tag{25.1}$$

If the accumulation = 0 (assuming there is no increase/decrease in the sludge blanket inventory), then

$$\text{Solids in} = \text{Solids out} \tag{25.2}$$

where

Solids in = mixed liquor suspended solids concentration × (flow + return flow) and

Solids out = (effluent suspended solids concentration × flow) + [return concentration (return flow + waste flow)]

Some of the most common sources of error in a solids mass balance are

- Nonrepresentative samples (analytical accuracy and sampling techniques);
- Inaccurate flow monitoring;
- Impact of periodic recycle streams (the boundaries of the balance must be clearly defined and all inputs/outputs of the defined boundaries must be accounted for in the mass balance);
- Assumptions made concerning accumulations; and
- Time differences between sampling.

Process Capacity Diagram. Information from the data analysis and process loadings will be used to create a process capacity diagram (Figure 25.3). This process capacity

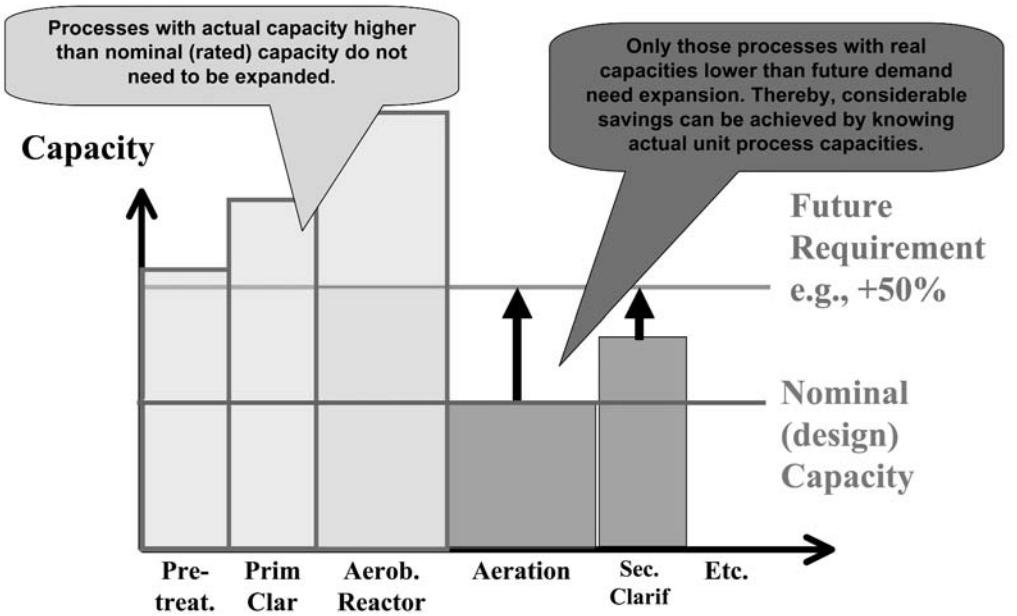


FIGURE 25.3 Unit process capacity.

picture of the facility highlights process bottlenecks and reveals differences between nominal (design) unit process capacities and actual capacities determined during process evaluation. When compared to the new or desired process capacity, this diagram can be useful to stage and program process performance improvements.

REASSESS. A detailed review of data may identify key areas where additional information is required to complete the plant performance assessment or point to potential process bottlenecks that may be further explored during the process performance improvement. After completing an historical data review, it may be necessary to reassess project objectives and/or prioritize subsequent process performance improvement tasks. This may change scope, budget, and schedules associated with the effort.

Examples of the impact of historical data review findings on subsequent process performance improvement tasks are provided in Table 25.2.

FLOW METER ACCURACY

Prior to presenting additional tools to assist in analyzing the existing plant's process performance, a discussion regarding flow meter accuracy is warranted. The success of

TABLE 25.2 Historical data review findings and derived process performance improvement tasks.

Historical Data Review Finding	Process Performance Improvement Tasks
Mass balance does not close within 15%	Assess flow metering accuracy and/or review offline sampling and analysis methods
Effluent biochemical oxygen demands and/or nitrogenous compounds' concentrations exceed criteria	Conduct aeration capacity tests
Return stream flows/concentrations not available	Include sampling of recycle streams in offline monitoring program
Clarifier loading rates less than design values	Conduct stress tests to determine capacity limits

any process improvement program is based on accurate information. Flow data is central to this effort.

Accurate flow measurement is essential for the efficient operation of a wastewater treatment facility. Accurate flow measurement is required by

- Regulatory agencies, to evaluate loadings to receiving waterbodies;
- Municipal authorities, to determine plant capacity status and project future expansion requirements;
- Operation staff, to control and optimize the treatment processes; and
- Plant administration, for billing purposes.

In addition, accurate flow metering is essential to evaluate actual treatment performance and ultimate plant capacity.

Because flow meters are central to evaluating process performance, background information on them has been included in Appendix A. Steps to ensure flow meter accuracy are covered in this section.

FIELD CALIBRATION. The overall accuracy of flow metering equipment can be determined using dye testing, fill-and-draw tests, redundant instrumentation, and hydraulic modeling.

Dye Testing Techniques. The dye dilution technique is a non-intrusive test that produces absolute measurements to accuracies of 2%. The procedure requires considerable care in set up and selection of sampling equipment and materials.

The procedure consists of injecting a tracer material at a constant and known rate upstream of the flow meter, and determining the concentration of the tracer in samples collected downstream. Complete mixing is required between the injection and sample collection points to ensure accurate results.

Suitable tracer material includes fluorescent dyes such as Rhodamine WT. The accuracy of the calibration is determined by the accuracy and precision of the tracer preparation and injection procedures, the degree of mixing achieved between the injection and sample collection point, and the accuracy of the analytical method used to determine the downstream concentration. General procedures for conducting tracer dye studies using Rhodamine WT dye are discussed by Crosby (1987).

Fill-and-Draw Test. The simplest and most reliable method of checking flow meter accuracy is a fill-and-draw test. The test involves drawing down the liquid level in a basin or tank and filling it back up while recording the meter reading.

To perform a fill-and-draw test, a method for measuring changes in water surface elevation and a means of recording the flow meter reading during the test are required. Measurement can be done either during drawdown, if the flow meter is on a pipe downstream of the tank, or during fill, if the flow meter is on a pipe upstream of the tank. Sufficient drawdown is required for accuracy (at least 0.3 m [1 ft] is preferred).

If possible, the test should be repeated at several flowrates (preferably three) to check accuracy over the potential operating range. The actual flowrate is calculated by dividing the volume of tank filled or drawn down by the length of the test period. The measured flow is then compared to the flow meter output.

Redundant Instrumentation. Many wastewater treatment facilities measure flow in more than one location. For example, some facilities have raw influent flow meter(s) plus flow meter(s) on each parallel process stream, as well as effluent flow meter(s).

Flow measurements from a redundant meter can be used to calibrate a suspected meter over a range of flows. The procedure involves

- Obtaining a series of measurements over time (e.g., at time intervals of approximately 1 minute) from both meters;
- Evaluating recorded flows to determine the time required for the hydraulic perturbations to travel between the meters; and
- Performing a statistical analysis of time-delay corrected flows from both meters to determine the best-fit equation for calibration of the suspected meter.

Alternatively, a portable flow meter, such as a “strap-on” Doppler meter for full pipe flow measurement or a velocity-area meter for open-channel flow, can be used to

calibrate a permanent installation. This method of calibrating a suspect meter relies on the accuracy of the redundant meter. Therefore, it should be used with caution and only when the aforementioned methods are not available.

Hydraulic Modeling. Hydraulic modeling techniques can be used to develop the head versus flow relationship for nonstandard flume and weir installations. Marsalek (1991) presents a detailed description of the application of hydraulic modeling based on similarity theory and scale model development to the analysis of a nonstandard flow measurement structure.

TESTING AND ANALYSIS TOOLS

The following three sections ("Hydraulic Capacity Analysis," "Tracer Testing," and "Aeration System Analysis") provide tools or analysis techniques that are used to better understand the existing process.

HYDRAULIC CAPACITY ANALYSIS. Plant hydraulics is a major focus in process performance improvement programs. Plant capacity and flexibility are a function of its hydraulic and flow distribution characteristics. Hydraulic capacity analysis will identify capacity exceedance indicators, bottlenecks, and flow splitting imbalances. Hydraulic modeling techniques are normally used to perform hydraulic capacity analysis.

Hydraulic Capacity—General. The hydraulic capacity of an existing WWTP is defined as the ability of the facility to pass flow through the unit processes in a controlled manner. It is one of the defining factors governing the capacity of existing facilities as well as the performance of treatment works under high loading conditions.

Hydraulic capacity is determined by structure elevations, hydraulic control section elevations, channel arrangements, pump capacity, and pipe and fitting sizes (it is important to note that changes brought about by construction and upgrades can modify the hydraulic capacity of the facility).

Most WWTPs are constructed as a series of parallel unit processes, interconnecting channels, and pumped recycle flows. As a method of reducing both operating and capital costs, gravity flow and passive flow splitting techniques are used as much as possible. Flow distribution between parallel unit processes is accomplished through overflow structures, flow control gates, and control valves. Flow distribution between parallel unit processes is often difficult to measure and control over the range of hydraulic loading experienced at a plant. Loss of control leads to flow imbalances between parallel unit processes and the inefficient use of available resources.

Capacity Exceedance Indicators. Performing a hydraulic capacity analysis entails the identification of capacity exceedance indicators. These indicators are site-specific and include one or more of the following items:

- Hydraulic grade line (HGL) exceeds the set point elevation in a bypass structure resulting in unintentional bypass;
- The HGL in an open-channel section exceeds the minimum allowable freeboard requirements (or top of concrete elevations), resulting in splashing and overflow out of the structure;
- The HGL downstream of a flume or weir structure exceeds the critical depth in the throat section, resulting in the loss of accurate flow measurement;
- The HGL downstream of a flow distribution weir exceeds the weir elevation, resulting in a loss of control over the flow distribution between parallel unit processes; and
- The HGL in the launder sections exceeds the overflow weir elevations, resulting in a loss of control over the flow distribution between parallel unit processes.

Exceedance indicators are best determined with a hydraulic model. Using the model, flow can be increased in increments until the model shows that one or more of the hydraulic exceedance indicators have been reached.

Hydraulic Bottlenecks. A hydraulic bottleneck is defined as a hydraulic element that limits the hydraulic capacity of an existing WWTP. Hydraulic bottlenecks are identified during capacity analysis by determining the difference between the upstream and downstream HGL (calculated headloss) for each element. Elements with relatively high headloss will limit the hydraulic capacity of the existing facilities.

Common hydraulic bottlenecks include

- Process tank inlet structures,
- Sudden and multiple changes in channel cross-section and direction,
- Inappropriately sized flow control structures, and
- Flow measurement and distribution structures.

A calibrated hydraulic model can be used to investigate methods of reducing the hydraulic bottlenecks that are identified. The effects of modifications to channel cross-sections, weir elevations, and control sections are evaluated by changing the hydraulic elements in the model and evaluating the performance under high hydraulic loading conditions.

Flow Splitting Imbalances. Flow distribution between parallel unit processes is often difficult to measure and adequately control over the range of hydraulic loading experienced at a plant. The loss of control leads to flow imbalances between parallel unit processes and the inefficient use of available resources. Hydraulic modeling techniques are used to estimate the flow distribution between parallel unit processes under a variety of hydraulic loading conditions. A calibrated model is used to investigate alternative strategies for improving flow distribution.

Use of Hydraulic Modeling Techniques. Hydraulic modeling is an important component of a process performance evaluation and improvement project. Hydraulic modeling entails three main steps:

- Development of the mathematical model,
- Calibration, and
- Manipulation of the model to predict performance.

The general steps for preparation of a hydraulic model are as follows:

1. Preparation of a plant flow schematic, including recycle flows, flow splits between parallel tanks, flow control structures, and bypass structures.
2. Listing of all hydraulic elements to include in the model. The number of elements included will be determined by the objectives of the study. Hydraulic elements include channels, pipes, weirs, gates, obstructions, and flow control structures.
3. Identification of theoretical equations and parameters required to model each hydraulic element, including the physical geometry and minor loss coefficients.
4. Model assembly, starting from the downstream control section (outfall weir or water surface elevation in the receiving water).
5. Construction of the model in a modular approach using a spreadsheet, computer programming language, or commercial software package.

Once the model is constructed, field verification and calibration are required. Field verification consists of measuring the flow and water surface level (HGL) at key locations in the plant. The number of measurements required for field verification is determined by the level of detail in the model and the objectives of the study. Data requirements for field verification include water surface levels upstream and downstream of key model elements and hydraulic control structures.

Standard survey techniques are used to determine elevations of key control sections as well as top-of-concrete elevations for the hydraulic elements. During the veri-

fication survey, the water surface level is measured from the reference points established during the standard control survey. Important considerations during field verification include

- Calibration of permanent flow metering devices prior to field model verification;
- Measurement of all flow streams, including the recycle streams; and
- Determination of flow distribution between parallel units.

The model should be calibrated at a minimum of two flowrates:

- Current dry weather flow and
- Maximum (attainable) flow.

Once calibrated, the model is used to predict performance under various flow conditions. The model will provide the operator important information regarding

- Maximum plant throughput,
- Hydraulic limitations and bottlenecks, and
- Existing flow imbalances.

Designers can use information generated from the model to maximize hydraulic capacity, eliminate hydraulic limitations and bottlenecks, and correct flow imbalances (Daigger, 1998; Ontario Ministry of the Environment et al., 1995; WEF, 2005; WERF, 1999).

TRACER TESTING. From hydraulic capacity, analysis provides the operator with an understanding of the plants hydraulic limitations and can identify opportunities for process improvement. Another hydraulic tool, tracer studies, provides additional information helpful to the performance improvement program.

Tracer test techniques evaluate the hydraulic characteristics of unit process tanks. Test results serve to indicate hydraulic short-circuiting, determine existing mixing regimes, locate dead zones within the fluid volume, evaluate enhancements using baffling arrangements, and identify predominant flow patterns within the unit process (Ontario Ministry of the Environment, 1996; WERF, 1998).

Tracer testing techniques can be used to evaluate the following unit processes:

- Aerated grit chambers, to identify hydraulic short-circuiting and locate dead zones;
- Primary and secondary settling tanks, to identify hydraulic short-circuiting and locate dead zones, identify density currents and sludge blanket carryover prob-

lems, evaluate baffling arrangements, and develop static and dynamic hydraulic models for further assessment of the basin;
- Aeration basins, to determine the predominant mixing regime (from plug flow to complete mix), identify hydraulic short-circuiting, and locate dead zones;
- Chlorine contact chamber, to determine disinfection concentration and contact time parameter, evaluate baffling arrangements, identify hydraulic short-circuiting, and locate dead zones; and
- Anaerobic digesters, to identify hydraulic short-circuiting, determine effective (active) reactor volume and dead zones, and evaluate mixing needs (a case study of digester tracer testing is presented in Appendix E).

Tracer techniques provide quantitative and qualitative evaluations of the hydraulic characteristics of unit processes. There are two basic techniques: dispersion tests and flow pattern tests.

Dispersion tests consist of injecting a slug of tracer upstream of the unit process and sampling the effluent over a period of time. This test is used to determine hydraulic retention time (HRT), estimate the degree of hydraulic short-circuiting, and determine the level of actual mixing.

A flow pattern test consists of injecting the tracer at a constant rate over a period of time upstream of the unit process and collecting samples at different locations and depths through the body of the unit process over a short period of time. Flow pattern tests are used to evaluate the spatial distribution of flow through the unit process, including the location of dead zones, density currents, and the effect of baffle arrangements.

A complete description of the various methodologies for tracer testing unit processes can be found in *Guidance Manual for Sewage Treatment Plant Process Audits* (Ontario Ministry of the Environment, 1996).

AERATION SYSTEM ANALYSIS. The transfer of oxygen to wastewater is one of the most fundamental and costly processes in aerobic biological wastewater treatment systems. Benchmarking studies performed in the United States and Canada indicate that power costs represent approximately 20% of the operating cost of a wastewater treatment facility (WERF, 1998). Out of total plant energy consumption, the energy spent in aeration represents close to 60%. This operating cost suggests that evaluating the aeration capacity and achieving process performance improvements in the aeration system by eliminating its bottlenecks will provide a substantial payoff in a WWTP.

In this section, three analysis approaches are presented: oxygen transfer, aeration electrical efficiency, and empirical equations/modeling. This is followed by a discus-

sion of approaches to meeting oxygen demands as well as saving energy in the aeration process.

Oxygen Transfer Tests. One of the objectives of performing oxygen transfer tests is to compare the existing aeration capacity with current and future oxygen demands. Experience with conventional activated sludge plants designed for 5-day carbonaceous biochemical oxygen demand ($CBOD_5$) and total suspended solids (TSS) removal has shown that (Newbigging et al., 1999; Nolasco et al., 1994b)

- Activated sludge systems often have adequate capacity to provide nitrification without additional aeration tank volume; and
- Energy savings can be obtained by a variety of means, including retrofits of coarse-bubble diffusers to fine-pore diffusers, changes to the aeration system process configuration, and introduction of automatic dissolved oxygen control loops.

Oxygen transfer tests can be used for one or more of the following purposes:

- To determine aeration system capacity,
- To troubleshoot aeration systems,
- As part of WWTP commissioning and certification,
- To compare diffuser systems under different process conditions,
- To determine diffuser cleaning schedules and to evaluate the effectiveness of various diffuser cleaning methods,
- To evaluate changes in airflow within the aeration basin and to verify metered airflow readings, and
- To gather oxygen transfer information to be used for design of an aeration system.

Determination of the most appropriate oxygen transfer test at a given facility requires previous understanding and knowledge of

- Various oxygen transfer tests available,
- Objectives of the aeration study,
- Instrumentation and equipment required,
- Aeration system to be evaluated, and
- Costs and time involved in completing the analysis and achieving the objectives of the test.

Many factors affect the oxygen transfer efficiency of an aeration system. Key factors and examples of how they affect oxygen transfer are presented in Table 25.3.

TABLE 25.3 Factors affecting oxygen transfer (U.S. EPA, 1989).

Factor	Example of Effect on Oxygen Transfer
Equipment factors	
Diffuser type	Generally, fine-bubble diffusers have higher oxygen transfer efficiency than coarse-bubble diffusers.
Diffuser density	Under similar installation conditions, tanks with a greater number of fine-pore diffusers per unit area have higher oxygen transfer efficiency.
Diffuser submergence	As submergence increases, the oxygen transfer efficiency increases. The mass of oxygen transferred per unit of energy typically remains almost constant with submergence.
Diffuser layout	Grid patterns produce higher oxygen transfer than spiral-roll, mid-width, or cross-roll configurations.
Diffuser age	Loss of plasticity and creep, in addition to other changes in membrane materials, may cause a decrease in oxygen transfer.
Flow regime	Generally, plug flow basins have higher overall oxygen transfer efficiency than completely mixed basins.
Basin geometry	Tanks that are short and wide have less variation in the α factor and the F factor throughout the tank than tanks with high length-to-width ratios. Note: α is the ratio of the dirty water to clean water oxygen mass transfer coefficient (k_La), i.e., $\alpha = k_La$ (dirty water)/k_La (clean water) F is the diffusers fouling factor, F = k_La dirty diffuser/k_La clean diffuser
Operational Factors	
SRT/nitrification	Processes with higher SRTs have higher oxygen transfer efficiencies. Likewise, processes that are nitrifying have higher oxygen-transfer efficiencies than processes that are not nitrifying.
F:M ratio	Increases in F:M ratio cause decreases in oxygen-transfer efficiency because of potential fouling of diffusers.
Airflow rate per diffuser	As the airflow rate per diffuser increases, the oxygen transfer efficiency of most fine-bubble devices decreases. For other devices (e.g., coarse-bubble diffusers), oxygen transfer efficiency may increase, remain unchanged, or decrease with increased flow.
Mixed-liquor dissolved oxygen	As dissolved oxygen increases, actual oxygen transfer efficiency decreases.
Diffuser fouling	Fouling caused by formation of a biofilm on the diffuser surface decreases oxygen transfer efficiency.
Temperature	Temperature increases the oxygen transfer coefficient, but decreases the saturated dissolved oxygen concentration.
Elevation	Elevation affects the horsepower consumption and oxygen saturation concentration.
Wastewater Conditions	
Wastewater characteristics	Increases in interfering agents, such as surfactants (often associated with increases in biochemical oxygen demand), cause a decrease in oxygen transfer.

Prior to performing an oxygen transfer test, the following background information should be assembled (this information will also be helpful for subsequent data interpretation):

- Diffuser type and pattern (e.g., coarse-bubble, cross-roll, surface turbines, and panels);
- Number of diffusers and blower characteristics (subsurface systems) or number and type of mechanical surface aerators and motor characteristics;
- Typical airflow rate to each basin (for subsurface systems) and reactor configuration (for all aeration systems);
- Typical dissolved oxygen concentrations;
- Aeration basin dimensions;
- Aeration basin freeboard;
- Description or sketch of the aeration basin (e.g., elevation above grade, handrails, and power access); and
- Frequency of foaming events in aeration basins (foaming can be a health hazard during an aeration test).

Techniques Used to Determine Oxygen Transfer. There are a variety of techniques used to determine oxygen transfer. The more commonly used techniques include

- Off-gas analysis,
- Hydrogen peroxide test, and
- American Society of Civil Engineers (ASCE) Clean Water Test (ASCE, 1984).

Off-Gas Analysis. Off-gas analysis measures the composition of the air entering an aeration tank and the off-gas exiting an aeration tank. By comparing the oxygen content of these two gas streams, it is possible to calculate the overall oxygen transferred to the mixed liquor (Daigger et al., 1992; Groves et al., 1990; Kayser, 1979; Nolasco et al., 1994a, 1994b; Redmon et al., 1983; U.S. EPA, 1989).

Off-gas analyses are conducted by collecting gas from under a floating hood and sending it to an analyzer circuit where the airflow rate and oxygen content are measured. Appendix B provides a detailed discussion of this test.

Hydrogen Peroxide Test. In this test, hydrogen peroxide (H_2O_2) is added to an aeration basin to elevate the dissolved oxygen level to approximately 25 mg/L. The aerators then strip the excess oxygen from the basin and reestablish an equilibrium dissolved oxygen concentration. By recording the dissolved oxygen concentration over time, a

deoxygenation curve is developed, the inverse of which corresponds to the oxygenation potential of the aerators. By fitting a theoretical curve to the field results, the overall process oxygen mass transfer coefficient ($\alpha F k_L a$) can be determined (Daigger et al., 1992; Kayser, 1979; Speirs and Stephenson, 1985). A detailed discussion of this test can be found in Appendix C.

American Society of Civil Engineers Clean Water Test. The clean water oxygen transfer test measures the rate of oxygen transfer in tap water. Because the test is performed with clean water, test results provide information on the oxygen transfer system independent of any effects of wastewater. This test can be used to

- Verify performance claims by aeration system manufacturers;
- Compare different aeration devices; and
- Observe the effects of specific factors (such as submergence) on aeration system devices in conjunction with wastewater oxygen transfer tests, to determine alpha factors.

The test is conducted by removing dissolved oxygen from the clean (tap) water in the aeration basin using sodium sulfite in conjunction with a catalyst (cobalt chloride or cobalt sulfate), then re-oxygenating. Dissolved oxygen concentrations are measured at several points throughout the aeration tank during re-oxygenation. A detailed discussion of the test appears in Appendix D.

A complete description of the ASCE Clean Water Test can be found in *Standard for Measurement of Oxygen Transfer in Clean Water* (ASCE, 1984) and U.S. EPA's *Design Chapter—Fine Pore Aeration Systems* (1989).

Aeration Electrical Efficiency. The oxygenation capacity of the aeration system is defined as the capacity to transfer oxygen to the mixed liquor per unit time (kg O_2/d).

In a process performance improvement project, the oxygenation capacity determined by field tests (i.e., available firm capacity) is generally compared to the oxygenation requirements of the plant at current and future operating conditions (i.e., system needs). Based on this comparison, the following questions can be answered:

- Can the plant meet current oxygenation requirements (i.e., oxygen demand) with the available oxygenation capacity? If not, the results may explain problems such as low dissolved oxygen conditions leading to filamentous bulking, lack of nitrification (when nitrification is required), carbonaceous removal below required limits, and so on.
- Can the plant meet future effluent requirements (e.g., complete nitrification) at current and future flowrates?

- How much additional oxygenation capacity is required to meet future (or potential) effluent requirements?
- Does the plant have oxygenation capacity in excess of the expected (design) values? If so, then how much?
- How much additional treatment capacity does the plant have?
- Can a plant expansion be postponed or minimized? For how long?

The aeration (electrical) efficiency can be defined as the mass of oxygen transferred to the mixed liquor per unit of electrical energy consumed by the system (kg O_2/kWh):

$$\text{AE [kg } O_2\text{/kWh]} = \text{Oxygen transfer [kg } O_2\text{/d]/ Active power [kW]} * 1\text{ d/24 h} \quad (25.3)$$

where the consumption is expressed as active power.

The aeration efficiency value obtained with the selected aeration test can be expressed at standard operating conditions (i.e., T = 20 °C, p = 100 kPa [1 atm], and dissolved oxygen = 0 mg/L). The standard aeration (electrical) efficiency (SAE) can be used to compare the aeration system of the plant, where the process optimization project is performed with other aeration systems. Based on this comparison, the following questions can be answered:

- Is the submergence of a surface aerator adequate?
- Are the surface aerator blades deteriorated?
- Are the results from the tests within reasonable values? If not, should the tests/calculations be repeated to confirm/reject previous results?
- Is the SAE within the expected range of efficiency for this type of aeration system?
- If the SAE is on the low end of the range, can the efficiency be improved without major retrofit? For example, in the case of fine-pore diffusers, do the diffusers need to be cleaned more often? How often do they need to be cleaned to compensate for energy costs (i.e., where is the economical operation point?)?
- How much energy savings can be expected from retrofitting the current aeration system to a more efficient one?
- Is it cost-effective to retrofit on an energy savings basis only? When or at what flowrate, and for what effluent requirements?

One of the main objectives of performing oxygen transfer tests is to obtain the information required to answer these questions.

Empirical Equations/Modeling. In some cases, the aeration capacity measurement methods described in previous sections (i.e., off-gas, H_2O_2, and clean water tests) can-

not be performed. In these cases, or when an oxygen capacity estimate is needed for comparison or confirmation of the results obtained in the field, other methods can be used at relatively low costs. Two of the most common desktop analysis techniques used to estimate oxygen transfer capacity are empirical equations and modeling (steady-state or dynamic) of the aeration system.

These analysis techniques do not require major equipment preparation (with the exception of special dynamic models, where special training, software, and field calibration may be required). The background information required for field tests is also useful for desktop analysis. In addition to background information, online and offline data from the secondary treatment system are also required.

Empirical Equations. Aeration system needs are generally determined by the oxygenation requirements or oxygen demand). Oxygen demand can be determined using the following empirical equations (Boon and Chambers, 1982):

$$\text{OD} = F * Q_{\text{IN}} * (\text{CBOD}_{5,\text{IN}} - \text{CBOD}_{5,\text{SE}})\ \text{CBOD}_5 \text{ removal} \quad (25.4)$$

$$+ 0.002 * \text{MLSS} * V_{\text{AB}}\ \text{Endogenous respiration} \quad (25.5)$$

$$+ 4.3 * Q_{\text{IN}} * (\text{NH}_3\text{-N}_{\text{IN}} - \text{NH}_3\text{-N}_{\text{SE}})\ \text{Nitrification} \quad (25.6)$$

$$- 2.83 * Q_{\text{IN}} * [(\text{NH}_3\text{-N}_{\text{IN}} - \text{NH}_3\text{-N}_{\text{SE}}) - (\text{NO}_{3,\text{ SE}} - \text{NO}_{3,\text{ IN}})\ \text{Denitrification} \quad (25.7)$$

Where

OD = oxygen demand, kg O_2/d;
F = factor that is equal to 1 for nonsettled influent and 0.75 for settled influent (i.e., primary effluent);
Q_{IN} = influent wastewater flowrate, ML/d;
$\text{CBOD}_{5,\text{IN}}$ = influent carbonaceous biochemical oxygen demand, mg/L;
$\text{CBOD}_{5,\text{SE}}$ = secondary effluent carbonaceous biochemical oxygen demand, mg/L;
$\text{NH}_3\text{-N}_{\text{IN}}$ = influent total ammonia-nitrogen, mg/L;
$\text{NH}_3\text{-N}_{\text{SE}}$ = influent total Kjeldahl nitrogen, mg/L;
$\text{NO}_{3,\text{ IN}}$ = influent nitrate-N concentration, mg/L (typically zero);
$\text{NO}_{3,\text{ SE}}$ = secondary effluent nitrate-nitrogen concentration, mg/L;
MLSS = mixed-liquor suspended solids concentration, mg/L; and
V_{AB} = volume of the aeration basin being assessed, ML.

This is an empirical equation based on observations performed at various treatment plants in the United States and the United Kingdom. Under certain environmental con-

ditions in the reactor (e.g., low dissolved oxygen concentrations), denitrification reduces the overall oxygen demand of the system. Denitrification is considered as a credit in the last term of the equation.

Using online and offline information retrieved from historical data records or from a data acquisition program, the peak oxygen demand can be calculated. The peak oxygen demand calculated with the actual secondary effluent concentrations obtained during the study period will approximate the maximum rate of oxygen transferred to the mixed liquor (kg O_2/d) in that period.

For example, to obtain the future oxygen demand for complete nitrification, Q_{IN} is set equal to the future flow. To be on the conservative side, the $CBOD_5$, secondary effluent (SE), and TKN_{SE} values are set to zero and the denitrification term is eliminated.

Modeling. Dynamic simulators (e.g., BioWin [EnviroSim Associates Ltd., Flamborough, Ontario, Canada] and GPS-X [Hydromantis, Inc., Hamilton, Ontario, Canada]) can also be used to estimate current and future oxygen demands. If a calibrated model of the secondary treatment system is available, future influent characteristics can be incorporated to determine future oxygen demand.

Meeting Oxygen Demand. If current or future oxygen demand cannot be met with the current oxygenation capacity available, potential ways of increasing oxygenation capacity must be analyzed and evaluated. Typical approaches to increasing oxygenation capacity without plant expansion are

- Increasing the number of blowers in subsurface aeration systems,
- Retrofitting from coarse-bubble to fine-pore diffusers, and
- Increasing the power of drives in mechanical aerators.

Another approach is to look for ways to decrease the oxygen demand to the aeration system. Experience with WWTP optimization and debottlenecking has shown that the aeration influent characteristics can be modified and the biological reactor (aeration basin) configuration can be designed to reduce oxygen demand to the aeration system. The following process modifications can potentially reduce oxygen demand to the aeration system:

- Pre-precipitation in the primary clarifiers: Metal salts and polymers can be used to improve total suspended solids (TSS) and biochemical oxygen demand (BOD) removal in the primaries. In this way, oxygen demand to the aeration system can be reduced, thereby leading to energy savings. Moreover, the amount of precipi-

tants to be added to the primary influent can be designed to reduce BOD loadings to the aeration basins to values such that the resulting oxygen demand matches the available oxygenation capacity for higher flowrates (i.e., capacity increase). Pre-precipitation will increase the raw sludge production, reduce biological sludge production, and increase the use of chemicals.

- Retrofitting the primary clarifiers: In some plants, the inefficient operation of primary clarifiers may lead to higher TSS and BOD loadings to the aeration basins (Nolasco et al., 1994b). Improved BOD removal in the primaries will reduce oxygen demand in the aeration system, thereby leading to energy savings and additional oxygenation capacity.
- Flow equalization: Reducing the flowrate daily peaks can be used to reduce oxygen demand and energy requirement peaks. Flow equalization will not change the daily average oxygen demand or energy requirement values. However, depending on the price of energy at the specific plant, the cost of energy may be reduced by reducing the peaks. In addition, a reduction in the daily peak oxygen demand may generate an increase in the aeration system treatment capacity.
- Solids recycle stream control: The impact of solids recycled back to the aeration system has been studied at various facilities (Boyle and Gruenwald, 1975; Daigger, 1998; Lawler and Singer, 1984; Loi, 1972; Newbigging et al., 1995, 1999). In some plants, an increase in oxygen demand up to 15% was found to be related to solids recycle streams. The ways in which the impact of recycle stream loadings can be reduced to produce energy savings in the aeration system and an increase in the aeration system treatment capacity vary widely from plant to plant. In some cases, an evaluation and optimization of the solids train may be the best way to optimize the overall energy and treatment process requirements at a given facility.
- Denitrification in the aeration basins: When the existing aeration basins have enough volume to allow for installation of anoxic zones for denitrification, the oxygen bound in nitrates and nitrites can be used for further oxidation of organic matter. In this way, savings in oxygen requirements (and related aeration energy) of up to 10 to 20 percent can be achieved (Nolasco and Stephenson, 1991; Nolasco et al., 1994b).

In all of the aforementioned cost-saving options, a cost/benefit analysis using life-cycle costs will be required to determine the viability of using one or more of these process modifications as a means to reduce operating costs at a specific facility without impacting process performance.

Reducing Aeration Energy Consumption. Several ways of achieving energy savings at the aeration system of an existing facility are available, including

- Equipment and diffuser retrofits,
- Implementation of automatic dissolved oxygen control, and
- Treatment process modifications.

Energy optimization work funded by the New York State Energy Research and Development Authority, the Empire State Electrical Energy Research Corporation, and the Electrical Power Research Institute is worth mentioning here (Ferguson, 1998). In this project, a series of process performance improvements and optimization studies were conducted at six municipal WWTPs in New York State. The objective of the project was to determine if the process performance improvement methodology (i.e., the one described in the book) was an effective method of identifying energy conservation opportunities at municipal WWTPs. The test sites were selected to provide a representative sample in terms of size, location, and treatment technology. Online process monitoring, offline sampling, electrical submetering, and specific performance efficiency testing techniques were used to obtain real-time process and electrical consumption data. The study results indicated that this methodology was an appropriate tool for identifying energy conservation opportunities and quantifying achievable savings at existing WWTPs.

CHEMICAL ADDITION

In the previous section, testing and analysis tools were presented. These tools help the operator better understand the performance of the existing processes. This section describes how chemicals can be used to obtain process performance improvements.

INTRODUCTION. Chemical enhancement is generally defined as the addition of chemicals to increase the performance of a unit process or treatment system beyond its normal design limitations (U.S. EPA, 1979a).

Various chemical products can be used to enhance the performance of WWTP unit processes in several ways. These products may assist in overcoming long- and short-term deficiencies, such as short-term overloads, providing interim treatment capacity, improving long-term performance, or reducing the costs of process operation. Most often, operators apply the enhancement products on a short-term basis to overcome problems associated with overloading or violations of effluent limitations.

There are many potential uses for chemicals in the treatment of wastes and the enhancement of process operation. Table 25.4 presents a summary of these uses as

TABLE 25.4 Chemical dosage guide for wastewater treatment.

Chemical	Use	Average dosage
Activated carbon	Organics removal	30–216 mg/L (250–1 800 lb/mil. gal)
Chlorine residual	Trickling filter flies and ponding Bulking sludge Breakpoint chlorination Odor control Prechlorination	0.5–1.0 mg/L 5–60 mg/L 10 mg/L per 1 mg/L NH_4-N 1 mg/L residual 2–5 mg/L
Copper sulfate	Lagoon algicide	0.6–1.2 mg/L (5–10 lb/mil. gal)
Hydrogen peroxide	Bulking sludge Odor control	50–200 mg/L 1–1.5 mg/L per 1 mg/L H_2S
Methanol	Denitrification	3 mg/L methanol per 1 mg/L NO_3-N
Ozone	Odor control	1–2 mg/L (by volume of air treated)
Polymer	Scale prevention Improve sand bed drying	0.5–5.0 mg/L 2.5–15 g/kg of sludge (5–30 lb/dry ton)
Sulfur dioxide	Dechlorination	1.0–1.6 mg/L SO_2 per 1 mg/L Cl_2 residual

well as the average dosages for several chemicals commonly used in treatment (U.S. EPA, 1979a).

Chemicals are routinely used in situations where there is limited plant capacity or where reductions in energy consumption are desired. The application of a chemical to one unit process in many cases has positive effects plant-wide.

LIMITED PLANT CAPACITY. Facility managers sometimes need additional treatment capacity to handle short-term or seasonal load fluctuations or to serve as a long-term substitute for structural improvements. Under certain conditions, the prudent use of chemicals can provide improved removal or handling of organic and solids loadings, stabilize recycle rates and loadings, reduce stress on energy-limited processes, and reduce hydraulic loadings to sidestream systems such as digesters.

Various chemicals can also be used to improve settling and decrease the volume of pumped materials. This decrease often renews capacity of otherwise overloaded or undersized pumping systems.

ENERGY CONSUMPTION. Chemical enhancement may reduce the amount of thickened sludges and scums. This, in turn, creates less volume to pump and lowers pumping costs.

The energy consumption associated with aeration of activated sludge can sometimes be reduced significantly through chemical enhancement of primary sedimentation. Addition of iron salts and specialized organic polymers before primary sedimentation can enhance the removal of TSS and particulate BOD. Used during periods of peak organic and solids loading, this practice can lower the oxygen demand in the secondary system. This translates to lower aeration power requirements.

IMPACTS OF CHEMICAL APPLICATION PLANT-WIDE. Often, chemical use can result in several improvements simultaneously. For example, addition of metal salts and polymers to the plant influent can improve the removal of suspended solids and BOD in primary sedimentation tanks. In turn, this improvement will lower the organic load to the biological secondary system and result in reduced energy demand associated with aeration. At the same time, improved settling in the primary clarifiers can often provide a thicker sludge, reducing the volume of water pumped to the digesters. This reduction not only provides additional capacity in primary and secondary systems, but also aids in reducing the hydraulic load and increasing the hydraulic detention time of the digesters. This can result in better digestion of the organic material.

CHEMICAL SELECTION. There are many steps involved in ensuring you have the right chemical for the intended application. The following steps (listed in somewhat chronological order) are used in a typical investigation:

- Obtaining industry experience,
- Plant testing,
- Ensuring process compatibility,
- Defining byproducts and residual management considerations,
- Selecting points of application,
- Selecting dosing control options,
- Confirming availability,
- Defining storage and handling requirements,
- Determining environmental effects, and
- Defining costs.

OBTAINING INDUSTRY EXPERIENCE. The operator should first review information regarding experience and operating results from jar tests, pilot projects, or

full-scale applications at other WWTPs. Caution should be exercised when applying data obtained from other WWTPs because results may not be reproduced at every plant. The effectiveness of a particular product in improving treatment efficiency may change, particularly under differing wastewater characteristics, process designs, and loading conditions.

PLANT TESTING. Plant testing consists of jar, pilot, and full-scale testing. Testing begins in the lab and ends with full-scale trials.

In the lab, jar testing is performed on a variety of samples that reflect a range of operating conditions. All chemicals for consideration are used throughout the tests. Results from jar testing will result in a "short list" of chemicals to be used in pilot trials.

Pilot trials use larger quantities of wastewater than that used in jar tests and are usually continuous-flow as opposed to batch-flow. The size of a pilot trial can vary from a laboratory/bench top unit to a skid-mounted plant with relatively large capacities. From these trials, more is learned about how the chemicals behave in a continuous-flow environment, dosing, and appropriate application points. The chemical candidate list should now be narrowed to more than two.

Full-scale testing involves considerably more preparation than jar or pilot trials. Decisions must be made about what fraction of the plant will be used. In many plants, there are multiple trains. Although isolating one train is desirable, it involves process control planning and a host of other details. Temporary chemical storage and dosing systems must be obtained and positioned with all required utilities. Deliberate decisions must be made to ensure that the trial is representative of operating conditions. The testing duration should be sufficient to

- Stabilize the process,
- Represent the normal variations to be expected,
- Provide for adjustments to feed points, and
- Allow for collection of sufficient data to perform further analysis.

Testing for each trial should not be shorter than a month.

The trails need to be repeated for each chemical under consideration. In this case, the operator must take considerable care to ensure that a true comparison can be made between the two trials.

From full-scale testing, the operator learns

- Optimum dosing points and control methods,
- Impacts of the chemical addition on other portions of the plant, and
- To identify process compatibility issues.

All of this information is helpful in subsequent steps of the investigation.

ENSURING PROCESS COMPATIBILITY. Another consideration in chemical selection is compatibility with other processes used in the overall treatment scheme. An operator cannot afford to overlook possible adverse effects of chemical addition on waste streams or recycle solids. These effects are best determined in two steps: a laboratory feasibility study and pilot tests or, when possible, full-scale WWTP tests. The laboratory study should provide a preliminary evaluation of various chemicals to determine their general effectiveness and estimated dosage. Subsequent pilot or full-scale WWTP tests should provide more detailed information on overall compatibility with other WWTP processes.

DEFINING BYPRODUCTS AND RESIDUALS MANAGEMENT CONSIDERATIONS. Chemical enhancement may affect both the quantity and quality of solid material normally produced by treatment processes. It may also impact downstream solids handling and stabilization unit processes.

Increased removal efficiencies and the chemical flocs themselves can both result in significant increases in the amount of product. Tables 25.5 and 25.6 provide an estimation procedure for calculating the increase in sludge mass when either iron or aluminum

TABLE 25.5 Sample calculation for estimating sludge mass (lb/mil. gal).[a]

	Conventional	Iron to primary	Iron to aerator	Aluminum to aerator	Aluminum to TF[b] clarifier
Primary					
Sludge solids	1 250[c]	1 875	1 250	1 250	1 250
Iron solids		605			
Aluminum solids					
Total	1 250	2 480	1 250	1 250	1 250
Activated sludge					
Secondary solids	715	536	804	804	
Iron solids			541		
Aluminum solids				425	
Total (system)	1 965	3 016	2 595	2 479	
Trickling filter					
Secondary solids	656				745
Aluminum solids					483
Total (system)	1 906				2 478

[a]lb/mil. gal × 0.119 8 = g/m^3.
[b]Trickling filter.
[c]Represents 50% removal.

TABLE 25.6 Basis for sludge mass calculation.

Cation/P[a] dose (mol/mol)	lb chemical sludge/lb cation[b]	
	lb/lb aluminum	lb/lb iron
1.5	3.9	2.4
1.75	3.8	2.3

Assumptions:
Cation/P dose = 1.5 mol/mol to aerator
Cation/P dose = 1.75 mol/mol to primary or before filter clarifier
Influent wastewater
BOD[c] = 230 mg/L
SS[d] = 300 mg/L
P = 10 mg/L

[a]Phosphorus.
[b]lb/lb × 1 000 = g/kg.
[c]Biochemical oxygen demand.
[d]Suspended solids.

is added at various points in the WWTP. The quantity of sludge resulting from the use of these chemicals in secondary treatment WWTPs can be estimated from wastewater analyses as shown in Table 25.7.

Increased removal efficiency in the primary system caused by chemical addition will not only increase the amount of primary solids, but it will also change the ratio of primary to secondary sludge generated. The primary sludge mass will increase due to more solids removed and the added chemical. The secondary sludge mass will decrease because the aeration tank loading has decreased.

There can be quality issues resulting from the use of chemical additives. Two common examples are the deposition of vivianite in sludge lines and pumping systems and the loss of quality in biosolids because of an increase in trace metals and trace organics.

Downstream solids handling equipment and stabilization unit process can be impacted by chemicals added to the liquid side of the facility. Common impacts are

- Changes to dewatering characteristics;
- Changes to the quality of recycle flows (filtrate, centrate, and pressate);
- Changes to digester performance; and
- Changes to the quantity of biosolids requiring disposal/recycling.

These considerations (quantity, quality and solids handling, and disposal impacts) further underscore the need to consider all factors when contemplating chemical addition for process performance improvement.

TABLE 25.7 Additional sludge to be handled with chemical treatment systems: phophorus removal by mineral addition to secondary plants.

Sludge protection parameters		Lime addition	Aluminum addition	Iron addition
Level of chemical addition (mg/L)	—	268–450	16	10–30
Percent sludge solids	Mean	1.1	2	0.29
	Range	0.6–1.72	—	—
lb/mil. gal[a]	Mean	4 650	2 000	507
	Range	3 100–6 800	—	175–781
gal/mil. gal[b]	Mean	53 400	12 000	22 066
	Range	50 000–63 000	—	6 000–36 000

In summation:

- Lime addition in the primary causes the greatest increase in sludge mass production.
- The minimum increase in sludge mass comes from use of alum in the aeration basins.
- Sludge mass and volume depend critically on wastewater characteristics and clarifier performance.
- Selection of a treatment chemical and point of application should take into account the relative sludge processibility as well as added sludge mass.

[a] lb/mil. gal × 0.119 8 = g/m^3.
[b] gal/mil. gal × 1 000 = mL/m^3.

SELECTING POINTS OF APPLICATION. When determining the application point(s), the operator needs to consider many factors. Factors include the reaction rate of the chemical, interferences and inhibitory conditions, and the presence of adequate mixing. If more than one chemical is involved, proper sequencing and separation of feed points as well as the proper order of addition of chemicals must also be considered. If a hydraulic model was constructed for the facility, it can be used to optimize the application point.

Table 25.8 presents a summary of general considerations for selecting chemical addition points. Temporary points of addition can be tested before establishing permanent feed points. This procedure enables evaluation of performance for both initial selection and seasonal variation.

As noted previously, cases requiring the addition of more than one chemical call for proper sequencing and separation of feed points as well as proper order of addition. For example, if both chlorine and ferric chloride are needed in a system, the chlorine should be added first. Otherwise, chlorine will react with the ferric chloride, caus-

TABLE 25.8 Criteria for selecting chemical addition locations.

Primary chemical	Purpose[a]	Selection criteria[b]
Ferric chloride	Odor and corrosion control	Adequate mixing; before free fall or aeration; do not use metal fixtures; use PVC pipe and fittings
	BOD, SS, PO_4 reduction	Before polymer addition; not with chlorination; adeqate mixing; headworks area or primary influent channel; low polyphosphate concentration
Aluminum sulfate	BOD, SS, turbidity, PO_4 reduction	Flash mix or high turbulence; preferred after secondary treatment; before filtration; pH 7
Anionic polymer	BOD, SS, PO_4 reduction	After ferric or lime addition; just before clarifier, good mixing and low turbulence
Lime	BOD, SS, PO_4 reduction	Not recommended before activated sludge without pH control; after secondary clarifier; good mixing and high turbulence; low alkalinity; may require post-application pH control
Cationic polymer	SS and turbidity reduction	Before secondary clarifier; end of aeration basin or in clarifier feed channel; without channel aeration; good mixing and low turbulence
Ferrous chloride	BOD, SS, H_2S reduction	Adequate mixing; before free fall or aeration; directly into digester feed lines
Chlorine	Odor control	Good mixing; submerged injection; before hydraulic jumps or aeration; closed pipe better than open channel or tank
	Filament control	RAS line, after pump; direct application to aeration basin (HTH)
	Algae control	Batch feed in laggons (HTH) peripheral feed in clarifiers, fed through perforated annular tubing
Hydrogen peroxide	Bulking control	Prior to aeration basin; influent channel; RAS pipe after pump
	Odor control	Good mixing; prior to hydraulic jumps or aeration; closed pipes better than open channel or tanks
	Sludge odor control	Good mixing; closed pipes only; prior to bends
Potassium permanganate	Sludge odor control	Prior to dewatering system; prior to polymer addition; closed pipe addittion best
Sodium aluminate	PO_4 reduction	Warm temperature storage; flash mix or high turbulence; preferred after secondary treatment; prior to filtration

[a]BOD = biochemical oxygen demand; SS = suspended solids; PO_4 = orthophosphate; and H_sS = hydrogen sulfide.
[b]RAS = return activated sludge.

ing the release of gases that can float solids in downstream processes, which can impair operation of primary sedimentation tanks and gravity thickeners. Chlorine is normally used for inexpensive control of odors in headworks. While ferric chloride can be used for the same purpose, it is much more expensive. However, ferric chloride may also be applied effectively in some WWTPs to concurrently enhance removal of suspended solids, BOD, and phosphorus in primary sedimentation. Where both chlorine and ferric chloride are needed in the headworks for specific functions, the ferric chloride should be added at a point after the chlorine has been consumed.

As noted previously, hydraulic models can be used to optimize chemical application point(s). The model can determine the velocity gradients and contact time through the hydraulic elements of an existing WWTP for a variety of hydraulic loading conditions. The velocity gradient profile is used to determine the optimum mixing location for chemical addition.

SELECTING DOSING CONTROL OPTIONS. Once the operator has defined application points, he or she must now focus on dosing control options. The method and sophistication of dosage control depend on such variables as cost of controls, cost of chemicals, mechanical complexity, operator availability, and maintenance requirements. Typical considerations for control systems are

- Manual, constant dosage, independent of flow;
- Periodic dosage as a function of time;
- Flow pace dosage at a constant concentration;
- Flow pace variable dosage as a function of flow and time; and
- Variable dosage as a function of feedback of residual concentration.

CONFIRMING AVAILABILITY. The operator has selected the chemical(s) and now must confirm that a continuous supply is available. Factors the operator must consider include vendor capability, fluctuations in usage, and on-site storage. The vendor's ability to provide an adequate supply under all conditions must be confirmed. The operator needs to consider consumption rates during the period extending from order placement until receipt of the material. The supply on hand must include enough for an adequate safety margin, particularly when the material must be transported long distances or under difficult weather conditions.

DEFINING STORAGE AND HANDLING REQUIREMENTS. Storage and handling of treatment chemicals must receive serious consideration. Factors that should be included in the analysis are safety, labor requirements, and shelf life.

Staff must be properly trained in the handling, storage, and feeding of chemicals. Problems and accidents can result from improper or inadequate training regarding chemical hazards. Material safety data sheets should be consulted before any purchase and installation, and reviewed frequently by operating staff to maintain their familiarity with hazards and safety equipment.

Shelf life requires review because it may affect the amounts to be ordered and stored on-site. For chemicals with a shelf life of 1 year or more, purchase and storage of annual amounts may be advisable. However, such purchase and storage would be unwise if the shelf life were 6 months or less. For similar reasons, the operator should check the production date of the material being shipped by a vendor, particularly if the vendor is not the manufacturer.

Weather must also be taken into consideration when designing receiving and storage facilities. Extreme heat or cold may radically reduce the shelf life or activity of a chemical. For example, extreme heat deteriorates certain polymers quite rapidly and extreme cold reduces the reactivity of alum in phosphorus removal.

Even under best management practices, there will be occasions when chemicals deteriorate (lose potency) and require proper disposal. Plans should allow for the removal and safe disposal of such materials.

The operator must become familiar with the physical properties of chemicals and how they are affected by changes in temperature. Many chemicals, such as alum and sodium hydroxide, may separate or crystallize when exposed to low temperatures. In other cases, compounds may become quite viscous, impairing both pumping and storage.

The operator should consider labor requirements, particularly the operations and maintenance (O&M) requirements of handling and feeding equipment. The labor associated with the use of various chemicals depends not only on the amount of the particular chemical, but also on the characteristics of the chemical and the forms in which it is purchased, stored, and used. For example, use of a chemical that is purchased and fed in the same form will generally require less labor than a chemical that is purchased in dry form, dissolved for storage, and later diluted for feeding. Accordingly, staffing requirements for use of various chemicals will differ considerably; these differences should be considered when selecting chemicals.

DETERMINING ENVIRONMENTAL EFFECTS. Preference should be given to chemicals that will be least hazardous to WWTP staff and the community and that will be environmentally safe upon final reuse or disposal. For example, chlorine is commonly used not only as a disinfectant, but also for odor and filamentous bulking control. However, chlorine is a hazardous material requiring special handling under any

circumstances. Its increased use can increase the exposure of WWTP personnel or the community to unnecessary hazards. Generally, either gaseous or liquid chlorine represents a hazard to the surrounding community as well as to WWTP staff. Although it is more expensive, calcium hypochlorite is significantly less hazardous. While the operator should consider the most suitable chemical for an application, reduction of hazards should receive special emphasis.

For several other groups of chemicals, selection may be influenced by environmental effects. Table 25.9 provides examples of such chemicals and the reasons they may be considered environmentally undesirable. The appropriate local health and safety agencies should be consulted before making any firm plans for using a new chemical in the treatment system.

DEFINING COSTS. Part of the selection process involves comparing capital and operating costs for the chemicals under consideration. Factors that influence cost are initial cost, byproduct and residual management, and storage and handling requirements. Some elaboration of cost considerations follow.

The cost estimate must also account for the cost of handling and removing the resulting solid material relative to the initial cost of the chemical. For instance, although the unit cost for lime is typically less than that for alum, larger amounts of lime may be required to produce the same results. Concurrently, the increased lime usage may significantly increase the quantity of material produced. Therefore, the total cost of chemical addition, including removal, must be considered and compared for each chemical. Also factored into this equation should be the final use or disposal costs of the solids product. In some cases, the revenue generated through the sale of biosolids can be an

TABLE 25.9 Environmental effects of chemical discharges.

Chemical	Potential use	Environmental effect
Ammonia	Control of pH and alkalinity	High ammonia concentrations can be toxic to fish, deplete oxygen in receiving waters, and encourage algae growth
Alum or iron salts	Coagulation	Increases effluent TDS; increases sludge disposal volume
	Disinfection	Increases effluent TDS; high residuals can be toxic to fish; can increase concentration of chlorinated hydrocarbons
Chlorine	Breakpoint chlorination	May produce acidic effect on effluent, requiring addition of neutralizing chemicals; increases effluent chlorides

important consideration in selecting chemical additives. In other cases, capital costs and supply costs may be close for alternative chemicals, but O&M costs for the alternatives may differ greatly depending on labor requirements, product quality, energy requirements, and chemical handling costs.

Cost comparisons should consider the use of only one chemical for a variety of purposes. For example, use of only chlorine for control of odors, bulking sludge, and disinfection may be more cost-effective than using a combination of iron salts, hydrogen peroxide, and chlorine for the same purposes. Use of a single chemical allows for consolidation of storage facilities and feed equipment, and avoids the increased safety requirements for using a wider variety of chemicals.

Transportation costs and local market conditions can impose significant operational expenses for some facilities. For instance, some useful chemicals are byproducts of some industrial processes. These chemical surrogates, such as those for alum, may be much less expensive than industrial-grade primary chemicals. Chemical surrogates are often available in areas of high market demand, but they may not be available in remote areas with low market demand.

ONGOING PERFORMANCE. The operator has selected and is applying the chemical(s) of choice. The question remains, however, whether the chemicals will continue to provide the same benefits as conditions change.

The operator should periodically verify operating conditions and determine the acceptability of the chemical(s) over the long term. Routine efficiency tests are necessary to ensure that chemicals are not being wasted and that dosages remain adequate under fluctuating conditions. These tests involve periodically adjusting dosages higher or lower and measuring the resulting changes in performance and control criteria.

EXAMPLES. The previous section detailed the steps taken in selecting the appropriate chemical to attain process performance improvement. More specifics about the following unit processes and chemical application are discussed here:

- Primary treatment,
- Secondary treatment,
- Lagoons,
- Thickening,
- Anaerobic digestion, and
- Aerobic digestion.

PRIMARY TREATMENT. Chemicals used to provide process improvement in primary treatment are polymer, lime, and ferric or ferrous chloride coupled with polymer.

Table 25.10 shows clarifier performance before and after polymer addition and illustrates significant variations in BOD and suspended solids removals (U.S. EPA, 1979a). The greatest improvement normally resulting from polymer addition occurs where the existing clarifier performance is poor.

Lime is added at many locations for reduction of phosphorus and soluble metals. In all cases, significant improvements in both suspended solids and BOD removal were also observed, as shown in Table 25.11. Lime dosages depend mostly on initial alkalinity of the wastewater, but typically range from 75 to 300 mg/L as CaO (U.S. EPA, 1979a).

Lime addition at 100 mg/L has been used successfully to aid primary sedimentation (Keo and Tan, 1987). However, lime requires large volumes of chemicals, imposes major expense, impairs anaerobic digestion, and produces large volumes of sludge.

The use of iron salts requires the addition of polymers (usually anionic polymers) to achieve suspended solids removals ranging from 60 to 80% in primary sedimentation. The use of iron salts and polymer generally costs less than lime, reduces the odors of raw wastewater and sludge, moderately affects O&M of dosage equipment, and does not affect digestibility.

SECONDARY TREATMENT. Chemicals used to improve process performance of secondary treatment include iron and aluminum salts, polymers, chlorine, soda ash, and caustic soda. Dosages of metallic coagulants and coagulant aids in secondary systems are similar to those for primary sedimentation (50 to 300 mg/L and 0.5 to 0.7 mg/L, respectively). The range of dosages for synthetic polymers vary widely, from 2 to 60 mg/L, depending on the proportion of active polymer. With coagulants

TABLE 25.10 Effects of polymer addition to primary clarifier on process performance.

			Primary clarifier				Total plant			
			Removal before polymer addition, %		Removal after polymer addition, %		Removal before polymer addition, %		Removal after polymer addition,%	
Process	Coagulant	Dose	BOD[a]	SS[b]	BOD	SS	BOD	SS	BOD	SS
Activated sludge	Purifloc A–21	1 mg/L	26	—	48	—	83	—	90	—
Trickling filter	Purifloc A–21	1 mg/L	23	43	33	76	79	72	85	84
Activated sludge	Purifloc A–23	0.21 mg/L	31	31	46	51	79	85	83	89

[a]Biochemical oxygen demand.
[b]Suspended solids.

TABLE 25.11 Effects of lime addition on primary clarifier performance.

Location	Lime added, mg/L CaO[a]	Removal before lime, %		Removal after lime, %		Remarks
		BOD[b]	SS[c]	BOD	SS	
Duluth, MN	75	50	70	60	75	—
	125	55	70	75	90	—
Rochester, NY	100	—	—	50	80–90	Jar tests
Lebanon, OH	145	—	—	66	74	Pilot plant
Richard Hill, Ont.	175	21	37	71	77	Full scale
Central Contra	378	46	71	74	79	Full scale
Costa County, CA	303	37	71	69	76	Full scale

[a]Calcium oxide.
[b]Biochemical oxygen demand.
[c]Suspended solids.

added to the secondary system, turbidity can be reduced to levels of 1.5 to 3.0 nephelometric turbidity units.

When added directly to the aeration basin, iron salts, aluminum salts, or polymers may be used. Typically, as a means of avoiding floc shear, the chemicals are added to aeration basins or transfer channels just ahead of the secondary clarifiers.

Some studies have indicated that the turbidity of final WWTP effluent may be increased when alum is added to the aeration system. This increase may occur when the alum dosage is high enough to reduce the pH below the optimum level for good alum flocculation, resulting in pinfloc carryover into the final effluent.

For removal of suspended solids and turbidity, Shutoko et al. (1987) found aluminum hydroxide chlorides to be more effective as coagulating agents than alum. Obermann et al. (1987) conducted jar tests over a pH range of 3.5 to 11.4 to show that a blend of aluminum chloride and polyaluminum chloride is more effective than ferric chloride for removal of phosphorus and turbidity combined.

Polymers. Adding polymer to secondary clarifiers is intended to improve settling without destroying either the floc or the filaments. The technique involves adding synthetic polymers to the mixed liquor as it leaves the aeration tank or at the point of entry to the clarifier. The polymer typically has a high molecular weight, possesses a cationic charge, and may be applied alone or in combination with an anionic polymer.

Chlorine. Chlorine is often used to control filamentous bulking, principally because it is readily available at most WWTPs. It is generally added at one of three points in the system: directly into the aeration tank; into a loop in which mixed liquor is withdrawn

from the aeration tank, chlorinated, and returned to the tank; or into the return activated sludge stream. The last option is the most popular. Chapter 20 presents a thorough review of chlorinating mixed-liquor suspended solids (MLSS) for filament control.

Chlorine, dosed at 0.5 to 3 mg/L, is also used to control the growth of algae on weirs and in launders of secondary clarifiers. Low dosages through perforated hoses placed between effluent scum baffles and weirs prevent the growth of filamentous algae, which can otherwise contribute to periodic increases in suspended solids and turbidity because of sloughing. This problem is particularly acute where associated with downstream filtration.

Soda Ash and Caustic Soda. Specific chemical imbalances or deficiencies that inhibit nitrification can occur in the treatment process. Under these circumstances, chemical addition may stabilize or enhance the process by providing adequate pH and alkalinity.

Although the range of reported optimum pH values is wide, it is universally accepted that the rate of ammonia oxidation decreases as pH drops below 6.3 (U.S. EPA, 1975). Because of the effect of pH on the nitrification rate, it is especially important that the wastewater contain sufficient alkalinity to buffer the acid produced by the nitrifiers. Moreover, because 7.14 mg of alkalinity (measured as CaCO3) is consumed for every milligram of ammonia-nitrogen oxidized to nitrate-nitrogen, the addition of soda ash (sodium carbonate) or caustic soda (sodium hydroxide) may be required to supplement alkaline-deficient wastewaters and prevent the lowering of pH.

Soda ash is one of the best and safest sources of carbonate alkalinity. However, for most cases in which nitrification is impeded by low pH, less expensive chemicals, such as lime or caustic soda (sodium hydroxide), may be used.

Alkalinity and nitrogen loads to the nitrification process may fluctuate widely. As such, the operator should pay attention to diurnal fluctuations of ammonia relative to alkalinity and, in particular, monitor supernatant returns from anaerobic digesters and recycle streams from dewatering processes. Typically, these recycles can have high ammonia concentrations. However, their alkalinity may be less than the concentration required to support full nitrification. Introduction of this recycle stream into a nitrifying activated sludge system can exhaust the system's available alkalinity and oxygen.

DISINFECTION. Ammonium compounds can be added to secondary effluent to improve disinfection and reduce the chlorine dosage under certain conditions of nitrification. If the WWTP discharge permit allows increased ammonia levels, this addition can provide short-term capacity until chlorination and dechlorination facilities can be expanded.

LAGOONS. Lime, alum, or ferric chloride can be added to lagoons to lower the concentrations of BOD, suspended solids, and orthophosphate. In lagoons, batch treatment with alum at 150 mg/L has been shown to reduce total phosphorus to less than 1 mg/L and to suppress algal blooms. Concurrently, suspended solids and BOD were reduced to less than 20 mg/L each (Caldwell, 1946). A chlorine dosage of 12 mg/L has produced similar results in oxidation ponds. Dosage at this level has effectively killed the algae and reduced BOD from approximately 45 to 25 mg/L and suspended solids from approximately 110 to 40 mg/L (Dinges and Rust, 1969).

THICKENING. Chemical aids are routinely used in thickeners for concentrating sludges and controlling odors and septicity. Polymers are routinely used in dissolved air flotation thickeners and gravity bed thickeners. Activated alumina has been found to be effective in reducing odors associated with activated sludge thickening; it is also more cost-effective than various aluminum chloride products (Keo and Tan, 1987). Chlorine is commonly used to sweeten makeup water in gravity thickeners.

ANAEROBIC DIGESTION. In a properly operating anaerobic digester, the bicarbonate alkalinity should be maintained at a level no lower than 1000 mg/L as calcium carbonate to ensure adequate pH control. In an upset condition, net buffer consumption takes place and the process is in danger of pH failure. When this happens, an external source of alkalinity must be supplied to maintain or reestablish the pH in the proper range.

The most common chemicals used to adjust the pH of anaerobic digesters are lime, soda ash (sodium carbonate), caustic soda (sodium hydroxide), and ammonium hydroxide. The best method for determining the amount of chemical to be added to a digester includes first measuring the amount of chemical required to raise the pH and alkalinity of a large, constantly mixed sample of digester sludge to the minimum desired level. This should be calculated in grams per cubic meter (pounds or gallons of chemical per thousand gallons) of digester sludge volume.

Any buffering and Ph-adjustment chemicals must be added slowly over a period of several days to avoid an overdose, excessive pH, alkaline toxicity, or waste of expensive chemicals. Chemicals used for pH adjustment must be handled with care and thoroughly mixed with feed sludge before digester entry. Chemicals may be mixed in a hopper of a dissolved air flotation thickener or ahead of a digester feed pump. In no instance should raw chemicals—especially lime or sodium hydroxide—be added directly to a digester. Lime and sodium hydroxide react with water to produce extreme heat. Hot sludge entering an anaerobic digester can cool quickly, causing a vacuum

that may implode the lid of the digester or break the water seal, drawing air into the gas storage area. Air intake results in an explosive gas mixture.

AEROBIC DIGESTION. Control of pH and alkalinity is an important element of operating aerobic digesters. Typically, aerobic digestion is a nitrifying process, especially in the absence of primary sludge. When nitrification occurs, both pH and alkalinity are reduced.

Similar to activated sludge nitrification, alkalinity below 100 mg/L as calcium carbonate and a rapid drop in pH to below 6 may inhibit nitrification and subsequently interfere with proper solids separation during decanting because of rapid denitrification of nitrite-nitrogen.

Soda ash or caustic soda are the two chemicals commonly used for pH and alkalinity adjustment. Although high pH will not affect aerobic digestion as negatively as it does anaerobic digestion, chemicals should be added in small increments to avoid overdose and wastage.

BIOAUGMENTATION

Bioaugmentation is the addition of specific biological cultures and byproducts to a unit process or system to achieve performance objectives not achievable by normal biological or mechanical means (Tabak, 1986). Bioaugmentation, a relatively new concept in wastewater treatment, has not received wide acceptance. Bioaugmentation generally involves the addition of selected microorganisms to the normal population of a wastewater treatment system with the purpose of enhancing the biological activity of the system. A variety of bacterial preparations (including some with added nutrients or enzymes) are commercially available for treatment of municipal, industrial, and agricultural wastes and wastewater.

Generally, developers of bioaugmentation products use two distinct approaches. The first is the addition of specific organisms to artificially establish dominance over other undesirable or ineffective organisms (population control). The second is the addition of exotic bacterial cultures with beneficial metabolic capabilities that differ from those of the existing populations. Thus, the added cultures do not necessarily compete with the existing populations, but rather supplement them. These cultures presumably consume or oxidize specific compounds that would otherwise be considered untreatable or difficult to treat (Tabak, 1986).

In either approach, the philosophical basis for biological supplementation (bioaugmentation) rests on the apparent need for added specialized bacteria that are capa-

ble of metabolizing specific problem substrates. These bacteria maintain an artificial presence in the microbial population intended to improve and stabilize treatment performance.

Proponents of bioaugmentation claim that it offers a practical means of controlling the effectiveness of the biomass. With systematic bacterial inoculations, sufficient quantities of selected bacteria are introduced into the system on a repetitive basis to produce a competitive population of supplemental organisms. Maintenance doses are used on a variable basis, depending on the nature of the system.

Numerous articles (Baig and Grenning, 1976; Bower, 1972; Grubbs, 1974, 1983) have described the successful use of cultures to control grease within wastewater collection systems as well as wet wells to reduce clogging. Reduction of odors and control of hydrogen sulfide emissions have also been reported (Grubbs, 1974, 1983; Tabak, 1986). Reports by bioaugmentation technologists also claim improvement of reliability in wastewater treatment systems stemming from decreased sludge production, reduced foam in the aeration process, color reduction, suppressed filamentous organisms in activated sludge, improved response from peak loads, and overall improvements in effluent quality (Grubbs, 1974, 1983).

While some literature proclaims the advantages of bioaugmentation products, a substantial amount of experience indicates instances of no benefit or negative effects resulting from bioaugmentation. Several products, however, have shown specific benefits. Still, many disappointments with bioaugmentation have resulted from poor product representation, misapplication, or poor process control.

According to Young (1976), a number of significant recommendations were made by the Special Committee on Enzyme and Biocatalytic Additives. The recommendations, published in MOP No. 16, *Anaerobic Sludge Digestion* (WPCF, 1987), are summarized as follows:

- Biocatalytic additives should not be purchased until they have performed as claimed in accordance with a written guarantee.
- Advertising literature should be written clearly and correctly so as not to misrepresent the merits of the product.
- Distributors should deal with engineers, superintendents, or operators rather than attempt to influence mayors, councilmen, or members of boards of public works.
- Before the additive is considered, it should be tested so that fundamental and reliable data can be obtained.
- When digestion problems develop, major efforts should focus on proven methods of analysis and recovery.

U.S. EPA has established a formal protocol for evaluating legitimate bioaugmentation products (Tabak, 1986). The testing protocol is divided into three areas of effort: label verification and product classification, bench-scale performance (efficacy) testing, and field performance testing. Additionally, potential product applications have been divided into four major categories. The major categories and their respective applications are outlined in Table 25.12. U.S. EPA protocol should be carefully followed when selecting bioaugmentation products.

APPENDIX A: FLOW METER BACKGROUND INFORMATION

FLOW METER TYPES. Flow metering equipment commonly found in wastewater treatment facilities can be divided into two basic categories: open-channel flow meters and full-pipe flow meters. Advantages and disadvantages of five types of flow meters commonly found in WWTPs are summarized in Table 25.13.

OPEN-CHANNEL METERS. The most commonly used open-channel flow meters consist of a primary hydraulic structure inserted into the flow stream and a secondary element that measures the water elevation at a known location upstream of the hydraulic structure. The purpose of the hydraulic structure is to produce a flow that is characterized by a known relationship between liquid-level measurement (head) and flowrate. The head-flow relationship of the primary device, commonly referred to as the rating curve, is used to convert the water elevation measured by the secondary ele-

TABLE 25.12 Possible treatment applications of bioaugmentation products.

Aerobic treatment	Sludge handling	Anaerobic treatment	In-sewer treatment
Reduce sludge production	Sidestream improvement	Digestion improvement	Odor control
Improve efficiency	Thickening and dewatering	Septic tanks	Corrosion control
Improve clarification	Composting	Improve main stream treatment	In-line treatment
Specific substrate removal			
Improve start-up line			

TABLE 25.13 Flow metering equipment commonly used in wastewater treatment facilities

Type	Accuracy	Advantages	Disadvantages
Open-Channel Flume	5 to 7%	Low headloss, self-cleaning	Requires careful construction, susceptible to flooding
Open-Channel Weir	5 to 7%	Low cost, ease of installation	High headloss, requires a well-developed flow profile, cleaning required
Full-Pipe Electromagnetic	1 to 3%	No head loss, bi-directional	Minimum conductivity required, expensive, well-developed velocity profile required
Full-Pipe Doppler	2 to 5%	No headloss, low cost, not affected by air bubbles	Not suitable for some pipe material, well-developed velocity profile required
Full-Pipe Venturi	1 to 3%	Low headloss, high accuracy	Expensive, well-developed velocity profile required

ment into a flowrate. The overall accuracy of the open-channel flow meter is determined by the accuracy of both primary and secondary elements.

The primary device can be divided into two categories: weirs and flumes. A detailed discussion of different types of weir and flume configurations used in North America is presented in the *Isco Open Channel Flow Measurement Handbook* (Grant, 1989). The performance of the primary device is determined largely by the quality of the installation. Weirs require a uniform velocity profile in the upstream approach channel, free discharge over the weir crest, and an aerated nappe to ensure accurate measurement.

Flumes require a uniform velocity profile in the upstream approach channel, free discharge through the flume throat, and accurate conformance to the standard geometry, including location of the secondary element measurement, for the flume type. The standard requirements for common types of flume and weir installations are presented in literature by Grant (1989), U.S. EPA (1988), and Kulin (1984a).

The secondary element measures the water surface elevation at a specified location within or upstream of the primary element. Common secondary elements include

- Ultrasonic level measurement,
- Bubbler system,
- Mechanical float,

- Submerged pressure transducer, and
- Electrical transducer—capacitance or reactance type.

Ultrasonic- and bubbler-system level measurements are commonly used at WWTPs because of their simplicity of installation, low maintenance requirements, and level of accuracy provided.

FULL-PIPE FLOW METERS. Full-pipe flow measurements commonly used in wastewater treatment facilities include

- Electromagnetic flow meters,
- Ultrasonic flow meters (Doppler) or transit time,
- Venturi, and
- Flow tubes.

Electromagnetic flow meters are based on Faraday's law of electromagnetic induction. The meter creates a magnetic field perpendicular to the direction of flow. Flow through the magnetic field induces a voltage that is proportional to the flowrate. The magnitude of the induced voltage is proportional to the magnetic field strength, distance between electrodes, and the velocity of the fluid. The achievable level of accuracy for an electromagnetic meter is 1 to 3% of flow.

Ultrasonic Doppler meters are used in "dirty water" applications. The ultrasonic beam is interrupted by particulate matter in the moving fluid and reflected toward a receiver. The difference between the propagated and reflected frequencies is proportional to the velocity of the particulate matter in the fluid and, therefore, to the fluid flowrate. Doppler meters require a minimum concentration and size of solids or air bubbles for reliable operation. They also require a minimum velocity through the meter to maintain the particulate matter in suspension. The achievable level of accuracy for a Doppler meter is 2 to 5% of flow.

Venturi meters are differential pressure meters. The change in cross-sectional area through the throat constriction of the meter forces a change in the fluid velocity, resulting in a change in pressure. The flowrate is a function of the differential pressure. Venturi meters use a gradual change in pipe diameter upstream and downstream of the throat constriction to reduce the headloss through the meter. The achievable level of accuracy for a Venturi meter is 1 to 3% of flow.

Flow tubes are modified Venturi meters, where the sectional geometry and profile are proprietary to the manufacturer of the meter. Flow tubes are usually shorter than the classical Venturi meter; however, they are more sensitive to upstream disturbances.

TROUBLESHOOTING. The achievable accuracy of flow metering equipment quoted in the previous section is based on the meter installation conforming to the established standards. Most standards are well-documented and can be found in the standard reference material (U.S. EPA, 1988; Kulin, 1984a, 1984b, 1984c). Unfortunately, many WWTP meter installations do not meet recommended standards and, therefore, the accuracy of the measurement is adversely affected.

Common installation problems in flow metering equipment are summarized in Table 25.14. Useful checklists and summaries to evaluate the installation of flow measuring equipment are provided in a report on flow meters prepared by the Water and Wastewater Instrumentation Testing Association (1991).

OPEN-CHANNEL FLOW METERS. Accurate and appropriate level measurement is a common installation concern with open-channel flow meters. Standard flume and weir equations were developed and calibrated using empirical data based on specified location (distance from the throat) for level measurement. Open-channel flow meters in many installations do not meet the standard configuration and, therefore, the standard equations converting the level measurement to flowrate are not applicable.

TABLE 25.14 Common installation concerns of flow metering equipment.

Type	Concerns
Flume	• Flooded (discharge not free flow) • Flume geometry and location of level measurement not conforming to standard • Nonparallel flow upstream • Level measurement out of calibration
Weir	• Minimum/maximum flow exceeded • Nonparallel flow profile upstream • Level measurement in an inappropriate location • Level measurement out of calibration
Electromagnetic	• Insufficient clear length of straight pipe upstream and downstream of meter • Entrained air collecting in meter section
Doppler	• Insufficient clear length of straight pipe upstream and downstream of meter • Insufficient solids in fluid • Sensors mount on the vertical plane • Vibration in pipe
Venturi	• Insufficient clear length of straight pipe upstream and downstream of meter • Pulsating flow • Pressure sensor out of calibration

Nonstandard weir and flume configurations must be calibrated in the field. The secondary element that measures the water surface level requires maintenance and calibration on a regular basis to ensure an accurate level measurement.

Both weir and flume installations require uniform flow upstream and free discharge downstream of the hydraulic structure. The required straight length of channel upstream of the flow measurement device for each type of hydraulic structure is specified in published standards. The discharge over a sharp crested weir requires a free fall with an aerated nappe for accurate measurement. The nappe is defined as the section of the flow stream immediately downstream of the weir crest where the flow direction changes from horizontal to vertical and the sides of the flow stream contract. An air vent on both sides of the channel under the downstream edge of a rectangular weir crest will help aerate the nappe under low-flow conditions.

FULL-PIPE FLOW METER ACCURACY. The accuracy of most full-pipe flow meters is affected by meter orientation and the velocity profile in the pipe cross-section upstream and downstream of the meter. Installation guidelines for full-pipe meters include minimum pipe lengths upstream and downstream, direction of flow, and minimum and maximum velocities.

Electromagnetic meters require full-pipe flow at all times and a clear length of 5 pipe diameters upstream and downstream. Doppler meters require a pipe material that will allow penetration of an ultrasonic signal (concrete pipe is very poor), horizontal installation, and a clear length of 10 pipe diameters upstream and 5 diameters downstream. Venturi meters require full-pipe flow at all times and a clear length of pipe 20 throat diameters upstream and 10 throat diameters downstream.

Three steps are recommended for evaluating and troubleshooting full-pipe flow metering equipment:

1. Record checks to ensure design specifications for the meter are suitable for the application.
2. Physical inspection of the installation to determine if the device meets the design specifications and recommended standards for installation.
3. Field calibration to verify the accuracy of the device.

Record checks are used to provide initial screening of the flow meter installation. Questions to be addressed during this phase of the evaluation include the following:

- Is the type of meter suitable for the application?
- Is the expected level of accuracy acceptable?
- Is the meter size appropriate for the expected flow range?

Following the record check, a physical inspection of the meter is required to determine if the installation is appropriate for the type of meter and if it meets the applicable recommended standards.

Physical inspection for weirs and flumes includes

- Physical measurements of the hydraulic structure, including the approach channel, throat or weir section, throat or weir elevations, and the location of the level measurement; and
- Calibration (zero and span) of the secondary device.

Physical inspection for full-pipe meters includes

- Meter orientation and
- Clear length of pipe upstream and downstream of the meter.

APPENDIX B: OFF-GAS ANALYSIS TESTING DETAILS

Off-gas analyses are conducted by collecting gas from under a floating hood and sending it to an analyzer circuit where the airflow rate and oxygen content are measured. The off-gas system consists of (see Figure 25.4)

- A floating hood;
- A hose connecting the hood to an analyzer;
- A vacuum source that draws the off-gas from the hood through the analyzer; and
- An off-gas analyzer that measures off-gas flowrate, the oxygen content of the off-gas, and the off-gas temperature and pressure.

In the off-gas analyzer, all of the gas collected from the hood first passes through flow meters. Because the gas flowrate exiting the aeration tank is essentially equal to the gas flowrate entering the tank, the flow meters provide information on airflow entering the aeration basin at each sample location.

After the off-gas passes through the flow meter in the analyzer, a portion is passed through the analyzer circuit. Ambient air, referred to as *reference air* (which is equivalent to the air entering the aeration basin), and off-gas from under the hood are alternately passed through the off-gas analyzer. Comparison of the composition of the gas entering (reference air) and the gas exiting (off-gas) the aeration basin provides data on the changes the gas is undergoing within the basin.

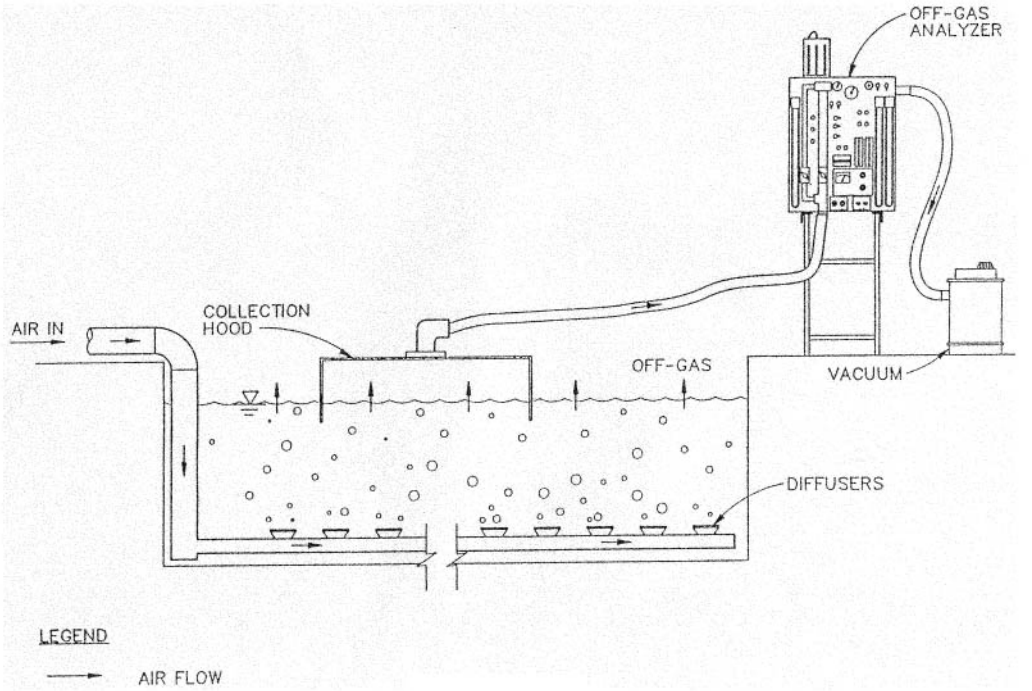


FIGURE 25.4 Offgas analyzer.

In the off-gas analyzer, the off-gas and ambient air are passed through a column where moisture and CO_2 are removed, eliminating the need to correct for these parameters. Next, the dry gas is passed through an oxygen content sensor under controlled pressure and flowrate. In some off-gas analyzers, a CO_2 analyzer is provided to eliminate the need to remove CO_2 from the air tested.

The use of a floating hood to collect off-gases prevents off-gas tests from being used in surface (mechanical) aeration systems. Therefore, for surface aeration system tests in process water, the hydrogen peroxide method is recommended.

When troubleshooting diffused aeration systems, the off-gas test provides localized data on the performance of diffusers. In addition, oxygen transfer throughout the aeration basin can be measured to evaluate the behavior of tapered diffuser systems or assess the need to incorporate a tapered system where it is not in place (Groves et al., 1990).

As with the other aeration efficiency methods discussed in this section, off-gas analysis is useful when making choices about costly diffuser systems and their configurations. Full-scale, side-by-side comparisons performed before a major aeration system retrofit provide actual data on which to base decisions.

By metering the off-gas flowrate, the off-gas analyzer provides data on airflow at each sample location. This capability can be used for evaluation of long-tem changes in airflow at specific locations within the basin. In addition, the total airflow for the basin can also be calculated from the off-gas analysis results. The data can be used to verify the readings from the plant airflow meters.

A diffuser cleaning schedule can be determined with off-gas analysis in conjunction with dynamic wet pressure (DWP) analysis (U.S. EPA, 1989). This is done by performing periodic analysis and cleaning the diffusers when the oxygen transfer efficiency drops and/or the pressure drop rises to a predetermined point. A cost-effective cleaning schedule can be calculated by using an energy analysis (Newbigging et al., 1999). The effectiveness of various diffuser cleaning methods can be evaluated by using different cleaning methods on separate parts of the aeration system and comparing oxygen transfer efficiencies and DWP after cleaning (Redmon et al., 1991).

Finally, off-gas analyses provide oxygen transfer data for various systems and conditions. These data can be used as a design aid for new systems or expansion of existing systems. One of the main advantages of using the off-gas method is that the operation of the aeration basins does not need to be interrupted during the test. This is usually not the case for the hydrogen peroxide desorption method, where the aeration influent is generally interrupted a few hours before the beginning of the test.

A summary of recommendations for determining if the off-gas test is the most appropriate method to use in a given aeration capacity evaluation is presented in Table 25.15.

The oxygen transfer efficiency (OTE) values obtained from the off-gas test are for individual locations (metering stations) distributed throughout the aeration basin tested. Because a single OTE value is desired, it can be obtained as a weighted average of the OTE values using the individual airflow rates recorded at each location as weighting factors. *Oxygen Transfer Efficiency Measurements in Mixed Liquor Using Off-Gas Techniques* (Redmon et al., 1983) should be reviewed for a complete description of the off-gas instrument and testing methodology.

DATA ANALYSIS AND CALCULATIONS FOR THE OFF-GAS TEST.

The primary result of interest from this test is the oxygenation capacity of the system under various operating conditions. The important calculations are presented herein.

The oxygen transfer rate (OTR) or oxygenation capacity at field (normal operating) conditions can be calculated as follows:

$$OC = OTE_F \times O_2 \text{ mass flow} \tag{25.8}$$

TABLE 25.15 Examples of when to use the off-gas test.

Recommended to Use	Not Recommended to Use
• In diffused aeration systems • When the aeration basin to be tested cannot be taken out of service • When the aeration basin does not have proper mixing • To obtain data on aeration system operation under different influent/process conditions (e.g., high/low loads, nitrification, etc.) • To obtain localized data on performance of diffusers • To measure airflow rates in different sections of the same aeration basin (leak detection) • To evaluate long-term changes in airflow and oxygen transfer efficiency at specific locations within one aeration basin • In full-scale side-by-side comparisons of diffusing systems • In large aeration basins where H_2O_2 costs become prohibitive • In side-by-side comparisons of diffuser cleaning methods	• When off-gas collection is not possible due to: – Surface aeration systems – Covered tanks without access to off-gas – Covered tanks with contaminated off-gas (e.g., combined off-gas from various sources) – Coarse-bubble diffusers in a spiral-roll pattern, unless the basins are covered and off-gas can be sampled from the confined space above the water surface • When costs of purchase/rental or transportation of the off-gas analyzer makes the test not cost-effective

$$O_2 \text{ mass flow} = Q_{AIR} \times \delta_{AIR} \times O_{2/air} \tag{25.9}$$

where

OC = the oxygenation capacity or OTR at temperature, T, ambient pressure, p_b, with process wastewater, and the residual dissolved oxygen concentration recorded during the test (C_r), kg O_2/d;

O_2 mass flow = the mass of oxygen pumped into the aeration basin, kg O_2/d;

Q_{AIR} = the airflow rate, m^3/d;

δ_{AIR} = the air density at standard conditions, approximately 1.2 kg/m^3; and

$O_2/_{air}$ = the oxygen content of air, approximately 0.21 kg O_2/kg air.

Similarly, the standard oxygen transfer rate (SOTR) or oxygenation capacity at standard operating conditions of residual dissolved oxygen of 0 mg/L, water temperature of 20 °C, and ambient pressure of 1 atm can be calculated as follows:

$$\text{SOTR} = \text{SOTE}_{PW} \times \text{O}_2 \text{ mass flow} \tag{25.10}$$

The standard aeration (electrical) efficiency of the equipment is defined as the oxygen transfer rate per unit of power input, and can be calculated as

$$\text{SAE} = \text{SOTR}/(P \times 24) \tag{25.11}$$

where

SAE = the standard aeration efficiency, kg O_2/kWh; and
P = the active power of the blower or mechanical aerator, kW.

APPENDIX C: HYDROGEN PEROXIDE TESTING DETAILS

In this test, hydrogen peroxide (H_2O_2) is added to an aeration basin to elevate the dissolved oxygen level to approximately 25 mg/L. The aerators then strip the excess oxygen from the basin and reestablish an equilibrium dissolved oxygen concentration. By recording the dissolved oxygen concentration over time, a deoxygenation curve is developed, the inverse of which corresponds to the oxygenation potential of the aerators. By fitting a theoretical curve to the field results, the overall process oxygen mass transfer coefficient (αFk_La) can be determined (Daigger et al., 1992; Kayser, 1979; Speirs and Stephenson, 1985).

Dissolved oxygen concentrations are recorded at various locations in the basin using chapter or online dissolved oxygen meters. To define the number of dissolved oxygen probes required and their locations for the test, a dissolved oxygen profile should be constructed to determine the mixing conditions within the tank to be tested. Well-mixed reactors require less dissolved oxygen sampling locations and probes.

When all equipment is ready, the basin to be tested is taken offline. The H_2O_2 is then added to the basin and dissolved oxygen readings are recorded. Data recording can occur in several ways: the dissolved oxygen probes can be tied into an online monitoring system or dissolved oxygen concentrations can be recorded periodically. Data are typically recorded for at least 2 hours. After the readings are taken, a desorption model curve is fit to the data using a computer program. The model parameter, αFk_La, is determined and the oxygen transfer capacity can be obtained from it.

A key issue to evaluate when considering the use of the hydrogen peroxide method is the flexibility of operation of the facility being evaluated. The hydrogen peroxide method requires taking the tank being tested out of service for a minimum of 2 hours prior to the beginning of the test, plus 2 hours or longer during the test. Therefore, if the facility does not have the flexibility to divert the aeration influent to another tank or section of the plant for a minimum of 4 hours, another method of testing should be considered. If required, an operating tank can be tested with the hydrogen peroxide method, but some corrections are required and the results obtained may not be as accurate as with the tank that is isolated (i.e., offline). It should be noted that the quality of the mixed liquor and the viability of the microorganisms present in it are not affected by the addition of H_2O_2, and normal operation can resume immediately after the test is completed.

A summary of recommendations for determining if the hydrogen peroxide test is the most appropriate method to use is shown in Table 25.16. If the maximum aeration capacity needs to be determined, then maximum submergence power draw for the aerators or maximum airflow in a diffused air system should be provided. The relationship between aerator submergence and power draw should be evaluated and graphed before the test (preferably before installing equipment or ordering H_2O_2). Calculations to estimate H_2O_2 requirements are shown herein.

For better results, multiple tests (at least three) should be performed. If a dissolved oxygen control study is being conducted, tests will be run at minimum and maximum energy input rates. For the test, the mixed-liquor volatile suspended solids concentration should be within the normal operating range.

TABLE 25.16 Examples of when to use the hydrogen peroxide test.

Recommended to Use	Not Recommended to Use
• In surface aeration systems • In diffused (subsurface) aeration systems, when the off-gas test is not warranted or not practical	• When the aeration basin to be tested cannot be taken out of service for approximately 3 to 4 hours per test • When thorough distribution and mixing of H_2O_2 is not possible due to – Covered tanks without appropriate access points – Large tanks with difficult access – Poor mixing conditions • In very large tanks where quantity of H_2O_2 required make the test too expensive • When mixing and dissolved oxygen distribution conditions require an impractical large number of dissolved oxygen probes

DATA ANALYSIS AND CALCULATIONS FOR THE HYDROGEN PEROXIDE TEST. The desorption curve obtained from the test follows a standard equation or model that can be fitted using a nonlinear method. The form of the model is (Metcalf & Eddy, 1991; Speirs and Stephenson, 1985)

$$C_t = C_\infty^* + (C_0 - C_\infty^*)^{-\alpha F k_L a \times t} \tag{25.12}$$

where

α = the ratio of the process water, $k_L a$, of a new diffuser to the clean water, $k_L a$, of a new diffuser, also known as the "alpha factor" (dimensionless);
F = the ratio of the process water, $k_L a$, of a diffuser after a given time in service to the process water, $k_L a$, of a new diffuser, also known as the "fouling factor" (dimensionless);
$k_L a$ = the apparent volumetric oxygen mass transfer coefficient in clean water at temperature, T (h^{-1});
C_t = the dissolved oxygen concentration at time, t (mg/L);
C_∞^* = the steady-state dissolved oxygen saturation concentration attained at infinite time, at water temperature, T, and field atmospheric pressure, P_b (mg/L);
C_0 = the initial dissolved oxygen concentration (mg/L); and
t = the time (h).

The primary result of interest from this test is the oxygenation capacity of the system under various operating conditions.

The SOTR or oxygenation capacity (OC) at standard conditions is calculated as follows:

$$\text{SOTR} = k_L a_{20} \times C_{\infty 20}^* \times V \times 24/1000 \tag{25.13}$$

where

SOTR = the standard oxygen transfer rate, (kg O_2/d);
$C_{\infty 20}^*$ = the steady-state dissolved oxygen saturation concentration attained at infinite time, at 20 °C, and standard atmospheric pressure of P_S = 1 atm, (mg/L);
V = the aeration tank volume (m^3); and
$k_L a_{20}$ = apparent volumetric oxygen mass transfer coefficient in clean water at 20 °C (standard conditions: clean water conditions, dissolved oxygen = 0 mg/L, T = 20 °C, ambient pressure, p_s = 1 atm).

The SOTR can be calculated if the α factor for this particular wastewater and aeration system is known and the H_2O_2 test was performed on a relatively new system ($F = 1$), in which case

$$k_La = \alpha F k_La / \alpha F \tag{25.14}$$

The oxygen mass transfer coefficient (k_La) varies with temperature and can be corrected to the standard temperature of 20 °C using the following equation:

$$k_La_{20} = k_La\ \theta^{(20-T)} \tag{25.15}$$

where

T = the actual test liquid temperature (°C) and 20 °C is the base temperature and
θ = the Arrhenius temperature coefficient with a typical value of 1.024.

The equilibrium dissolved oxygen concentration (C^*_∞) measured during the process water H_2O_2 test can be corrected for dissolved solids, pressure, and temperature differences between field and standard conditions using the following equation:

$$C^*_{\infty 20} = C^*_\infty / \beta\Omega\tau \tag{25.16}$$

where

β = the correction factor for dissolved solids and can be assumed to be equal to 1 if the plant treats domestic wastewater. For wastewater with a considerable industrial component, its value can be calculated based on the dissolved solids content of the process water. In this case, β should be calculated as the ratio of the dissolved oxygen surface saturation concentration in water, with dissolved solids equal to that of the process water, to the dissolved oxygen surface saturation concentration in clean water;
Ω = the correction factor for pressure and at tank depths of less than 6 m it may be approximated by p_b/p; and
τ = the correction factor for temperature that can be calculated based on published dissolved oxygen surface saturation values as

$$\tau = C^*_S / C^*_{S,20} \tag{25.17}$$

where

C^*_S = the tabular value for dissolved oxygen surface saturation concentration at water temperature, T (i.e., that recorded during the test), standard atmospheric pressure, p_s, and 100% relative humidity;

$C^*_{S,20}$ = the tabular value for dissolved oxygen surface saturation concentration at water temperature 20 °C, standard atmospheric pressure, p_s, and 100% relative humidity; and $C^*_{S,20}$ = 9.08 mg/L (Metcalf & Eddy, 1991).

The standard aeration (electrical) efficiency of the equipment is defined as the oxygen transfer rate per unit of power input, and can be calculated as

$$\text{SAE} = \text{SOTR}/(P \times 24) \tag{25.18}$$

where

SAE = the standard aeration efficiency, kg O_2/kWh; and
P = the active power of the blower or mechanical aerator, kW.

The OTR or oxygenation capacity at field (normal operating) conditions is also dependent on the residual dissolved oxygen concentration required. Therefore, the oxygenation capacity calculation is similar to the SOTR calculation, but with corrections for aeration basin operating conditions (all the aforementioned parameters) and taking into consideration the dissolved oxygen concentration desired in the aeration basin. The oxygenation capacity is calculated as follows:

$$\text{OC} = \alpha F k_L a_{20}\, \theta^{(T-20)}\, (\beta \Omega \tau\, C^*_{\infty\, 20} - C_r) \times V \times 24/1000 \tag{25.19}$$

where

OC = the oxygenation capacity or OTR at temperature, T, ambient pressure, p_b, with process wastewater and residual dissolved oxygen concentration, C_r, kg O_2/d;
C_r = the residual dissolved oxygen required in the aeration basin, mg/L; and
T = the mixed-liquor temperature, °C.

The residual dissolved oxygen used (C_r) is usually 0 mg/L to estimate the maximum oxygenation capacity or 2 mg/L to estimate the capacity at a recommended dissolved oxygen value.

Another value that can be calculated from the clean water tests is the standard oxygen transfer efficiency (SOTE), defined as the mass of oxygen transferred to the mixed liquor per mass of oxygen supplied to the tank. The SOTE is calculated as follows:

$$\text{SOTE} = 100 \times \text{SOTR}/\text{O}_2 \text{ mass flow} \tag{25.20}$$

$$O_2 \text{ mass flow} = Q_{AIR} \times \delta_{AIR} \times O_2/\text{air} \quad (25.21)$$

where

SOTR = the standard oxygen transfer rate or oxygenation capacity at standard conditions, kg O_2/d;
SOTE = the standard oxygen transfer efficiency, %;
O_2 mass flow = the mass of oxygen pumped into the aeration basin, kg O_2/d;
Q_{AIR} = the airflow rate, m^3/d;
δ_{AIR} = the air density at standard conditions, approximately 1.2 kg/m^3; and
O_2/air = the oxygen content of air, approximately 0.21 kg O_2/kg air.

Similarly, OTE under field or process conditions can be calculated as follows:

$$\text{OTE} = 100 \times \text{OC}/O_2 \text{ mass flow} \quad (25.22)$$

APPENDIX D: AMERICAN SOCIETY OF CIVIL ENGINEERS CLEAN WATER TEST

The clean water oxygen transfer test measures the rate of oxygen transfer in tap water. Test results provide information on the oxygen transfer system independent of any effects of wastewater because the test is performed with clean water. This test can be used to

- Verify performance claims by aeration system manufacturers,
- Compare different aeration devices,
- Observe the effects of specific factors (such as submergence) on aeration system devices, and
- Determine alpha factors when used in conjunction with wastewater oxygen transfer tests.

The test is conducted by removing the dissolved oxygen from the clean (tap) water in the aeration basin using sodium sulfite in conjunction with a catalyst (cobalt chloride or cobalt sulfate), then re-oxygenating. Dissolved oxygen concentrations are measured at several points throughout the aeration tank during re-oxygenation. Oxygen transfer parameters (Fk_La and C_S) are calculated by performing nonlinear regression on the dissolved oxygen values obtained at each sample location during re-oxygenation. Because the test is done with clean water, the alpha factor, α, is assumed to be 1.0.

TABLE 25.17 Examples of when to use the clean water test.

Recommended to Use	Not Recommended to Use
• To obtain information on the oxygen transfer efficiency and mass transfer coefficient of an aeration system independently of any effects of wastewater • To combine with a dirty water test and determine the alpha factor (α) of the system • In mechanical (surface) or diffused-air (subsurface) aeration systems • Prior to start-up of newly constructed or retrofitted aeration systems • To compare on-site clean water efficiency results with manufacturers' estimates	• When the aeration basin to be tested does not have clean (tap) water meeting ASCE standards for the tests • When thorough distribution and mixing of the reagents required (e.g., Na_2SO_3 and $CoCl_2$ or $CoSO_4$) is not possible due to – Covered tanks without appropriate access points – Large tanks with difficult access – Poor mixing conditions • When mixing and dissolved oxygen distribution conditions require a very large number of dissolved oxygen probes

Some of the requirements of this test are similar to those of the hydrogen peroxide test:

- The number of dissolved oxygen measurement locations required increases with decreasing levels of mixing within the tank to be tested (ASCE, 1984),
- The aeration tank to be tested has to be taken out of service, and
- The data analysis approach is similar.

In addition to these requirements, clean water (i.e., tap water) is required in the tank. Therefore, this test is usually performed to test new aeration equipment prior to starting the normal operation of the tank. A summary of recommendations to determine if the clean water test is the most appropriate method to use is shown in Table 25.17. A complete description of the ASCE Clean Water Test can be found in literature by ASCE (1984) and U.S. EPA (1989).

For clean water, the rate of oxygen transfer is proportional to the difference between the existing dissolved oxygen concentration and the equilibrium concentration of the oxygen in the water. In other words, the greater the difference between the existing concentration and the equilibrium concentration, the greater the driving force for oxygen transfer through the film. This is expressed by the following equation:

$$dC/dt = k_L a \times (C_\infty^* - C) \tag{25.23}$$

where

dC/dt = the rate of change of oxygen concentration, mg/L·h;
k_La = the apparent volumetric oxygen mass transfer coefficient in clean water at temperature, T, also referred to as oxygen mass transfer coefficient, h^{-1};
C^*_∞ = the steady-state dissolved oxygen saturation concentration attained at infinite time, at water temperature, T, and field atmospheric pressure, P_b (i.e., the equilibrium concentration of the oxygen in the water), mg/L; and
C = dissolved oxygen concentration in the water, mg/L (all the aforementioned nomenclature is from ASCE's *Standard for Measurement of Oxygen Transfer in Clean Water* [1984]).

When integrated between time zero and time, t, Equation D.1 becomes

$$C = C^*_\infty - (C_0 - C^*_\infty)^{-k_La \times t} \tag{25.24}$$

where

C = the dissolved oxygen concentration at time, t (mg/L), and
C_0 = the initial dissolved oxygen concentration, (mg/L).

A nonlinear regression is performed on the test data for dissolved oxygen concentration, C, over time, t. The result of the nonlinear regression are values for k_La and C^*_∞ for each sample point in the test basin. Either a commercially available software program or a program developed specifically for the ASCE standard clean water oxygen transfer test can be used for the nonlinear regression.

The values of k_La and C^*_∞ can be adjusted to standard conditions and used in calculating the standard oxygen transfer rate or oxygenation capacity, the standard aeration (electrical) efficiency, and the standard oxygen transfer efficiency using the equations shown for the H_2O_2 test.

APPENDIX E: CASE-HISTORY TRACER TESTING ANAEROBIC DIGESTER

Digester tracer studies are performed on digesters with suspected mixing problems. Indicators of poor mixing in digesters include grit or scum buildup in the digester, low gas production, and poor volatile solids destruction.

Digester tracer studies are also used to evaluate mixing equipment, equipment layout, and digester geometry. Rectangular and large-diameter digesters are more susceptible to mixing problems than standard cylindrical or egg-shaped digesters. Digesters that experience large variations in sludge or solids concentration and/or compositing may also experience large variations in mixing efficiency. The performance of digesters operating near the design HRT is more sensitive to poor mixing.

EXAMPLE: SKYWAY WATER POLLUTION CONTROL PLANT DIGESTER TRACER STUDIES. ***Background and Project Objectives.*** The Skyway Water Pollution Control Plant has two primary digesters (No. 1 and No. 2) followed by a secondary digester (No. 3). The plant staff was concerned that the volatile solids destruction had deteriorated over the years and may not meet future guidelines for solids disposal. At the time this optimization project started, the plant was considering investing up to $6.5 million for digester upgrades.

The objective of this optimization project was to evaluate the active volume of the anaerobic digesters and the effect of digester cleaning on mixing and operating efficiency. Information resulting from this project was used to decide whether to expend for this proposed upgrade of the digester mixing and heating system or simply implement a digester cleaning program for the rest of the plants in the region.

The primary digesters have not been taken out of service since construction in the mid-to-late 1970s. In 1999, Digester No. 1 was cleaned and, having Digester No. 2 still uncleaned, the mixing conditions in both digesters were determined and compared to investigate any potential improvements realized by cleaning. In summary, the goal of this project was to compare the mixing and performance of the clean digester to the uncleaned unit.

Test Method. Tracer tests were used to evaluate the mixing characteristics in both anaerobic digesters. Test results served to indicate potential hydraulic short-circuiting and dead (inactive) volumes. For the evaluation of effective digester volume, a slug test was used (Cholette and Cloutier, 1959; Monteith and Stephenson, 1981).

The test consists of injecting a known quantity of tracer as a slug upstream of the unit and then sampling and analyzing the effluent for this tracer over a period of time. The time period must be a minimum of at least 3 average HRTs. The HRT for a completely mixed anaerobic digester is typically in the order of 15 to 45 days. However, it may be shorter if the digester is ineffectively mixed.

Materials used to perform the digester mixing studies included a polymer mixing unit, a polymer pump, tracer chemical, and sample collection equipment (gloves and bottles). Technical-grade anhydrous lithium chloride (LiCl) was used as tracer.

Results and Data Analysis. Digester No. 2, the uncleaned digester, was tested while both digesters were in service. Digester No. 1, the clean digester, was tested later and received 100% of the incoming sludge because Digester No. 2 was being cleaned and repaired.

Lithium concentrations from Digester No. 2 and Digester No. 1 tests are shown in Figure 25.5 and Figure 25.6, respectively.

Initially, both digesters were modeled as single completely stirred tank reactors (CSTRs), with an initial Li concentration equal to that measured immediately after lithium addition (Figure 25.7). The Li data provided washout curves that were matched using a mass balance for Li around the digesters (Figure 25.8 and Figure 25.9).

The results from fitting this model (exponential curve) to the field data resulted in HRTs of approximately 12 days and 47 days, with R^2 values of 95% and 86% for Digester No. 2 and Digester No. 1, respectively.

To fit the results to this CSTR model, the influent flows to the digesters were assumed to remain constant at the average values for the duration of the test. Because the flowrate to the digesters actually varied during the test, the same CSTR model was used, but with the influent flow data varying dynamically, as it was recorded during the study. Because this analysis cannot be conducted with standard software, the General Purpose Simulator (GPS-X) was used for this analysis. The results from this

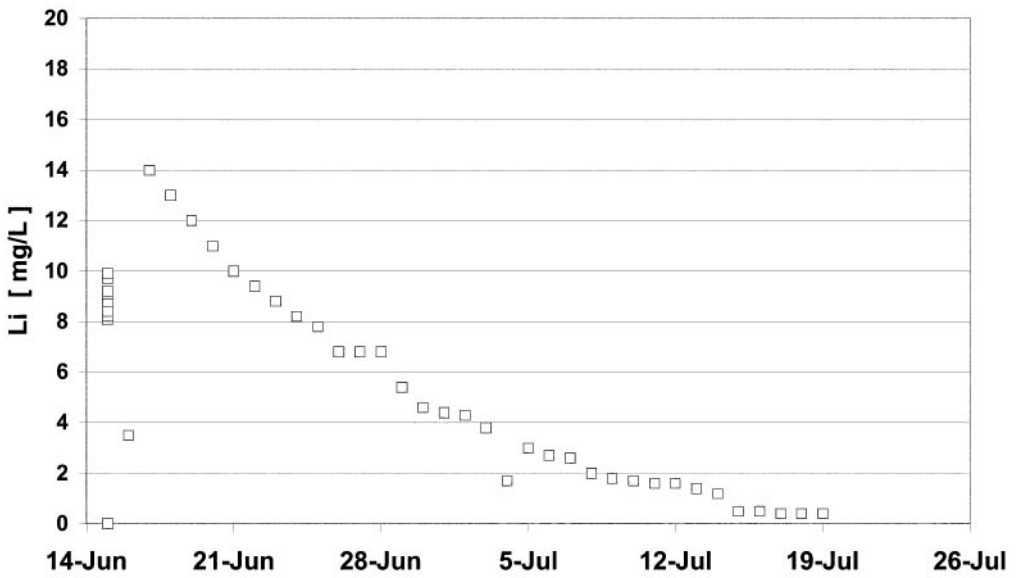


FIGURE 25.5 Tracer study results for Digester no. 2.

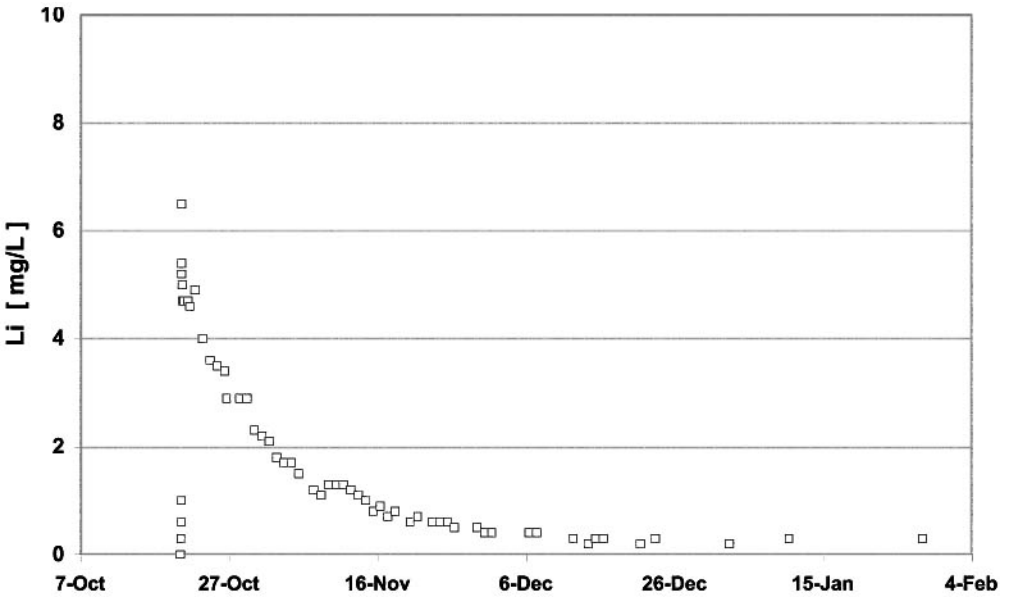


FIGURE 25.6 Tracer study results for Digester no. 1.

attempt resulted in HRT values of approximately 9 days and 31 days for Digester No. 2 and Digester No. 1, respectively. Both fits had R^2 values of 99%

Other models were tested in an attempt to corroborate the results from the simple CSTR washout curve. A model consisting of a CSTR combined with a bypass line also directed into a small CSTR was tested (Figure 25.10). This model resulted in HRTs of approximately 9 days and 33 days and R^2 values of 90% and 94% for Digester No. 2 and Digester No. 1, respectively. The results for Digester No. 2 are shown in Figure 25.11.

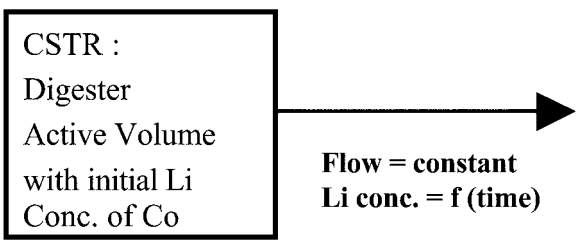


FIGURE 25.7 Completely stirred tank reactor with an initial Li concentration equal to that measured immediately after lithium addition.

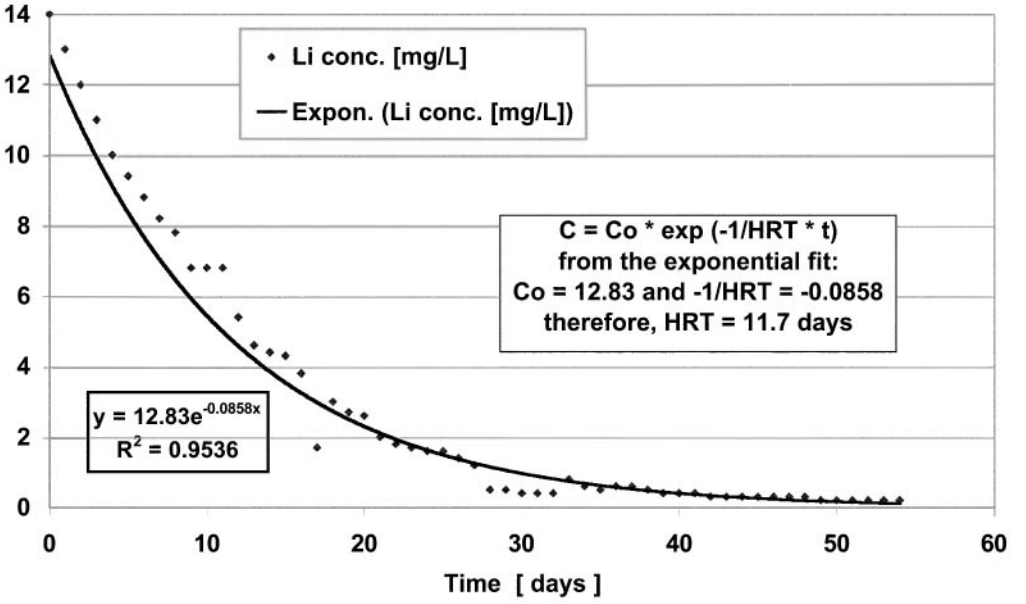


FIGURE 25.8 Lithium washout curve fitted to a simple CSTR model.

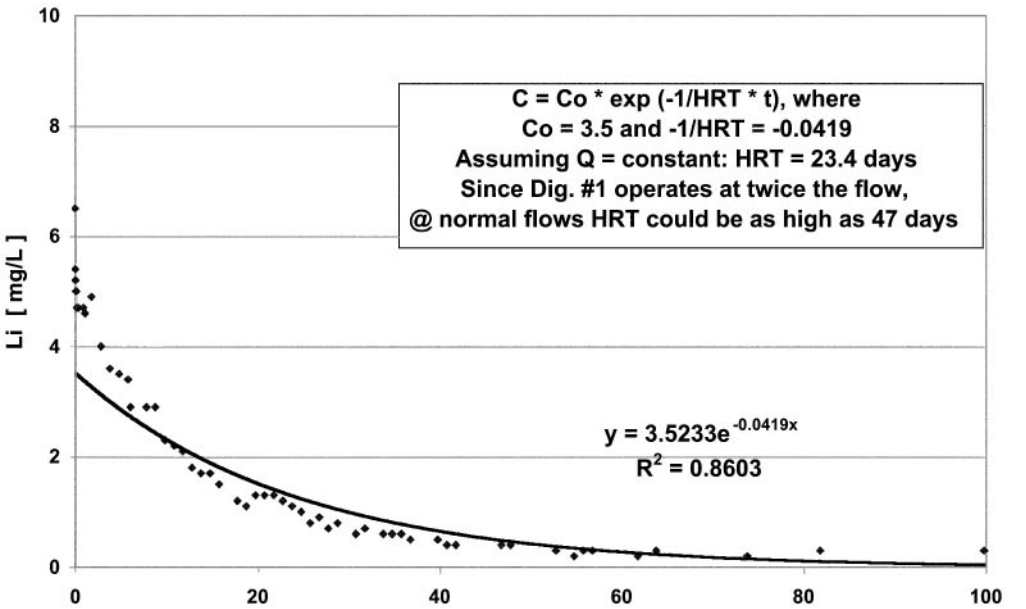


FIGURE 25.9 Lithium washout curve for digester no. 1 fitted to a simple CSTR model.

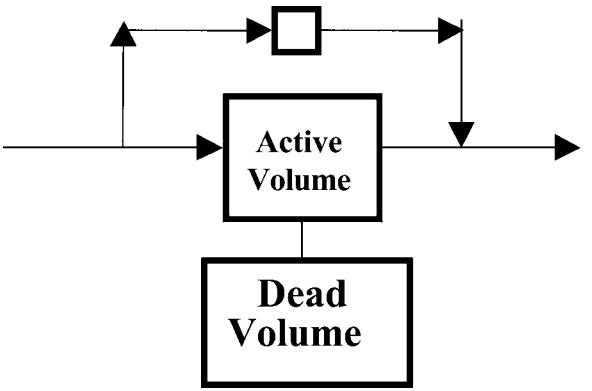


FIGURE 25.10 Completely stirred tank reactor combined with a bypass line directed to a small CSTR.

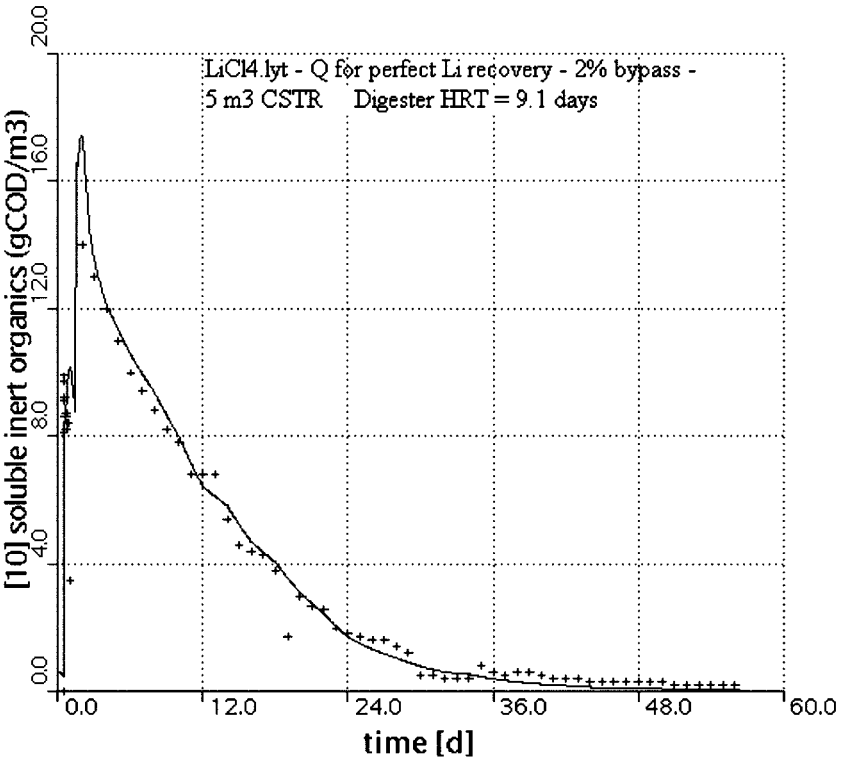


FIGURE 25.11 Results for Digester no. 2 using the model shown in Figure 25.10.

TABLE 25.18 Summary of results for mixing tests in Digester No. 1 and Digester No. 2.

	Average sludge Flowrate during test	Simple CSTR model at constant flow		Simple CSTR model at actual variable flows		Main CSTR with a bypass into a small CSTR at actual variable flows	
	(m^3/d)	HRT (days)	R^2	HRT (days)	R^2	HRT (days)	R^2
Digester No. 1 (clean)	486	47	86%	31	99%	33	94%
Digester No. 2 (uncleaned)	200	12	95%	9	99%	9	90%

A summary of the hydraulic regimes of these two tanks is provided in Table 25.18.

Conclusions and Recommendations Derived from the Digester Tracer Study. A comparison between the results for both anaerobic digesters indicates that the Li test on Digester No. 2 results in an active HRT that ranges from 9 to 12 days, with almost none or negligible bypass (hydraulic short-circuiting) occurring. The Li test on Digester No. 1 results in an active HRT that ranges from 31 to 47 days, with almost none or negligible bypass (hydraulic short-circuiting) occurring. These HRTs take into consideration the fact that, during the lithium test, Digester No. 1 was receiving twice the normal flow, and are corrected to show the retention time this digester would have if both digesters were in service and each digester was receiving half of the total sludge flow.

The lithium tests indicate that cleaning Digester No. 1 improved the mixing conditions and the active volume of the tank, resulting in an HRT time three to four times larger than under uncleaned conditions. This conclusion is based on the assumption that the mixing conditions of Digester No. 1 were not influenced by the fact that it was receiving twice the normal flow during the mixing tests. Both digester HRTs exceed the minimum HRT of 4 days suggested for completely mixed digesters operating at 35 °C (Metcalf & Eddy, 1991). This explains the similar volatile destruction values obtained for both digesters.

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INTRODUCTION

Disinfection of effluent from water reclamation facilities (WRFs) is required to decrease the disease risks associated with the discharge of wastewaters containing human pathogens (disease-causing organisms) into receiving waters. These microorganisms are present in large numbers in wastewater effluents, and waterborne disease outbreaks throughout history have been directly attributed to wastewater-contaminated drinking water supplies, water-contact recreational waters, and affected shellfish habitats.

The pathogens of greatest concern are enteric (intestinal) bacteria, viruses, and parasites. Diseases that can be spread via bacterial contamination include salmonellosis (e.g., typhoid and paratyphoid fevers), cholera, gastroenteritis from enteropathogenic *Escherichia coli*, and shigellosis (bacillary dysentery). Infectious viruses include the hepatitis virus, poliovirus, Coxsackie viruses A and B, echoviruses, reoviruses, and adenoviruses (U.S. EPA, 1986). Parasitic diseases include giardiasis and amoebic dysentery. Table 26.1 lists some of the diseases and their respective methods of transmission (Pipes, 1982).

TABLE 26.1 Waterborne diseases and transmission routes (Pipes, 1982).

	Reported in United States as transmitted via		
Waterborne diseases	**Drinking water**	**Recreational waters**	**Shellfish**
Bacterial diseases			
Bacillary dysentery (*Shigella* spp.)	Yes	Yes	No
Cholera (*Vibrio cholerae*)	No	No	Yes
Diarrhea (enteropathogenic *Escherichia coli*)	Yes	No	No
Leptospirosis (*Leptospira* spp.)	Yes	Yes	No
Salmonellosis (*Salmonella* spp.)	Yes	Yes	Yes
Typhoid fever (*Salmonella typhi*)	Yes	Yes	No
Tularemia *(Francisella tularensis*)	Yes	No	No
Yersinosis (*Yersinia pseudotuberculosis*)	Yes	No	No
Unknown etiology			
Diarrhea, acute undifferentiated	Yes	Yes	Yes
Gastroenteritis, acute, benign, self-limiting*	No	Yes	No
Viral diseases			
Gastroenteritis (Norwalk-type agents)	Yes	No	No
Hepatitis A (hepatitis virus)	Yes	Yes	Yes
Parasitic diseases			
Amebic dysentery (*Entamoeba histolytica*),	Yes	No	No
Ascariosis (*Ascaris lumbricoides*)	No	No	No
Balantidal dysentery (*Balantidium coli*)	No	No	No
Giardiasis (*Giardia lamblia*)	Yes	No	No

*Not a reportable disease, but transmission via recreational waters has been demonstrated by an epidemiological investigation.

Natural pathogen-reducing processes (e.g., dilution, physical removal, and die-off) must be considered first. The effects of dilution on the concentration of organisms discharged into a stream, river, lake, or other receiving water can be estimated using physical laws. Existing mathematical models can be used to estimate bacterial die-off (Berg, 1978; Hubly et al., 1985). Mathematical models and more information on die-off are available in *Design Manual—Municipal Wastewater Disinfection* (U.S. EPA, 1986). The idea of using die-off to determine the appropriate level of disinfection for wastewater discharges to receiving waters was first discussed by H. Chick in 1908 (Chick, 1908). Chick's law, which measures the basic effectiveness of disinfection processes, is as follows:

$$dN/dt = -kN \tag{26.1}$$

Where

dN/dt = rate of change of the number of organisms in the population,
k = organism die-off rate constant, and
N = number of surviving organisms per unit volume at any given time.

In addition to natural die-off, secondary treatment processes can remove up to 95% of waterborne microorganisms from raw wastewater. Tertiary treatment can remove even more. Nonetheless, regulators typically require more pathogen inactivation or removal than dilution, die-off, or secondary or tertiary treatment processes can achieve. Disinfection successfully meets their requirements.

A number of disinfection techniques have been used throughout history, starting with boiling water as early as 500 B.C. (Table 26.2). Generally, the effectiveness of disinfectants depends on exposure time and the disinfectant's toxicity. The kinetics of organism die-off (eq 26.1) is influenced by poor mixing, cell resistance, dispersion, complexion, oxidation, clumping, and detention time in the disinfection chamber.

TABLE 26.2 Disinfection techniques (Connell, 2002).

Method	Example
Physical	Heat, storage
Light	UV irradiation
Metals	Silver
pH	Acids, alkalis
Oxidants	Chlorine, sodium and calcium, hypochlorite, chlorine dioxide, ozone, peracetic acid
Others	Surface active agents

Operators can evaluate the chamber's effectiveness via a residence time test. These tests, which are relatively easy to perform, indicate the length of time the average cell will remain in contact with the disinfectant. U.S. Environmental Protection Agency (U.S. EPA) and Water Environment Federation manuals describe methods for performing and evaluating these tests (U.S. EPA, 1986; WEF, 1996).

Disinfection is an important step in deactivating potentially harmful organisms. This chapter will describe the most commonly used disinfection practices, including UV irradiation, chlorination and subsequent dechlorination, ozonation, and other methods (e.g., bromine chloride, chlorine dioxide, and peracetic acid).

ULTRAVIOLET DISINFECTION

For the past several years, concerns about chlorine-related storage, handling, and water-quality effects have prompted wastewater utilities to consider alternatives to chlorine disinfection. Ultraviolet disinfection has been the primary benefactor of this transition. Ultraviolet light is an invisible light radiation with wavelengths shorter than those associated with visible light. A useful and important resource for operators is *UV Disinfection Guidelines* (NWRI and AWWARF, 2000).

Ultraviolet systems are designed to reduce bacteria counts to a certain allowable level depending on the receiving water quality and permit requirements. The dose and intensity of UV light available to inactivate bacteria are measured in mW-s/cm^2 and mW/cm^2, respectively.

The UV dose is the product of the energy-emission (lamp-intensity) rate and the time the organisms are exposed to the germicidal energy at 253.7 nm. The equation is

$$D = It \tag{26.2}$$

Where

D = UV dose (mW-s/cm^2);
I = intensity of UV radiation (mW/cm^2 of lamp at 253.7 nm);
t = time of exposure (seconds).

Its effectiveness depends on the light's intensity and the length of time it is in contact with the organism. Any condition that reduces either the light intensity or the contact time will decrease the UV disinfection system's performance. Ultraviolet disinfection involves an interface of fluid dynamics, the light intensity profile in the reactor, and the microbial inactivation kinetics. Although tools exist to mathematically bring these

together to determine the delivered dose, the current state-of-the-art requires empirical validation of UV reactor performance using an empirical bioassay under a range of operating conditions and water qualities. The bioassay performance data can then be used as a site-specific design tool.

Flowrate affects the contact time. Increasing the flowrate across the UV lamps decreases the contact time and lowers the inactivation rate. Many wastewater treatment plants (WWTPs) have a wide variation in flow, especially comparing average daily design and peak flow values. Most UV systems are designed to disinfect at the peak flowrate. Some state regulators have allowed systems to be designed for full disinfection at the maximum recorded daily or hourly flow. If short-circuiting occurs in the contact channel, the contact duration will be reduced.

Wastewater characteristics also affect disinfection performance. The two parameters that most affect performance are UV transmittance and suspended solids concentration. The UV transmittance through water, defined as the percentage of UV light intensity not absorbed after passing through 1 cm of water, depends on dissolved and suspended matter. Reduced transmittance lowers the intensity of the light reaching the bacteria, resulting in less inactivation. Suspended solids can lower the UV transmittance by scattering and absorbing the light; suspended solids can also reduce the inactivation level by encapsulating the bacteria and protecting them from exposure to UV light. Plants using ferrous (as ferric salts) for enhanced sedimentation–coagulation also may reduce the effective performance of UV disinfection. The water's visual clarity is not always a good indicator of UV transmittance, because water that appears clear in visible light may actually absorb invisible UV wavelengths.

Ultraviolet light is typically considered when the treatment plant's permit requires little or no chlorine residual. Therefore, the UV approach is typically compared with ozonation and with chlorination and dechlorination. Safety issues and disinfection byproducts (DBPs) related to the use and onsite storage of chlorine gas have also contributed to the consideration of UV light. As more permits are revised to require low chlorine residuals and safety concerns are addressed, more UV systems (Figure 26.1) will be used.

Ultraviolet light efficiency is primarily limited by suspended solids, so UV light disinfects advanced treatment effluent most efficiently because of its low suspended solids concentrations. However, if the suspended solids levels are low enough, UV disinfection can treat secondary WWTP effluents, reliably achieving bacterial levels of fewer than 200 colonies of fecal coliforms/100 mL.

There are two basic types of UV-reactor system designs: one immerses quartz-sheath enclosed lamps directly in the final effluent, and the other conveys effluent

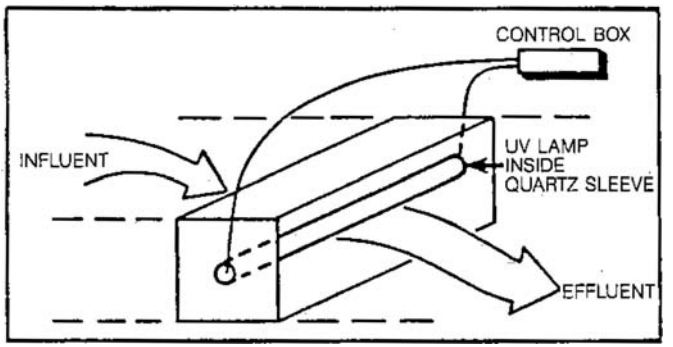


FIGURE 26.1 Schematic of ultraviolet disinfection system.

through transparent polytetrafluoroethylene (PTFE) or quartz tubes while adjacent, nonsubmerged UV lamps irradiate the wastewater. The first design is prevalent; the second is rarely encountered. Polytetrafluoroethylene absorbs UV rays better than quartz glass. Ultraviolet resemble fluorescent tubes and can be made of quartz glass containing low- or medium-pressure mercury vapor. The low-pressure lamps generate mostly germicidal 253.7-nm UV rays. The medium-pressure lamps are polychromatic and emit a broader range of wavelengths, including the germicidal wavelengths between 200 and 300 nm. Because disinfection occurs rapidly, the UV chamber (a plug-flow reactor) is relatively small, even at large treatment facilities, and maximizes disinfection efficiency. Turbulent plug flow past the tubes is necessary to ensure mixing and good microorganism exposure so all material in the effluent receives a lethal dose of UV.

DISINFECTION MECHANISM. Ultraviolet light inactivates bacteria and viruses by altering their cellular genetic material, thereby preventing cell replication. At a wavelength of 253.7 nm, ultraviolet light can inactivate microorganisms without significantly altering the effluent's physical and chemical properties. Unlike chlorine, UV light leaves no residual that can affect receiving waters; it adds nothing but energy, which produces some heat.

EQUIPMENT DESCRIPTION. The UV light process has several components (Figures 26.2 and 26.3), each with distinct functions (Table 26.3). The lamps typically are arranged horizontally (parallel to the effluent flow) or vertically (perpendicular to the effluent flow) (Figure 26.3).

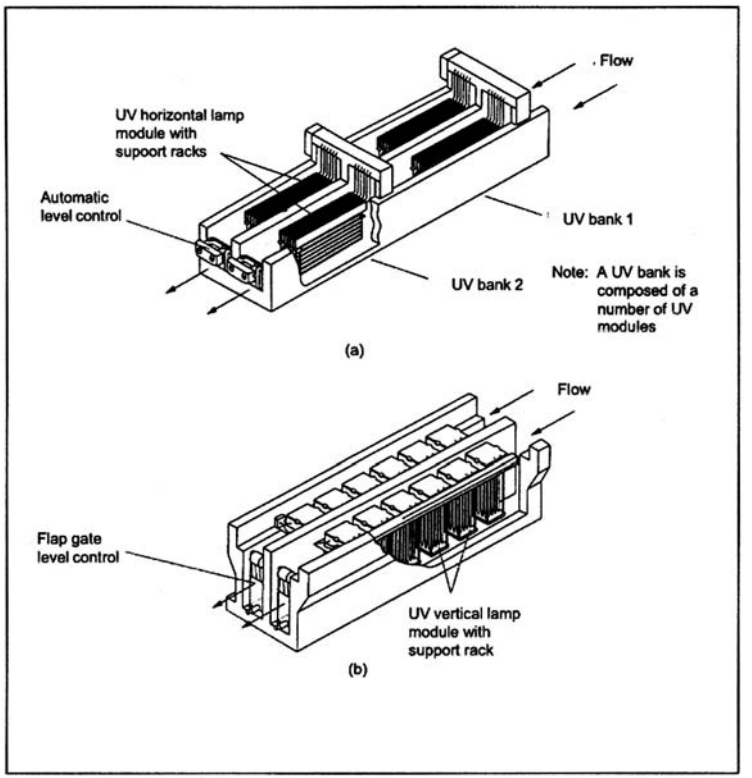


FIGURE 26.2 Ultraviolet disinfection channel and control building (Source: ITT Advanced Water Treatment–WEDECO).

BASIC STARTUP AND SHUTDOWN. Before starting the UV disinfection system, operators should check the following items:

- The power supply to the following units:
  —Motor control center,
  —Local disconnect, and
  —Local control panel;
- The standby power system (to ensure readiness during the disinfection season, test the UV system under standby power and periodically exercise the standby power supply);
- The normal operating positions of the valves upstream and downstream of the appropriate chambers;
- The readiness of the UV unit, including the indicator lights, monitors, and gauges;
- The effluent outfall (must be open); and
- The effluent flow control gate or adjustable weir (should operate freely and automatically).

Once the prestart checks have been completed, operators may move the local on–off switch to the "on" position.



Source: Crites and Tchobanoglous, 1998.
(a) adapted from Trojan Technologies, Inc.
(b) adapted from Infilco Degremont, Inc.

FIGURE 26.3 Typical lamp configuration for (a) horizontal and (b) vertical UV reactors.

When taking the UV unit out of service, operators should

- Move the on–off selector switch to the "off" position;
- Perform lockout–tagout safety procedures to isolate individual lamp racks without affecting the rest of the operating system;
- Close the appropriate valves upstream and downstream of the chambers;
- If shutdown is a result of mechanical failure (long-term) or is for routine preventive maintenance, then open, lock out, and tag all electrical breakers;
- Properly store UV equipment and controls; and
- Clean the channel to remove algae and other accumulated materials.

TABLE 26.3 Ultraviolet light disinfection system components and their uses.

Component	Features	Function
UV disinfection chamber	Flowthrough stream design for plug flow	Provides sufficient detention time for UV germicidal dose to take effect.
Control box	Remote signals, UV lamp ballasts	Control UV reactor's electrical operations and alarms.
UV lamp	Three-pin plug	Generates UV light.
	Elapsed time meter, nonresettable	Records elapsed time (in hours) and keeps a permanent record.
Flow control	Manually operated gates	Diverts flow to standby reactor for channel servicing.
	Counterweighted flow control (underflow) gate or downward opening gate weir	Maintains constant water level in the channel at varying flows to ensure that the water level over the UV lamps is constant.
Alarm	Remote warning buzzer and visible light	Indicates overflow or low UV output.
Intensity monitor	Photocell and electronic circuit	Measures and monitors the UV energy through the water or at the lamp surface.
Indicator light	Green	Safe condition.
	Amber	Warning: low UV output. Lamps need cleaning or replacement.
	Red	Warning: falls below the safe level.

Operators should establish a preventive maintenance procedure and perform it at least twice each year—once immediately after disinfection season ends and once in the month before disinfection season begins. They should clean all UV lamps and check the system's electrical features (e.g., lamps, ballasts, UV intensity meters, ground fault interrupts, and connections).

PROCESS CONTROL VARIABLES. Ultraviolet disinfection reactor efficiency depends on the following:

- Ultraviolet transmittance or absorbance,
- Equipment design,
- The reactor's hydraulic characteristics,
- The iron concentration,

- Wastewater quality, and
- Age of the UV lamps.

UV Transmittance or Absorbance. The disinfection rate correlates directly with the UV light's average intensity (the rate of germicidal energy transmission at 253.7 nm from the UV source to the wastewater effluent). This energy transmittance (intensity) depends on the lamp type, lamp spacing, effluent quality, and thickness of the foulant coating the lamp. Operators may affect the intensity by regularly cleaning the lamps to remove the coating if the technology does not have an automatic cleaning mechanism. The following equation approximates bacteria removal as a function of UV lamp intensity in an ideal UV reactor (no suspended solids):

$$N = N_0 \exp(-kIt) \tag{26.3}$$

Where

N = effluent bacterial density after UV radiation (coliform colonies/100 mL);
N_0 = influent bacterial density before UV radiation (coliform colonies/100 mL);
k = rate constant ($cm^2/mW{\cdot}s$);
I = intensity of UV radiation (mW/cm^2 of lamp at 253.7 nm); and
t = time of exposure (seconds).

Equipment Design. Both low- or medium-pressure UV systems are available. Both emit light at 253.7 nm, but medium-pressure lamps emit it at a much larger intensity. The medium-pressure lamps disinfect faster and have better penetration, but require more energy and run at higher temperatures. They also require fewer lamps, making them a good choice at large facilities, where the maintenance costs balance out the energy costs.

Exposure time, which is inversely related to fluid velocity, depends on the lamp configuration (lamp spacing and reactor detention time). Closely spaced lamps have more UV intensity than those spaced farther apart. Polytetrafluoroethylene-coated lamps require more exposure time than quartz lamps because polytetrafluoroethylene absorbs more UV radiation, lowering intensity. Adding more UV lamps or using lamps with higher UV output will allow effluent flow velocities to increase and exposure times to shrink.

The Reactor's Hydraulic Characteristics. The efficiency of any UV reactor depends on the dispersion index (E_x), which relates directly to exposure time and lamp configuration (spacing). Following is a mathematical expression for UV radiation efficiency:

$$\frac{L}{L_0} = \exp\left[\frac{ux}{2E_x}\left(1 - \sqrt{1 + \frac{4KE_x}{u^2}}\right)\right] + C(SS)^2 \tag{26.4}$$

where

L = concentration of organisms after UV exposure (colonies/100 mL);
L_0 = concentration of organisms before UV exposure (colonies/100 mL);
u = fluid velocity (cm/s);
x = forward distance traveled during exposure (cm);
K = disinfection rate constant (s^{-1});
E_x = UV reactor dispersion coefficient (cm^2/s);
C = constant (0.25 for fecal coliform and 0.9 for total coliform); and
SS = suspended solids concentration (mg/L).

The dispersion coefficient (E_x) notes the degree of deviation from ideal plug flow in the UV reactor. The ideal plug-flow value for E_x is 0, which is impossible to attain in practice. The UV system manufacturer usually provides the E_x values for various design flows; the smaller the value, the closer the reactor design approaches ideal plug-flow characteristics. Operators use E_x and the other terms in the above equation to calculate the UV system's disinfection rate constant and then use K to predict disinfection efficiency under various conditions.

Iron Concentration. Iron compounds can reduce the amount of germicidal energy transmitted to pathogens in secondary or tertiary effluent. Plants using ferrous (as ferric salts) for enhanced sedimentation–coagulation must consider this effect when designing a new or evaluating an existing UV disinfection system.

Wastewater Quality. As indicated by eq 26.4, the total suspended solids (TSS) concentration [and related turbidity (NTU)] most affect UV disinfection: the higher the TSS and NTU, the less effective the UV disinfection. For best UV reactor operation, the effluent will typically contain less than 10 to 15 mg/L TSS and less than 5 to 10 NTU.

Age of Ultraviolet Lamps. The lamp's age strongly influences intensity. *Lamp aging* indicates the lamp output decay (in watts) as operating time increases (Figure 26.4). Solarizing the lamp quartz glass decreases lamp output as operating time increases. Optimum lamp temperature is 40 °C (104 °F) for conventional low pressure–low intensity (LP–LI) lamps; if this temperature is exceeded, cooling is required. Modern low pressure–high intensity (LP–HI) lamps operate at 110 °C (230 °F). Lamp output should be monitored and recorded as part of the lamp history record. Also, an adequate inventory of replacement lamps should be maintained. The accuracy of in-place intensity meters should be monitored for reliability.

PROCESS CONTROL. The UV system needs controls that can turn lamps on and off and vary LP–HI lamp output (if appropriate) to maintain a UV intensity propor-

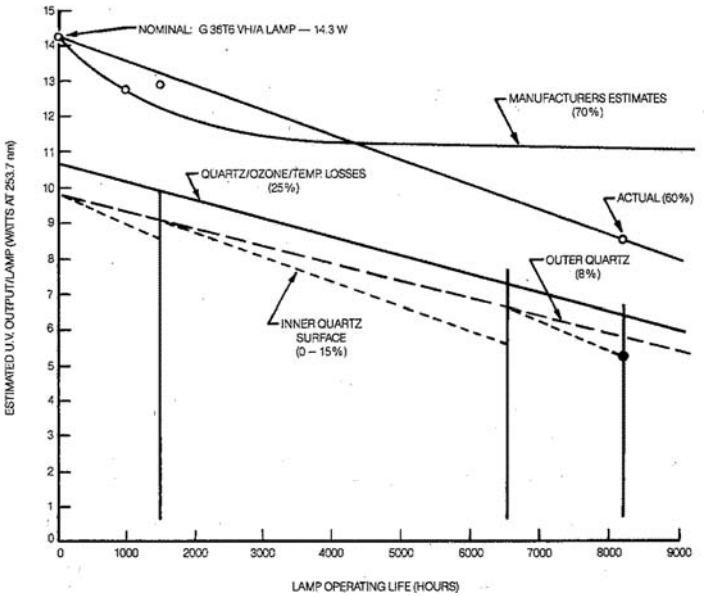


FIGURE 26.4 Estimated UV output per lamp versus operating life.

tional to the flow as required by the wastestream's transmittance. Other control-system elements, described in *Wastewater Disinfection* (WEF, 1996) include

- In-place intensity monitors,
- Power meters,
- Lamp-operation indicators,
- Elapsed-time meters,
- Lamp Temperature indicators,
- Ballast-panel temperature indicators,
- Appropriate alarms and instrumentation, and
- Low-water sensors.

Although some factors affecting the UV reactor efficiency depend on the system design, operators can at least partially control the three conditions that should be monitored to detect changes that could hurt performance:

- UV lamp output,
- Coating on the lamps' jackets, and
- The effluent's UV transmittance

Operators monitor lamp output by measuring the intensity of the UV light. The sensor probe on the UV module signals a meter on the control panel, and operators simply read the meter to check the intensity. Correlating the indicator bacteria counts (based on laboratory analyses) with the intensity reading will indicate the degree of disinfection obtained at the given UV dose.

Coatings may form on all UV lamps. To ensure proper disinfection, these coatings must be removed from all surfaces (e.g., quartz jackets, inspection sight ports, and disinfection chamber walls).

Interferences (e.g., color, suspended solids, turbidity, iron, organics, chlorine, and high levels of nitrates) will affect UV transmittance and lower UV lamp-intensity readings, but the system design should account for all these factors. If turbidity or suspended solids exceed normal levels, operators should take the steps necessary to reduce them. If any UV system component fails to operate properly, operators need to check and repair the equipment promptly. A properly operating UV-disinfection system must remain online continuously 24 hours per day. Therefore, the secondary unit should operate during maintenance of the primary unit. If the system lacks a secondary unit, the main unit must reenter service promptly following maintenance to minimize any adverse effects of inadequate disinfection of the wastewater on receiving waters.

ROUTINE OPERATIONS AND TROUBLESHOOTING. Table 26.4 lists routine operational checks for UV equipment and possible remedies if these checks indicate potential problems.

SAFETY. The primary safety rule is always to prevent exposure to UV radiation. Ultraviolet light may severely damage eyes and unprotected skin. Thus, operating personnel need routine instructions about the dangers of UV radiation. The best protection prevents exposure of any body part to UV light. So, employees should wear gloves, full-face shields, long-sleeved shirts, and full-length trousers. Because of the proximity of electricity to water, extra precautions are essential regarding electrical connections, proper grounding, and switches. Safety equipment (e.g., automatic power shut-off switches for hazardous circumstances) requires rigorous maintenance. Every UV facility must have proper storage for equipment and a means for disposal of UV lamps.

Cleaning of UV systems is accomplished via automatic wiping systems or a weak acid solution. Precautions in the solution-mixing and -handling procedures should be established. Similar safety procedures should be observed during the lamp-cleaning process. Chemical handling and safety measures should be incorporated into any UV-

TABLE 26.4 Routine operational checklist and troubleshooting guide for UV disinfection systems.

Items	What to check	Potential problems	Corrective actions
Ballasts	Surface temperature on ballasts when operating on normal utility power	Overheating due to poor panel ventilation	Add panel ventilation or cooling system.
	Surface temperature on ballasts when operating on standby power	Overheating due to power-distorting harmonics from electronic ballasts	Check power quality under various UV loads. May require adding equipment to filter out harmonics.
	Proper grounding	Frequent ballast failures	Supply adequate grounding per UV equipment supplier recommendations.
UV purifier	Lamp indicators	Burned out bulb	Replace as needed.
		Wrong sequence	Ensure respective lamps indicate sequence of individual components.
Intensity meter	Indicates UV intensity in chamber	Buildup on quartz jacket	Clean routinely as necessary.
UV lamps	Lamps	Burned out	Replace as necessary.
	Heat buildup	Little or no flow	Increase water supply.
	GFI indicator	Broken quartz sleeve or seal system failure	Check sleeve(s) for breaks and leaks; dry contacts; replace lamp-system components as required.
		Malfunction of level-control system	Clean level sensors; repair or replace as necessary.
Intensity monitor	Photocell, electronic circuit, indicating-meter alarm condition, and pilot lights	Nonfunctional	Repair or replace as necessary.
Control box	Amber	Low UV-output indicator lights	Clean chamber or replace bulb.
	Red	Poor water quality	Clean chamber or replace bulb. Check processes.
Gland seal assembly	O-ring	Water leaks	Tighten the gland nut to compress O-ring or replace.
Electrical service	AC volts, DC volts, and Ohms AC	Over range	Use multimeter and set ranges according to manufacturer's recommendations.
Lamp out warning system	Circuit board	Defective	Replace.
	Indicator bulb	Burned out	Replace.
	Pilot light	Burned out	Replace.

GFI = ground fault interrupter.

system cleaning program. Some UV equipment manufacturers offer automatic systems for cleaning UV systems without having to use chemicals or remove components.

PREVENTIVE MAINTENANCE. The reactor should be equipped with a system drain and have the capability of isolating modules or entire lamp banks without shutdown or major disruption of the remaining operating system. Either complete backup capability or multiple lamp bank designs may be needed to avoid impairing system efficiency during either preventive or corrective maintenance. Multiple bank systems can offer flexibility so half of the banks can remain in operation during average flow conditions, or during flows equal to or less than peak flow. Maintenance can therefore be performed during periods of low flow without impairing system efficiency. System flexibility may also require standby electrical power for use during emergencies or periods of high utility demand. Lamps and ballasts must be accessible. A spare-parts inventory needs to include lamps, quartz sheaths, ballasts, and other spare parts necessary to maintain the system. Records and documentation should be kept on lamp use, lamp life, and equipment-replacement cycles.

Biological scaling of the UV surface contacting the wastewater effluent is a severe, continual maintenance problem. Good maintenance practice calls for monthly inspections and, if necessary, cleaning. An important consideration during the design phase of a UV system is to cover the channel with a checker plate instead of grating. Grating will allow sunlight to enter the channel, which frequently results in significant algae growth on the channel surfaces and UV system components in the channel. Checker plates prevent sunlight from entering the channel. The four cleaning techniques, each discussed in *Wastewater Disinfection* (WEF, 1996), are

1. Mechanical wiper,
2. Ultrasonics,
3. High-pressure wash, and
4. Chemical cleaning with acid, caustic, or detergent.

Other preventive maintenance tasks are listed below:

- Replace UV lamps as dictated by disinfection-system performance and obvious loss of UV intensity.
- Monitor UV intensity using UV-intensity meters. Intensity readings, as well as UV-disinfection system performance, will dictate required cleaning frequency. Ultraviolet-intensity meters should also be maintained according to the manufacturer's recommendations.

- Periodically inspect and clean UV channels to remove algae and other accumulated materials.

CHLORINATION

The choice of disinfectant depends on its effectiveness, cost, practicality, and potential adverse side effects. For many years, WWTP designers selected chlorine because of its ability to disinfect wastewater with relatively low doses, its simple feed and control procedures, and its low cost compared with other substances. The low cost can be attributed to the large total U.S. production of chlorine; WWTPs use only approximately 5% of the annual production (White, 1998).

The disadvantages of chlorine disinfection include its lasting toxic effect on aquatic life and potential hazard related to employees and the public. As a result, many regulators have adopted stringent chlorine residual effluent limits leading to the development and use of alternative disinfection methods. Although chlorine continues to be the chemical disinfectant used at most WWTPs, use of other means of disinfection is increasing and will likely increase more rapidly in the future. A recent survey indicates that gaseous chlorination was the primary disinfectant at 94.9% of WWTPs in 1979; it was the primary disinfectant at only 76.5% of WWTPs in 1996 (Connell, 2002).

The basic concept of chlorine disinfection depends on the chemical's solubility in water. This near-saturated solution of chlorine in water is fed into the wastewater at a metered rate and then mixed thoroughly for a prescribed period of time.

The chemical symbol for chlorine is Cl_2, representing two atoms of chlorine joined into one molecule. The atomic weight of chlorine is 35.457; therefore, Cl_2 has 70.914 atomic mass units (Table 26.5).

DISINFECTION MECHANISM. Chlorine disinfects by oxidizing cellular material. More specifically, it destroys cell proteins by inactivating critical enzymes essential for microbial life. The chlorination compounds include chlorine gas, liquid hypochlorites (sodium and calcium hypochlorite), and chlorine dioxide. Chlorine dioxide is not widely used in wastewater treatment (only in specialized situations).

Each form of chlorine has a similar reaction with water and forms hypochlorous acid or hypochlorite as follows:

$$Cl_2(g) + H_2O \Leftrightarrow HOCl + HCl \quad (26.5)$$

Chlorine gas + Water ⇔ Hypochlorous acid + Hydrochloric acid

$$NaOCl + H_2O \Leftrightarrow HOCl + NaOH \quad (26.6)$$

Sodium hypochlorite + Water ⇔ Hypochlorous acid + Sodium hydroxide

TABLE 26.5 Physical properties of chlorine.

	Liquid	Gas
Boiling point at 101.3 kPa (1 atm)	−34.0 °C (−29.2 °F)	
Melting point at 101.3 kPa (1 atm)	−100.99 °C (−149.76 °F)	
Density	1422 kg/m^3 (88.79 lb/cu ft) at 16 °C (60 °F) and 590.1 kPa (85.61 psia)	3.2 kg/m^3 (0.200 6 lb/cu ft) at 1.1 °C (34 °F) and 101.3 kPa (1 atm)
Color	Clear amber	Greenish-yellow
Odor	Penetrating, irritating	Penetrating, irritating
Specific gravity	1.468 at 0 °C (32 °F) and (366 kPa) 3.617 atm	
Relative vapor density		2.482 at 0 °C (32 °F) and 101.3 kPa (1 atm)

$$Ca(OCl)_2 + 2H_2O \Leftrightarrow 2HOCl + Ca(OH)_2 \quad (26.7)$$

Calcium hypochlorite + Water ⇔ Hypochlorous acid + Calcium hydroxide

Adding any form of chlorine to wastewater results in hydrolysis. In the chlorine gas addition of eq 26.5, a mixture of hypochlorous (HOCl) and hydrochloric (HCl) acids are produced. This reaction is pH- and temperature-dependent, complete within fractions of a second, and reversible. The hypochlorous acid formed is a weak acid and dissociates or ionizes to form an equilibrium solution of hypochlorous acid and hypochlorite ion (OCl_2) (see eq 26.8). The equilibrium approaches 100% dissociation ($H^+ + OCl_2$) when the pH is above 8.5 and approaches 100% HOCl when the pH is below 6.0.

$$HOCl \Leftrightarrow H^+ + OCl^- \quad (26.8)$$

Hypochlorous acid ⇔ Hydrogen ion + Hypochlorite ion

Chlorine exists predominately as HOCl at pH levels between 2.0 and 6.0. Below a pH of 2.0, HOCl reverts to Cl_2 gas. Above a pH of 7.8, hypochlorite ions (OCl^-) are the predominant form.

Hypochlorous acid formed from the hydrolysis of hypochlorites—sodium (NaOCl) and calcium ($Ca[OCl]_2$) (eqs 26.6 and 26.7)—also dissociates in water to form hypochlorite ions (eq 26.8). Hypochlorous acid and hypochlorite ion solutions formed are at

an increased pH because of the hydroxide byproducts. Chlorine gas tends to decrease the pH because of the acids (hydrogen ions) formed. Both hypochlorites tend to raise the pH because of the alkalis (hydroxyl ions) formed.

When added to wastewater, chlorine gas solution will reduce alkalinity by 1.4 mg/L as calcium carbonate ($CaCO_3$) per mg/L of chlorine. Commercially available sodium hypochlorite may have an alkali added to enhance stability and reduce decomposition rates. Thus, commercial hypochlorite solutions, illustrated in eqs 26.6 and 26.7, will have a pH above 10.0, typically as high as 13.0. Although chlorine disinfection effectiveness can vary with the extremes of pH, the near-neutral pH range of municipal wastewater does not allow the pH of hypochlorite solutions to affect disinfection. In addition, the mass of wastewater is many times larger than the mass of the chlorine compounds added.

The sum of the chlorine present (hypochlorous acid plus hypochlorite ion) is defined as *free available chlorine* (FAC). It reacts with ammonia to form chloramines, also known as *combined available chlorine* (CAC).

The maximum rate for withdrawing gaseous chlorine from cylinders and ton containers is limited because liquid chlorine vaporizes to the gaseous form as it leaves the cylinder. This vaporization uses heat from the remaining liquid and from surrounding air. This cools the remaining liquid chlorine, slows vaporization, and may cause icing of the equipment. Based on a room temperature of 21 °C (70 °F) and 243 kPa (2.4 atm) exit pressure, the maximum withdrawal rate from a 68-kg (150-lb) cylinder is 0.79 kg/h (1.75 lb/hr) and 6.8 kg/h (15 lb/hr) from a 907-kg (1-ton) container. If higher rates are required, liquid feed systems and evaporators are necessary. Typically, a 907-kg (1-ton) container can deliver 181 kg/h (400 lb/hr) of liquid chlorine (U.S. EPA, 1986).

Chlorine may react with certain components in the wastewater that impair its efficiency as a disinfectant. These components include H_2S; SO_3^{2-}; NO_2^-; Fe^{2+}; Mn^{2+}; ammonia (NH_4^+); nitrite; amines; and organic materials, particularly unsaturated compounds (WEF, 1996). The use of chlorine for removing ammonia is described in Chapter 24.

ENVIRONMENTAL EFFECTS. Wastewater chlorination has greatly improved public health by eliminating or reducing the incidence of waterborne diseases. Initially, chlorine was applied for a broad range of purposes in wastewater plants (e.g., to control pathogens, odors, foaming, and sludge bulking). In the first years following the Water Pollution Control Act in 1972, disinfected wastewaters with significant levels of residual chlorine were routinely discharged. It has since been determined that the excessive use of chlorine had undesirable effects on receiving water biota. Combined chlorine in the effluent is less active as a disinfectant and more persistent. Its presence in receiving streams can be toxic to fish and to the ecosystem in general. The reaction of chlorine with ammo-

nia to form chloramines and with organics to form other disinfection byproducts (DBP) is also apparent. The most common of these DBPs are trihalomethanes (THMs). The U.S. Environmental Protection Agency has linked THMs to increasing cancer risks and birth defects and has since regulated their levels in drinking water supplies.

For these reasons, most regulators have imposed chlorine residual limits of less than 0.05 mg/L, depending on the receiving stream classification. As a result, dechlorination has become a necessary unit process for nearly all WWTPs using chlorine as a disinfectant. This has led to the increasing popularity of alternative means of disinfection (e.g., UV disinfection).

GASEOUS CHLORINATION

Equipment Description. The chlorination process includes several equipment components and devices, each with distinct functions (Table 26.6). Figures 26.5 through 26.9 show a 68-kg (150-lb) cylinder, 907-kg (1-ton) container, chlorinators, and a typical chlorination system.

Safety. Of the various substances present in a WWTP, chlorine is perhaps the most dangerous. Chlorine is a toxic gas and is considered an acutely hazardous substance under the Superfund Amendment and Reauthorization Act (SARA). If the gas is inhaled, it can injure or kill quickly. A major chlorine leak at a WWTP could injure or even kill plant personnel. Emergency planning must also consider the evacuation of facility neighbors. Care should also be given to releases to surrounding vegetation. Because chlorine is a regulated chemical under the community right-to-know laws (U.S. EPA, 2001), WWTPs using chlorine must comply with the reporting requirements and other provisions of that law (Chapter 5). Plant management must train employees in the proper handling and safety aspects of chlorine and inform neighbors and local government agencies (e.g., fire and police departments) about the physical system, chlorine safety awareness, and emergency procedures. The user should consult the material safety data sheet (MSDS) on chlorine for basic information on the use and handling of the substance (Chapter 5). Users also should consider obtaining Chlorine Institute pamphlets and safety videos (http://www.chlorineinstitute.org/).

Only trained and certified operators should work with chlorine. Operators should always use the "buddy system" when working with chlorine and use a self-contained breathing apparatus (SCBA) before opening valves or changing cylinders and containers. It is necessary to adhere to WWTP safety policies and review them with staff regularly. As an added safety precaution, operators should check the SCBAs before adjusting valves or changing cylinders and hold some practice drills.

TABLE 26.6 Chlorination system components and their uses.

Components	Features	Uses
Container hoist	Up–down and forward–reverse push buttons; at least a 2-ton capacity	To move 1-ton containers to and from a truck loading dock and to place and remove containers from a weight scale.
Container or cylinder scale	Weight tare bar	To set the tare weight of a specific container or cylinder. Each 150-lb cylinder or 1-ton container has a tare weight stamped on it.
	Readout faceplate or digital dial indicating pounds of chlorine remaining	To illustrate how much chlorine has been used by subtracting past and present weights remaining.
	Trunnions	To allow 1-ton containers to be rotated while on the scale to properly position valves. Also, if a leak occurs, trunnions allow a container to be rotated so the leak is "gas side up".
	Low-weight alarm	To alert operators that little chlorine remains so chlorine containers or cylinders can be replaced.
Automatic changeover system and pipeline device	Pigtail and yoke	To connect 1-ton container to main manifold.
	Pressure switch	To monitor chlorine pressure in-line from scale to evaporator or chlorinator. When pressure is low, automatically switches supply from empty container or cylinder to full container or cylinder.
	Motor-operated valves	To isolate empty container or cylinder and introduce chlorine from full container or cylinder to facilitate automatic switchover without interrupting chlorination.
	Rupture disk and expansion chamber	To protect the pipeline by allowing rupture disk to break and fill expansion chamber when chlorine (especially liquid) is trapped between two closed valves. Liquid chlorine expands about 460 times when converted to gaseous form. Pressure switches should activate an alarm before and after the rupture disk is broken, based on the calibrated pressure to break the rupture disk.

TABLE 26.6 Chlorination system components and their uses (*continued*).

Components	Features	Uses
Evaporator	Electric heater, steam, or hot water types	To convert liquid chlorine into a gaseous form for metering in a chlorinator and dissolution in an injector. Evaporators are necessary in facilities using more than 1500 lb/d of chlorine.
	Water bath and heat exchanger	To provide the heat needed to convert liquid chlorine into gas. Typically, immersion heaters in an external heat exchanger are thermostatistically controlled to automatically maintain a specified water-bath temperature.
	Magnesium rods	To protect the water bath by allowing sacrificial rods to take up the corrosion.
	Discharge-pressure-reducing valve (PRV)	To reduce the pressure of the outlet gas conveyed to the chlorinator. Also, to shut off chlorine when at least one of the following evaporator conditions occurs: (1) low gas temperature, (2) low water bath level, or (3) an evaporator power failure.
Chlorinator		To accurately meter chlorine gas for dissolution in an injector and inject solution into treated effluent (also, solution can be injected into influent for odor control, RAS for filamentous bacteria and odor control, wet scrubbers for H_2S oxidation, etc.).
	V-notch vacuum plug	To limit the maximum capacity of chlorine gas that can be drawn through a chlorinator (can range from 50 to 100 lb/d up to 8000 lb/d or more).
	Rotameter tube	To provide a metered amount of chlorine gas. Rotameters can be adjusted manually or automatically.
	Electric positioner	To automatically adjust rotameter based on 4- to 20-mA signals from an effluent flow meter or a chlorine residual analyzer.
	Vacuum regulator	To reduce the pressure of chlorine gas to 1.0 atm. Chlorine gas can then be conveyed through PVC pipes.

TABLE 26.6 Chlorination system components and their uses (*continued*).

Components	Features	Uses
Chlorinator (continued)	Pressure and vacuum gauges	To monitor the pressure of chlorine gas before regulation, and the vacuum created by the injector design and setting.
Chlorine residual analyzer	Loss of vacuum alarm	To activate an alarm when low vacuum conditions occur.
	Sample pump, detector cell, and electronics	To continuously monitor the effluent chlorine residual so it can be charted for trending purposes. Various analyzers are available to measure free or total chlorine residual.
Redox (ORP)	Submersible sensor, probe cleaning system electronics	To continuously control the chlorine dose based on demand (dose rates are set to achieve a predetermined level of biological activity). Redox will work in either free or total chlorine environments.
Gas injector	Water inlet, gas inlet, solution outlet, and variable throat	To dissolve chlorine gas into solution by creating a vacuum with a variable throat orifice. This vacuum draws the chlorine gas through the chlorinator, to the injector, and then discharges the solution to the application point.
Chlorine gas leak detector	Electromechanical cell, variable ppm detection range, and test push button	To monitor chlorine gas leakage in the scale, evaporator, chlorinator, and injector, and activate an alarm when a leak occurs.
Safety equipment	Self-contained breathing apparatus	To enter an area where chlorine is leaking (wearer breathes from the air tank via the face mask and regulator).
	Emergency repair kits: • 100- and 150-lb cylinders • 1-ton containers • Tank cars	To provide essential components for temporary repair of chlorine leaks.
	Room ventilation system	To purge escaped chlorine gas fumes from lower elevations of the chlorination area. Ventilation systems should be activated from an outside switch before anyone enters the room.

Note: kg/d = lb/d × 0.4536; kg = lb × 0.4536; kg = ton × 907.2; kPa = atm × 101.3.

Because of the hazardous nature of chlorine gas, security measures must be in place to ensure that only authorized personnel have access to chlorine storage and equipment areas.

Basic Startup and Shutdown. Startup and shutdown procedures for chlorination systems should follow a specific sequence (especially larger systems that include evaporators).

Startup. The following steps should be taken when starting a chlorination system:

1. Position full chlorine containers or cylinders on the scale. (The bottom valve draws liquid and the top valve draws gas. The 68-kg (150-lb) cylinders will produce gas only if they are upright.) Following all established safety procedures, connect the pigtails to the manifold and 907-kg (1-ton) containers. Always use new, approved gaskets to prevent leaks.
2. Open the appropriate valves at the point of solution application.

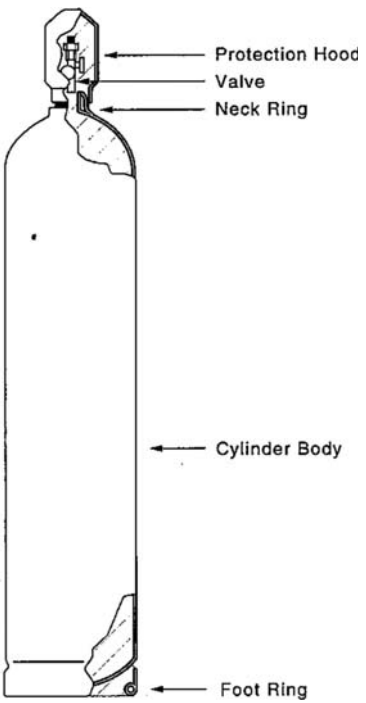


FIGURE 26.5 Chlorine cylinder.

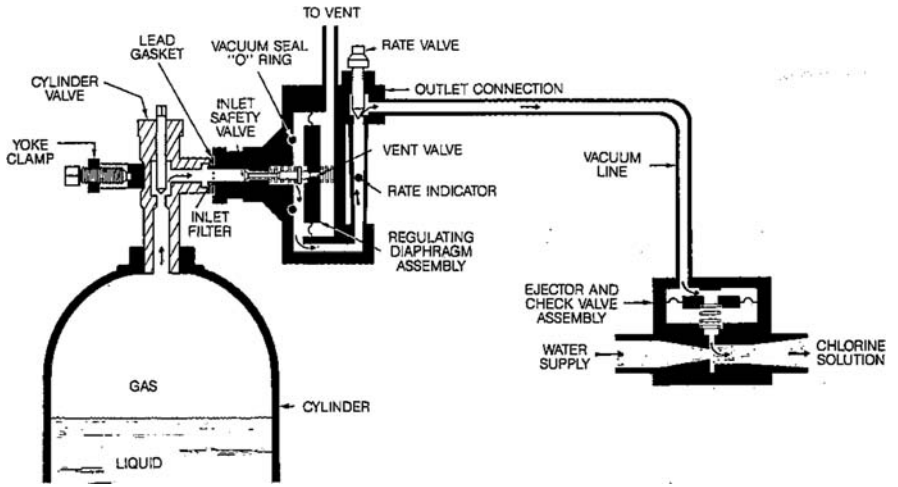


FIGURE 26.6 Flow diagram for sonic-flow chlorinator.

3. Activate water flow at the gas injector to create the required vacuum. Typically, a vacuum of at least 17 to 24 kPa (5 to 7 in. of Hg) is required at the chlorinator for proper chlorinator operation.

Note: Steps 4 and 5 apply only to systems with evaporators.

4. Activate the evaporator heat-exchanger system to attain the required operating temperature, typically 71 to 82 °C (160 to 180 °F).
5. Open the evaporator inlet and outlet valves.
6. Activate the chlorinator, alarm systems, and (if applicable) electric positioner.
7. Activate the chlorine gas-leak detectors.

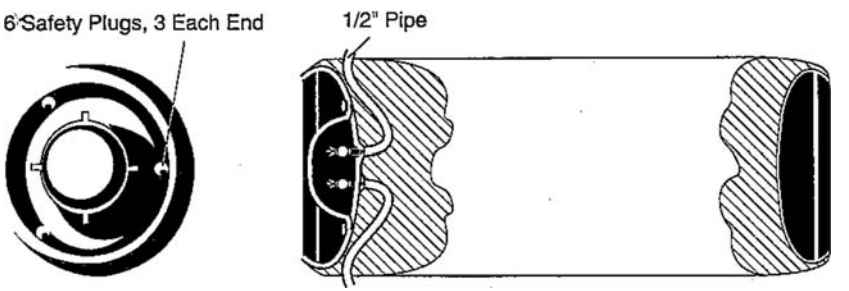


FIGURE 26.7 Chlorine container.

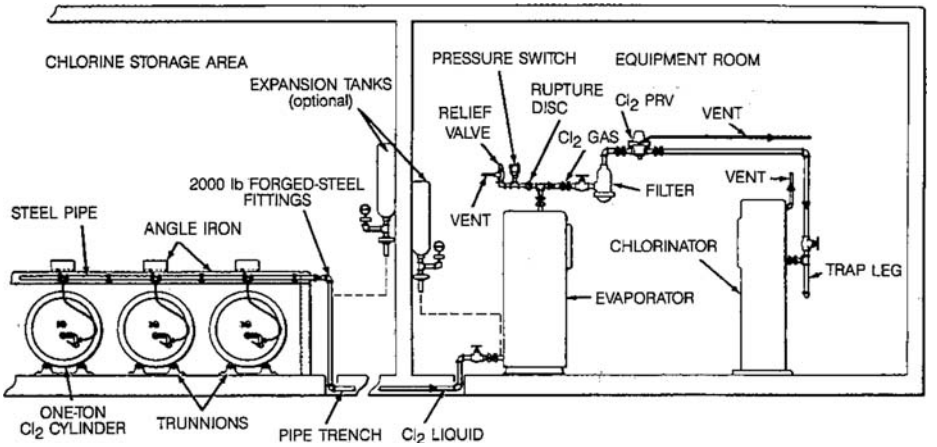


FIGURE 26.8 Liquid-withdrawal system showing chlorinator and evaporator spacing and ancillary equipment.

8. Open the chlorinator inlet and outlet valves.
9. Activate the automatic changeover system (if applicable).
10. While checking for leaks with fumes from an aqueous ammonia squeeze bottle (household ammonia is not adequate), slowly open the main chlorine manifold and tank valves no more than one turn (some WWTPs operate successfully with tank valves open only one-quarter turn). Repair any leak immediately.
11. Activate the chlorine-residual analyzer.
12. Monitor all chlorination-system devices for proper operation (as described in the following sections on "Troubleshooting Checklist and Process Control" and "Routine Operations").

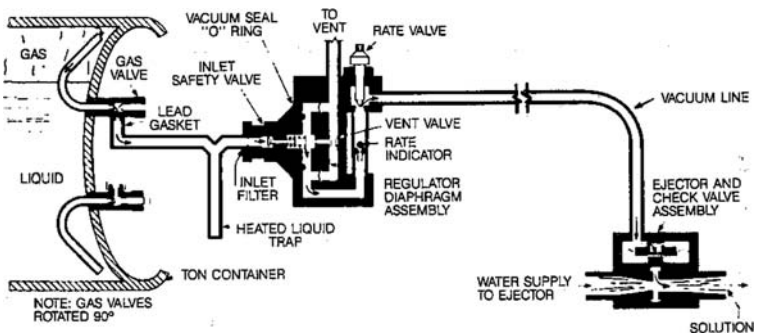


FIGURE 26.9 Flow diagram for container-mounted unit.

Shutdown. Some areas of the United States do not require year-round chlorination, and so seasonal shutdown of the chlorination process is necessary. The following steps should be taken to shut down the entire chlorination system:

1. Close the container or cylinder main valves.

Note: Allow all chlorination devices to operate until chlorinator gas pressure is zero and the rotameter has stopped bouncing. Then, proceed with the following steps:

2. Close the main manifold valves at the scale.
3. Close the water-supply valve at the injector.
4. Close the valve at the point of application for the solution (if this is a check valve, then it may remain open).
5. Deactivate the evaporator heat-exchange system.
6. Close the evaporator inlet and outlet valves.
7. Deactivate the chlorinator controls.
8. Close the chlorinator inlet and outlet valves.
9. Deactivate the automatic changeover system, chlorine-residual analyzer, and chlorine-gas leak detector.
10. Flush all systems that handle liquid or gas chlorine with dry nitrogen and maintain a nitrogen pad on equipment.

Note: If chlorine containers or cylinders remain onsite, then the leak detector should remain operational.

11. If necessary, remove chlorine containers or cylinders from the scale and store them properly (consult the chlorine supplier about long-term storage).

PROCESS CONTROL. The process-control variables associated with chlorination systems are

- Detention (contact) time,
- Chlorine residual,
- Oxidation–reduction potential,
- Indicator bacteria results, and
- Handling of chlorine containers or cylinders.

Detention (Contact) Time. The chlorine solution is best injected into the effluent via a diffuser or, preferably, a flash mixer. Otherwise, some of the chlorine gas could come

out of solution undissolved (stratification). This would impair the efficiency of disinfection and increase its costs.

Typically, depending on the WWTP's permit requirements or the state or regional regulatory requirements, chlorine detention time should range from 30 to 60 minutes at the average daily flow (ADF) and should equal or exceed 15 minutes at peak flows. Such detention times allow a safety factor for possible hydraulic inefficiency of the contact chamber, thus maximizing pathogen inactivation. Detention-time requirements, which are set by regulators, vary across the nation. Operators should check with the local regulator to learn the requirements for their plant. The following formula provides detention times:

$$\text{Detention time (minutes)} = \frac{\text{Contact chamber volume (cu ft)}}{\text{Plant flow (mgd)} \times 92.4 \text{ cu ft/min/mgd}}$$

$$\text{or} \qquad (26.9)$$

$$\frac{\text{Contact chamber volume } (m^3)}{\text{Plant flow (ML/d)} \times 0.694 \ (m^3/\text{min})/\text{ML/d}}$$

Example. Calculate the chlorine detention time for the chlorine contact chamber described below.

Given:

Contact chamber dimensions = 110 ft (33.5 m) long, 30 ft (9.14 m) wide, 10 ft (3.05 m) deep

Plant flow = 20 mgd (75.7 ML/d).

Solution:

Step 1. Calculate the volume of the chamber.

$$\text{Volume} = 110 \text{ ft} \times 30 \text{ ft} \times 10 \text{ ft}$$
$$= 33\,000 \text{ cu ft } (934 \text{ m}^3)$$

Step 2. Calculate the chlorine detention time.

$$\text{Detention time (minutes)} = \frac{33\,000 \text{ cu ft}}{20 \text{ mgd} \times 92.4 \text{ cu ft/min/mgd}}$$

$$\text{or}$$

$$\frac{934 \text{ m}^3}{75.7 \text{ ML/d} \times 0.694 \ (m^3/\text{min})/\text{ML/d}}$$

$$= 17.9 \text{ min}$$

The above example indicates that one 33 000-cu ft (934-m^3) contact chamber would provide sufficient contact time for a peak flowrate of 20 mgd (75.7 ML/d). However, if 20 mgd (75.7 ML/d) were the average daily flow, then two contact chambers would be necessary to provide the minimum 30 minutes of detention time required for average flow.

To confirm the results of the calculation and evaluate the potential for hydraulic short-circuiting, dye testing may be performed at various flowrates (WEF, 1996). Recent advances in diffusion equipment (e.g., chemical induction units) and emphasis on plug-flow regimes have increased tank efficiency at fixed contact volumes.

Chlorine Residual. Depending on the effluent-disposal method (receiving-water discharge or reclaimed-water reuse), the permit may require a chlorine residual in the contact chamber effluent. The three types of chlorine residuals are combined, free, and total. Free and total residuals are typically monitored.

The combined residual consists of chloramines and chloro-organic compounds that are formed by the reaction of chlorine with ammonia and organic compounds in the secondary or tertiary effluent. Each milligram per liter of ammonia consumes 10 mg/L of chlorine. The chlorine dose that satisfies the ammonia's chlorine demand is called the *breakpoint*. Note that the combined residual decreases slightly as the chloramines and chloro-organic compounds are oxidized at a narrow range of chlorine doses less than the breakpoint (Figure 26.10).

Chlorine demand is the amount of chlorine that is chemically reduced or converted to less active forms of chlorine by substances in the water (e.g., ammonia compounds, organic materials, and ferrous iron and some sulfur compounds). If a WWTP partially nitrifies, the chlorine demand exerted by nitrite may consume significant quantities of chlorine. Operators monitor this condition by checking for high chlorine demands. In

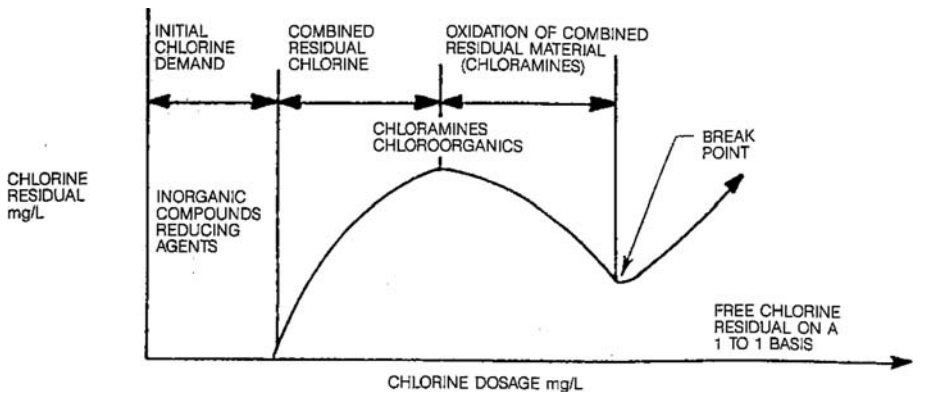


FIGURE 26.10 Breakpoint chlorination curve.

most cases, chlorine demand results from complete reaction with all chlorine-reactable materials. It is therefore defined as the difference between the concentration of free chlorine applied (as milligrams per liter of Cl_2) to the water and the concentration of chlorine residual remaining at the end of the contact period.

The free residual consists of hypochlorite ion (OCl^-) that is formed after the chlorine dose exceeds the breakpoint. After the breakpoint is reached, each milligram per liter of chlorine added increases the chlorine residual by 1 mg/L (Figure 26.10).

The *total residual* is defined as the combined and free residuals present in any chlorinated plant effluent. It is considered the standard form of chlorine residual. Total chlorine residual includes chloro-organics and chloramines, both of which are weaker oxidizing agents than free chlorine residual. However, chloramines disinfect longer than free chlorine does. The optimum chlorine residual, free or combined, is just enough to produce an effluent whose indicator bacteria count is within acceptable limits.

Oxidation–Reduction Potential. Also referred to as high-resolution redox (HRR), oxidation–reduction potential (ORP) is based on millivolt readings or potential created across a bipolar electrode. These millivolt readings are a unit of electromotive force (EMF) generated by adding chlorine to water. Higher voltage readings correspond to higher concentrations of chlorine in solution. The system responds directly to the balance between the oxidizers (chlorine) and the reducers (contaminants). The ORP hardware includes a sensing electrode and a reference electrode, which are immersed in the water to measure the electrical potential of the oxidizers present. This potential is then displayed in millivolts (Figure 26.11). The ORP system monitors and controls the chlorine feed based on immediate changes in chemical demand rather than on the residual.

Any change in electrical potential that occurs as a result of influences other than the oxidant may cause errors. Therefore, the ORP system uses electrodes whose material will remain stable in the presence of potentially interfering ionic species and differentiates between the electrical potential of chlorine and that of interfering ionic species, which are as small as 2 mV. This allows the ORP system to operate in highly oxidizing environments. Furthermore, the idea that any significant chlorine residual would eventually "poison" the electrodes is not true in the ORP system. The surface of these electrodes can be treated to resist substances that affect their stability and sensitivity. Automated cleaning systems, which use a small time-actuated pump to periodically rinse the electrode with cleaning solution, can quickly restore the electrodes' surface.

Every wastewater effluent will have a different ORP baseline. The ORP baseline of untreated water changes as the concentration of various electroactive contaminants changes, ultimately reaching equilibrium. If this reading happens to be 200 mV, then the ORP contributed by the chlorine will be added to this number. This ORP

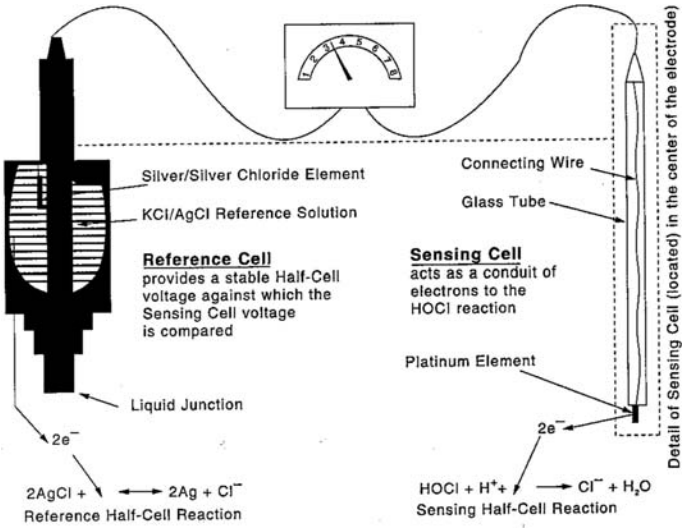


FIGURE 26.11 Oxidation–reduction potential cell system.

baseline is typically determined after the system has been in operation for at least 24 hours and operating conditions are normal. When equilibrium has occurred, the system is standardized via a titrimetric chlorine residual procedure. Care must be taken when standardizing the available chlorine residual to the ORP measurements to establish a consistent relationship necessary to meet the current National Pollutant Discharge Elimination System discharge requirements.

To allow some conversion of free chlorine to chloramine, most manufacturers recommend placing the ORP probe approximately 5 to 10 minutes downstream of the chlorine application point. Oxidation–reduction potential measurements are much simpler to obtain and the ORP cell is easier to maintain than either the membrane or amperometric chlorine analyzer cells. It has been observed that there is a marked difference in the ORP mV curves between free chlorine residuals and chloramine residuals. Therefore, HRR can be calibrated to control in either a free or a total chlorine environment.

Indicator Bacteria Results. Regardless of the chlorine residual method employed, enough chlorine solution must be injected into the effluent to sufficiently destroy or inactivate the indicator bacteria that signal the likely presence of pathogens. The primary objective of chlorination is to destroy pathogenic organisms; however, the coliform bacteria often used as indicators are not pathogenic. The indicator bacteria inactivation concept works because coliform and other indicator bacteria are much easier to detect than pathogens and more difficult to destroy than most pathogens, except possibly viruses.

Testing directly for pathogens is complex and costly. If the coliform count has been sufficiently reduced through disinfection, a corresponding proportion of pathogens has probably been inactivated.

Chlorine Container and Cylinder Handling. Chlorine can be good or bad, depending largely on the operations staff's training and capabilities. The following considerations will help operators with chlorine receiving and handling:

- Record the number stamped on each tank car, container, or cylinder when it is received or dispatched. Label full containers and keep them separate.
- Check each container or cylinder as follows:
  —Remove the protective bonnet and make sure the main valves are tightly closed.
  —Before connecting, remove the threaded caps from each valve and make sure the seats do not have deep scratches or scores.
  —Slowly and slightly tighten the valve packing nut.
  —Check each valve for leaks via fumes from a squeeze bottle of commercial-strength liquid ammonia. (Never apply liquid ammonia directly to a chlorine leak or fitting.)
  —Replace the threaded caps and protective bonnets.

Note: If any of the above tests fail, reject the container or cylinder.

- Keep the bonnet in place until the container or cylinder is positioned on the scale.
- Frequently inventory accessories and keep at least the following items on hand:
  —New approved gaskets,
  —A squeeze bottle one-half full of commercial-strength liquid ammonia,
  —Appropriate wrenches for 907-kg (1-ton) containers and 68-kg (150-lb) cylinders,
  —At least two SCBAs,
  —An emergency repair kit for the appropriate container type, and
  —One new pigtail connector tube long enough to connect the container to the manifold. (Note: Must be clean and dry before using.)

DATA COLLECTION, SAMPLING, AND ANALYSIS. Table 26.7 summarizes the analyses and data-collection duties associated with chlorination sampling. Chapter 17 describes sampling, sample handling, and the tests for chlorine residual and indicator bacteria. *Standard Methods* (APHA et al., 2005) describes the procedures for the tests. The sampling point is at the downstream end of the contact chamber or just before the discharge point.

TABLE 26.7 Testing for chlorination process.

Test	Data for analysis of results
Total chlorine residual (mg/L)	Chlorine dose Contact chamber detention time
Indicator bacteria count[a]	Total chlorine residual
MPN[b] or number of colonies	Contact chamber detention time

[a]The bacteria type and the test depend on the permit requirements.
[b]MPN = most probable number.

ROUTINE OPERATIONS AND TROUBLESHOOTING. Table 26.8 lists routine operational checks of chlorination equipment and remedies if these checks indicate potential problems.

PREVENTIVE MAINTENANCE. A comprehensive maintenance program is critical to WWTP safety and process efficiency. It should include equipment inspections (as often as manufacturers recommend). There should also be enough equipment and process redundancy to facilitate cleaning and repairs without loss of disinfection efficiency. Complete documentation of tasks and analyses plus a good recordkeeping system are also essential to ensure that relevant data are recorded for historical trends and comparison purposes. Some key elements of a chlorination-system preventive maintenance program are listed below:

- Weigh chlorine containers and cylinders on a scheduled basis. Consult chlorine supplier for details.
- Inspect and clean the stem, spring, passageway, trap, and filter on vacuum regulators.
- Check the operation of automatic changeover systems by closing container or cylinder main valves on in-service tanks.
- Inspect and replace pigtail connectors on a scheduled basis. Replace pigtail connectors immediately if discoloration or kinking is visibly evident.
- Lubricate evaporator heat-exchanger recirculation pump motor with nondetergent oil according to the manufacturer's recommendations.
- Inspect the cathodic-protection anode magnesium rods inside evaporators on a scheduled basis. Replace rods as recommended by the manufacturer.
- Inspect and clean the strainer, stem, spring, passageway, and, if applicable, trap and filter on pressure-reducing valves.

TABLE 26.8 Routine operational checklist and troubleshooting guide for chlorination system.

Items	What to check	Potential problems	Corrective actions
Record scale reading	Usage	Degrading effluent increases chlorine demand (nitrite demand increases use)	Monitor dose and demand. Adjust process to improve effluent quality.
		Low scale weight, chlorine about to run out	Replace container or cylinder before scale reaches zero to prevent sediment from entering system.*
Chlorine lines, valves, and unions	Erratic reading	Scale not tared out properly	If necessary, retare or calibrate scale.
	Presence of chlorine leaks	Personal injury (potential death), evacuation logistics, and corrosion of nearby equipment and electronics	Work with a trained assistant, wear SCBAs, and follow all appropriate safety procedures when closing container or cylinder main valve and evacuating chlorination pipe network. Repair all leaks immediately; they will only get worse. Notify emergency response teams if required.
	Iced container or cylinder	Chlorination rate too high	Reduce chlorination rate, or manifold containers or cylinders together. If an evaporator is being used, be certain liquid chlorine is being withdrawn from the container's bottom valve.
Solution lines	Leaks	Chlorine evaporating	Repair all leaks immediately. Evacuate chlorine network and repair PVC pipes. Follow all appropriate safety procedures when working with any chlorine leak.
System gauges	Gauges	Chlorination system downtime	Correct all potential problems immediately.
	Main manifold pressure	Could break rupture disk	If necessary, evacuate network and replace rupture disk. Check all network valves for correct positioning.

*This will prevent sediment in the container from entering the chlorination network and possibly damaging the process equipment.

- Clean out the chlorinator rotameter when deposits are noticed inside the glass rotameter tube, or if the float sticks.
- Clean the chlorinator V-notch while cleaning the rotameter.
- Lubricate the chlorinator's electric-positioner motor shaft with a few drops of nondetergent oil on a scheduled basis.
- Test the alarm circuitry of the chlorine-leak detector on a scheduled basis.

- Certify and hydrotest SCBA units.
- Check and adjust the leak-detector electrolyte level and sensor drip rate.
- Flush the leak-detector sensor with distilled water.
- Check the operability of the leak-detector air fan.
- Check for leakage at all O-rings and the leak detector's site glass.
- If applicable, replace the cartridge filter in the fill cap of the leak-detector electrolyte reservoir on a scheduled basis.
- Dewater the chlorine contact basin on a scheduled basis and clean out any accumulated grit and buildup.

LIQUID HYPOCHLORINATION. In wastewater disinfection, hypochlorination typically refers to the use of sodium hypochlorite. Calcium hypochlorite is less frequently used in WWTPs because of its costs, sludge-forming characteristics, and more hazardous (explosive) nature. In the wake of post-September 11, 2001, terrorist threats, many municipalities have considered converting from gaseous to liquid hypochlorite disinfection systems.

Sodium hypochlorite (NaOCl) is far less hazardous than chlorine and calcium hypochlorite and just as effective. However, it is considerably more costly than chlorine and may be more costly than calcium hypochlorite. Sodium hypochlorite is manufactured via the reaction of gaseous or liquid chlorine with a solution of sodium hydroxide (caustic soda) to produce a liquid containing sodium hypochlorite, salt, and small amounts of caustic soda. Sodium hypochlorite is typically sold as a commercial- or trade-grade solution containing 150 g/L (15%) available chlorine. (Solutions less than about 5% are available as common household bleach.) An amount of 3.8 L (1 gal) of solution weighs 4.5 kg (10 lb) and contains 0.6 kg (1.25 lb) of available chlorine. Sodium hypochlorite may also be generated onsite via the electrolytic decomposition of brine or seawater but in concentrations of no more than 1% of available chlorine.

Process Description. Sodium hypochlorite may be delivered in 19-L (5-gal) or larger carboys, in tank trucks of 7.6- to 18.9-m^3 (2000- to 5000-gal) capacity, or in tank cars or barges. Storage vessels may be made of polyethylene, hypochlorite-resistant fiberglass resin, or concrete or steel with protective linings. Unlike liquid chlorine, sodium hypochlorite will deteriorate, but not significantly in the 10 days or less that it is typically stored onsite. Lower-strength solutions will deteriorate much less rapidly, but it may not be worthwhile to dilute the material after delivery because larger storage tanks, pumps, and piping would be required. However, when sodium hypochlorite use is intermittent (e.g., for combined overflow WWTPs) dilution may prove desirable. If dilution is used, the chemical characteristics of the dilution water may affect the process.

Storage tanks should be protected against light and heat, both of which will hasten the solution's deterioration.

Sodium hypochlorite is withdrawn from the storage tanks under a positive or slightly negative head by diaphragm metering pumps or eductor piping systems. A spring-loaded, plastic-coated check valve in the pump discharge line or a solenoid-operated valve connected in parallel with the pump may be used to prevent siphoning through the pump under a positive head.

Process Control. The process-control variables described previously under "Gaseous Chlorination" are appropriate for liquid hypochlorination. In addition, because sodium hypochlorite solutions have a short shelf life, time and temperature will affect the concentration of available chlorine in these solutions, especially if the solution is stored more than 10 days. A residual chlorine analysis of the solution fed to the contact chamber is advisable to determine the solution's strength. Because the strength changes rapidly, it needs to be checked at least weekly.

Safety. Although it is relatively nonhazardous, a 15% solution of sodium hypochlorite should be approached with respect, because it may be irritating to the skin and hazardous to the eyes. Eye baths and overhead showers should be available in the storage and metering pump areas, as well as a containment area with an adequately sized drain to a settling or contact tank to reduce the hazards of a possible serious leak or failure of the piping or storage tanks.

Because of the highly corrosive nature of hypochlorite solutions, their handling calls for proper protective clothing and safety equipment. Because chlorine is released when hypochlorite solutions decompose, proper ventilation is essential for storage, mixing, and application of hypochlorite compounds.

Note: Operators should never mix petroleum-based oils, greases, or solvents with hypochlorite compounds.

Preventive Maintenance. The following preventive maintenance considerations apply to hypochlorination:

- Clean the pump and effluent water strainers regularly (wear rubber gloves).
- Regularly inspect the spring-loaded back-pressure valve and the balls and seats of pump valves; operate the piping valves regularly.
- Rotate the use of hypochlorite feed pumps and operate them briefly at all speeds.
- Sodium hypochlorite can release gas bubbles that accumulate in the suction piping to the feed pumps, causing air binding of feed pumps. Maintain a flooded suction or air-release mechanism to ensure proper operation.
- Maintain the proper oil level in the pump reservoirs.

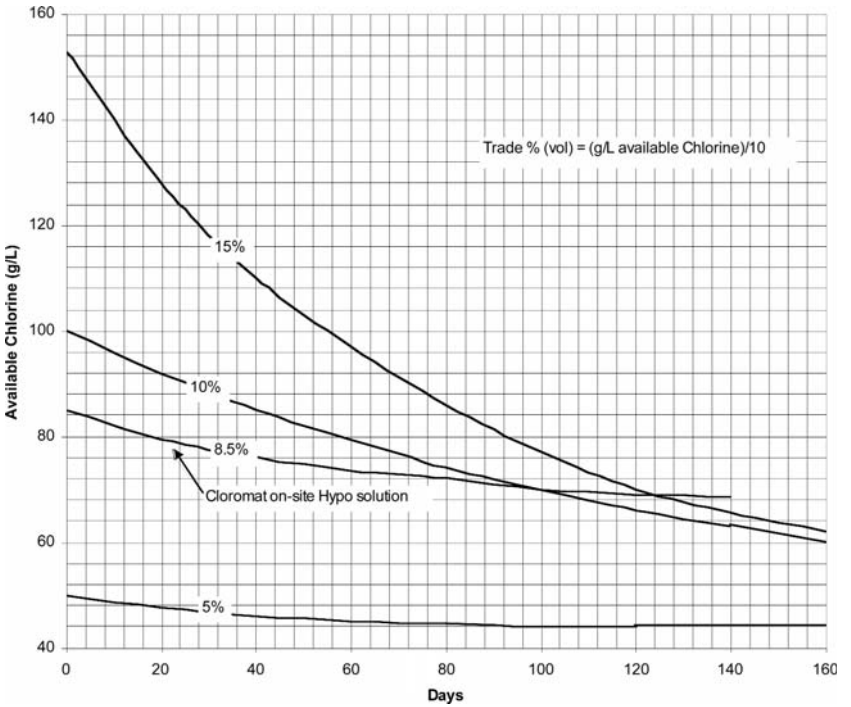


FIGURE 26.12 Decay rate of sodium hypochlorite solutions (White, 1998)(Reprinted with Permission of John Wiley & Sons, Inc.).

- Occasionally, pump a 5% solution of hydrochloric acid to prevent carbonate scale from accumulating in the pump; flush the pump with water before and after using the acid.
- Inspect and, as necessary, repair the storage-tank linings at least once per year (adhere to confined-space entry procedures).

Storage and Degradation. Typically, sodium hypochlorite is shipped to the site at a solution of 15% available chlorine, similar to commercial-grade bleach. It is typically stored in fiberglass reinforced plastic (FRP) tanks constructed with the appropriate binders and plasticizers. As previously discussed, solution strengths decline with time (Figure 26.12).

DECHLORINATION

For many WWTPs, final effluent must be dechlorinated to meet chlorine-residual permit requirements. Chlorine residuals are toxic to fish and other aquatic life. In addition, organics in receiving waters can, under some circumstances, react with chlorine

residuals to form trihalomethanes, a potential carcinogen. This is described in more detail in the "Environmental Effects" discussion in the "Chlorination" section.

Sulfur dioxide (SO_2), sodium metabisulfite, and sodium bisulfite can be used to dechlorinate chlorinated effluents. Sodium metabisulfite and sodium bisulfite are safer substitutes for sulfur dioxide. Once again, safety concerns have justified a trend away from gaseous sulfur dioxide and toward less hazardous liquid systems (e.g., sodium bisulfite). These sulfites may be liquids or solids, which are dissolved as indicated in the suppliers' literature and then fed via a chemical-feed pump. Such systems are sometimes more difficult to control than the sulfur dioxide system. Hydrogen peroxide (H_2O_2), an alternative to sulfur dioxide, has the advantage of harmless byproducts (oxygen and water) but it is dangerous to handle.

Sulfur dioxide is colorless and dissolves in water to form sulfurous acid, a strong reducing agent. When added to chlorinated effluent, sulfur dioxide reduces all forms of chlorine to chloride and converts sulfur to sulfate. Both chlorides and sulfates occur naturally in most waters.

DECHLORINATION MECHANISM. In theory, 0.9 mg/L of SO_2 is needed for every 1.0 mg/L of chlorine residual to be removed. In actual practice, however, the ratio is 1:1. The following formula is used to calculate the sulfur dioxide feed rate:

$$\begin{aligned}\text{Sulfur dioxide feed rate (lb/d or kg/d)} &= \text{Flow (mgd or ML/d)} \\ &\times \text{Chlorine residual (mg/L)} \times \text{Conversion factor}\end{aligned} \tag{26.10}$$

Sulfur dioxide removes free or combined residuals with equal efficiency. The reaction requires adequate mixing and produces almost instantaneous results, typically requiring a detention time of only approximately 2 minutes. The chemical reactions are as follows:

Free chlorine

$$SO_2 + H_2O + HOCl \rightarrow 3H^+ + Cl^- + SO_4^{-2} \tag{26.11}$$

Chloramine

$$SO_2 + 2H_2O + NH_2Cl \rightarrow NH_4^+ + 2H^+ + Cl^- + SO_4^{-2} \tag{26.12}$$

Sodium metabisulfite (NaS_2O_5) is a cream-colored powder that is readily soluble in water and available in solutions of various strengths. Theoretically, 1.338 mg/L of sodium metabisulfite reacts with 1 mg/L of chlorine or chloramine. In practice, 10% excess sodium metabisulfite is used to ensure sufficient dechlorination. The chemical reactions are as follows:

Free chlorine

$$Na_2S_2O_5 + 3H_2O + 2Cl_2 \rightarrow 2NaHSO_4 + 4HCl \quad (26.13)$$

Chloramine

$$3Na_2S_2O_5 + 9H_2O + 2NH_3 + 6Cl_2 \rightarrow 6NaHSO_4 + 10HCl + 2NH_4Cl \quad (26.14)$$

Sodium bisulfite ($NaHSO_3$) is a white powder or granular material. It can also be purchased in solutions with strengths up to 44%. Its reactions are as follows:

Free chlorine

$$NaHSO_3 + H_2O + Cl_2 \rightarrow NaHSO_4 + 2HCl \quad (26.15)$$

Chloramine

$$3NaHSO_3 + 3H_2O + NH_3 + 3Cl_2 \rightarrow 3NaHSO_4 + 5HCl + NH_4Cl \quad (26.16)$$

EQUIPMENT DESCRIPTION. The components of a sulfur dioxide dechlorination system resemble those of a chlorination system, except that sulfur dioxide is typically contained in 68-kg (150-lb) cylinders (Figure 26.13). *The Handbook of Chlorination* (White, 1998) explains the differences in valves and washers in the two systems.

Most sulfur dioxide dechlorination systems include 68-kg (150-lb) cylinders, using gas only. Therefore, evaporators are not typically needed. In larger-scale systems, 907-kg (1-ton) containers are sometimes used; these often include evaporators to provide sufficient gas supply. The gaseous withdrawal rate at 21 °C (70 °F) is 0.907 kg/h (2 lb/hr) for 68-kg (150-lb) cylinders and 11.3 kg/h (25 lb/hr) for the 907-kg (1-ton) containers. Higher feed rates are feasible with evaporation systems (U.S. EPA, 1986).

SAFETY. Sulfur dioxide is a nonflammable toxic gas that affects the central nervous system and is considered an acutely hazardous substance under SARA. If the gas is

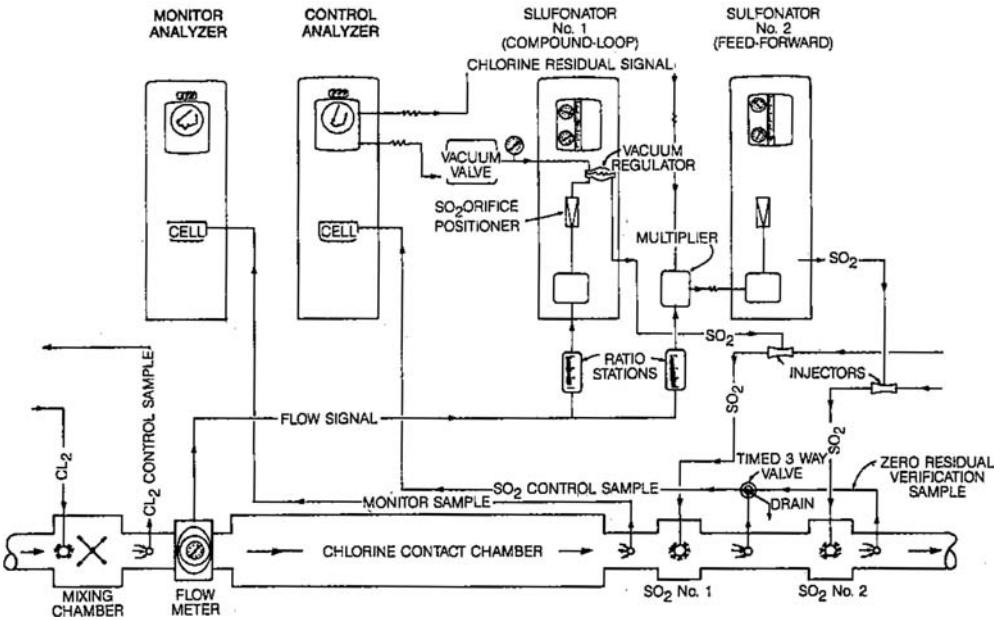


FIGURE 26.13 Schematic of a dechlorination system layout, components, and control methods.

inhaled, it can injure or kill quickly. A major sulfur dioxide leak at a WWTP could injure or even kill plant personnel. Emergency planning must also consider the evacuation of facility neighbors. Care should also be given to releases to surrounding vegetation. Because sulfur dioxide is a regulated chemical under the community right-to-know laws (U.S. EPA, 2001), WWTPs using sulfur dioxide must comply with the reporting requirements and other provisions of that law (Chapter 5).

Plant managers must train employees in the proper handling and safety aspects of sulfur dioxide and inform neighbors and local government agencies (e.g., fire and police departments) of the physical system, safety awareness, and emergency procedures. Users should consult the material safety data sheet (MSDS) on sulfur dioxide for basic information on the use and handling of the substance (Chapter 5).

Only trained and certified operators should work with sulfur dioxide. Operators should always use the "buddy system" when working with sulfur dioxide and use a SCBA before opening valves or changing cylinders and containers. It is necessary to adhere to WWTP safety policies and review them with staff on a regular basis. As an

added safety precaution, operators should check the SCBAs before adjusting valves or changing cylinders and hold some practice drills.

Because of the hazardous nature of sulfur dioxide gas, security measures must be in place to ensure that only authorized personnel have access to sulfur dioxide storage and equipment areas.

BASIC STARTUP AND SHUTDOWN. The necessary procedures for starting and stopping a sulphur dioxide dechlorination system are basically the same as those for a chlorination system. Nonetheless, a brief overview follows.

Startup.

1. Position full 68-kg (150-lb) cylinders of sulfur dioxide upright on the scales. Following all safety procedures, connect the pigtails to the manifold and cylinders.
2. Open the valves at the solution-application point.
3. Start the water flow through the injector.
4. Activate the sulfonator, alarm systems, and (if applicable) the electric positioner.
5. Open the sulfonator inlet and outlet valves.
6. Activate the sulfur dioxide leak detectors.
7. Activate the sulfur dioxide automatic changeover system (if applicable).
8. When checking for leaks with fumes from a squeeze bottle of commercial-strength liquid ammonia, open the manifold and cylinder valves no more than one turn.
9. Monitor all dechlorination-system devices for proper operation.

Note: Always use new lead washers. Use the same aqueous ammonia to test for sulfur dioxide leaks as that for checking a chlorination system. A similar white cloud indicates a chlorine or sulfur dioxide leak. Repair all leaks immediately. Testing dechlorinated effluent for chlorine residual will determine the effectiveness of dechlorination.

Shutdown.

1. Close the cylinder main valves and reduce the system pressure to zero.
2. After system drawdown, close the manifold valves.
3. Stop the water flow at the injector.
4. Close the valves at the solution-application point.
5. Deactivate the sulfonator controls.
6. Close the sulfonator inlet and outlet valves.

PROCESS CONTROL. The important process-control variables associated with dechlorination are mixing efficiency and chlorine residual. Reaction time is rapid.

Mixing Efficiency. The sulfur dioxide solution is injected to the disinfected effluent just after the contact chamber, followed by a rapid-mix period (either in-line within a pipe or in a chamber with a mechanical mixer). An aeration diffuser or chemical-induction unit at the sulfur dioxide-injection point can also provide an adequate mix of the sulfur dioxide solution and the disinfected effluent.

Chlorine Residual. A sample of the dechlorinated effluent should be obtained and routinely tested for chlorine residual. Regulators have varying requirements for maximum chlorine residuals in dechlorinated effluent. As mentioned, the dose ratio of sulfur dioxide to chlorine residual is approximately 1:1 (each 1 mg/L of chlorine removed will require 1 mg/L of sulfur dioxide). Overdosing may cause deoxygenation of the final effluent, as well as unnecessary chemical costs. The effect on effluent oxygen level is typically low because it takes approximately 2 mg/L of SO_2 to reduce dissolved oxygen by 1 mg/L. Dissolved oxygen levels in the final effluent should be monitored to ensure that a minimum dissolved oxygen level is maintained in the final effluent.

ROUTINE OPERATIONS AND TROUBLESHOOTING. Refer to the previous section (Chlorination) because the operational checks and problems of the dechlorination components will be similar.

PREVENTIVE MAINTENANCE. Refer to the previous section (Chlorination) because similar preventive-maintenance tasks apply to the dechlorination components.

OZONATION

In wastewater applications, ozone (O_3) is used for disinfection and other purposes (e.g., pretreatment of domestic and industrial wastewater and odor control). It is also used in potable water treatment for oxidation, disinfection, and taste and odor control. Ozone forms naturally in the atmosphere via photochemical or electrical processes. The addition of energy first disassociates molecular oxygen to atomic oxygen. As more energy is added, atomic and molecular oxygen combine to form ozone (an unstable compound).

Ozone is mechanically generated via photochemical or electrical excitation methods. Photochemical methods involve UV excitation at a wavelength of less than 200 nm and can only produce ozone in limited quantities and concentration. Therefore, wastewater disinfection systems typically produce ozone via electrical corona (electrical plasma) discharge.

Electrical production of ozone requires extremely dry air or oxygen [−60 °C (−76 °F)] dewpoint at 1 atmosphere] exposed to a controlled uniform high-voltage dis-

charge (high or low frequency). The yield of ozone is affected by the generator's geometry, the discharge gap's dimension and discharge area, the gas temperature and pressure, the applied frequency and voltage, and the physical properties of the dielectric. As heat, pressure, and the feed gas humidity increase, ozone production decreases.

Ozone is produced as a gas. It is an unstable, strongly reactive oxidant that requires onsite production. When dry air is used as a feed gas, the resulting ozone concentration (by weight) is 1 to 4%. When oxygen of sufficient purity is used as the feed gas, the ozone concentration (by weight) can vary from 3 to 10%, depending on the manufacturer. Even higher production rates are becoming both feasible and economical.

Ozone is a superior oxidant with generally rapid reaction rates and superior disinfectant capabilities. The disinfection process depends on the susceptibility of the target organism, the pH, contact time, and the concentration of the disinfectant. In general, the effectiveness of ozone as a disinfectant is not pH-dependent. Like oxygen, ozone has limited solubility. However, unlike oxygen, ozone exposure must be limited for safety reasons. Ozone will typically decompose faster in water than in air. Because of these limitations and ozone's reactivity, the ozone contactor requires special covered construction and often multiple addition points. Ozonated effluent is also subject to problems associated with disinfection byproducts, including the formation of aldehydes, acids, and brominated compounds.

The production system includes dryer, compressor or blower, ozone generator, dielectric (ground and electrode), step-up transformer (rectifier and inverter), and electrical control panel.

Ozone is a strong oxidant and virucide. The ozone disinfection mechanisms include

- Direct oxidation/destruction of the cell wall with leakage of cellular constituents outside the cell;
- Reactions with radical byproducts of ozone decomposition; and
- Damage to the constituents of the nucleic acids (purines and pyrimidines) inside the cell, which alters their genetic material, thereby preventing cell replication.

When ozone decomposes in water, the free radicals hydrogen peroxy ($\cdot HO_2$) and hydroxyl ($\cdot OH$) are formed. They have great oxidizing capacity and play an active role in disinfection. It is generally believed that the bacteria are destroyed because of protoplasmic oxidation, which results in cell wall disintegration (cell lysis).

EQUIPMENT DESCRIPTION. A typical ozonation system includes several elements (Table 26.9 and Figure 26.14).

TABLE 26.9 Ozone disinfection system components and their uses.

Components	Types	Functions
Air filters	Glass fiber, paper, or metal; low-pressure drop; minimum 6 months use	Inlet filter: 10 μm; pre-dryer filter solids 100%: 0.3 to 1 μm; moisture 100%: 1.75 μm; postdryer filter solids 100%: 0.3 μm; solids 95%: 0.1 μm; filter solids and moisture at various stages of air preparation.
Air compressor	Oil free—centrifugal, reciprocating, rotary	Provides continuous flow of air or oxygen.
Aftercooler	Air or water, single countercurrent shell and tube	Lowers gas temperature and lowers dewpoint.
Pre-dryer	Refrigerant dryer, direct expansion, chilled water exchangers	A pre-dryer to lower equipment for complete drying at 76 °F dewpoint.
Dryer	Dessicant, pressure swing, heat-generating	Dries gas to limit nitric oxide production and maximize ozone production.
Frequency inverter	Low frequency (none required)	Not used: 50 to 60 Hz.
	Medium frequency	60 to 1000 Hz.
	High frequency	Operating above 1000 Hz.
	Frequency converter	Used to increase power densities at generator cell; AC is rectified to DC, filtered, or thyristor-inverted back to AC current; both frequency and voltage are controlled.
Transformer	Low-input, high-output step-up	Low frequency, 8 to 20 kV; medium frequency, 8 to 12 kV; to achieve required power densities; the lower the frequency, the higher the applied voltage.
Potentiometer or voltmeter, ammeter and frequency meter	Powerstat or inverter; variable inverter	Low frequency, 5:1 turndown; medium frequency, 10:1 turndown; high frequency, 15:1 turndown; controls and indicates applied voltage frequency.
Dielectric	Typically in an ozone generator, the dielectric is a compound [air (oxygen) and glass (ceramic)]; it can be a plate or tube	The medium between two plates in a capacitor, the ozone generator, the generator cell.
Electrode	High voltage or ground	High-voltage electrodes provide more than 1000 V to charge the dielectric; this is discharged to the ground electrode (corona).
Gas-flow rotameter		

TABLE 26.9 Ozone disinfection systems components and their uses (*continued*).

Components	Types	Functions
	Graduated adjustable gas-flow tube with indicator	Adjusts air–oxygen flowrate into the ozonator.
Inlet gas-pressure gauge	Graduated	Indicates the inlet gas pressure to the gas-flow rotameter.
Pressure-relief valve	Spring-loaded or weighted air-pressure relief	Allows excess air pressure to be released from the reaction vessel shell.
Ozone destructor	Catalytical (manganese dioxide 0.25- to 018-in. extrusions) destructor to have 0.72-second residence time, a linear velocity of 2.2 ft/sec, gas stream temperature 15 °F above ambient or thermally at 300 °C for 3 to 5 seconds	Removes offgas ozone by converting it to oxygen.

Note: (°F − 32) 0.5556 = °C; in. × 25.4 = mm; ft/sec × 0.3048 = m/s.

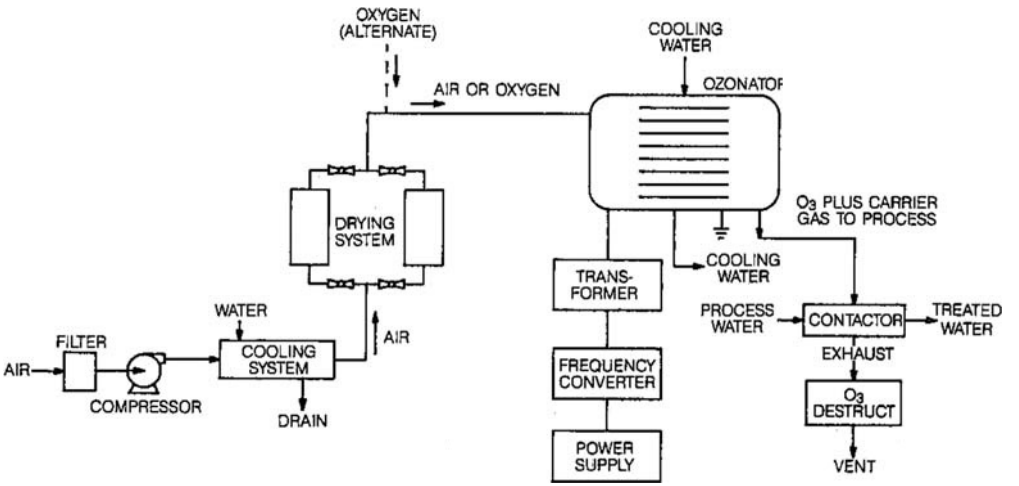


FIGURE 26.14 Schematic of an zone generation system.

BASIC STARTUP AND SHUTDOWN. Startup and shutdown procedures are as follows.

Startup. The following steps should be taken to start up an ozonation system:

1. Place the power-supply circuit breaker (on–off switch) in the "off" position.
2. Start the cooling water supply through the ozonator.
3. Make certain that the air path to the ozone contact chamber is open and that the ozone destruction unit is operating.
4. Start the air or oxygen supply to the ozonator.
5. Adjust the air pressure to the reaction vessel by operating the pressure-regulating valve. If air pressure exceeds the air-relief valve setting [typically approximately 90 kPa (13 psi)], the relief valve will open.
6. Purge the ozonator for at least 30 minutes with clean, dry air before applying power to the electrodes.
7. To begin producing ozone, place the circuit breaker in the "on" position.
8. Adjust the voltage with the potentiometer to the desired output, as indicated on the voltmeter.

Shutdown. The following steps should be taken to shut down an ozonation system:

1. Using the voltage potentiometer, turn off the power to the electrodes.
2. Place the power switch in the "off" position.
3. Purge with clean, dry air for 30 minutes to evacuate all ozone.
4. After purging, close all air valves to the reaction chamber.
5. Turn off the water.

PROCESS CONTROL. The principal process-control considerations are mixing and detention time. Because ozone decomposes naturally and is consumed rapidly, it must be contacted uniformly in a near plug-flow contactor. Maintenance of an ozone residual at a given concentration for a specific period (detention time) is necessary for proper disinfection. Contact time is dictated by aqueous residual.

DATA COLLECTION, SAMPLING, AND ANALYSIS. Chapter 17 describes sampling, sample handling, and analyses for indicator bacteria. *Standard Methods* (APHA et al., 2005) describes procedures for these bacterial tests and also for ozone dose and residual tests. Typically, both types of tests are needed.

For the ozone residual test, an ozonated effluent sample must be collected from the effluent end of the ozone contactor. The sample must be drawn directly into the testing vessel and the analysis performed immediately thereafter.

The ozone dose must be calculated based on the gas flow and concentration into the contactor versus the gas flow and concentration out of the contactor and the aqueous ozone residual and flow. The calculation requires consideration of gas volume and concentration versus aqueous volume and concentration.

ROUTINE OPERATIONS AND TROUBLESHOOTING. Table 26.10 lists routine operational checks for ozonation equipment and possible remedies if these checks indicate potential problems.

SAFETY. Exposure to even small quantities of ozone can cause serious health problems (Table 26.11). Ozone is extremely reactive and will corrode most metals, plastics, and elastometers; therefore, leaks can adversely affect electrical systems, seals, and metals. Properly calibrated ozone monitoring equipment is needed for both the work area and the ozone offgas destruction units. Care should also be given to releases to surrounding vegetation as a result of long-term ventilation or other release. Ambient monitors should provide for a work-area alarm at 0.1 ppm, and shutdown and area ventilation at the 0.3 ppm ambient residual level. The monitoring equipment should be tested weekly and calibrated as required by the equipment manufacturer.

Ozone can exist in gaseous form for a significant period of time. Extreme caution should be taken when dealing with ozone gas-handling systems. Therefore, the ozone generator, distribution, contacting, off-gas, and ozone destructor inlet piping should be purged prior to opening the various systems or subsystems. A minimum of two SCBAs must remain in the immediate vicinity of the ozonation system.

Entry into the ozone contactor should follow accepted confined-space-entry protocols. Personnel must recognize the possibility of oxygen deficiencies or trapped ozone gas despite their best efforts to purge the system. Steps to be followed include

1. Halt ozone flow to the contactor train. Valve off or, preferably, blank off the ozonized gas pipe to the contactor if possible.
2. Purge the contactor with oxygen or prepared air.
3. Valve off or, preferably, blank off all possible cross-connections with other ozonation trains.
4. Open all access hatches and begin ventilation as the contactor is dewatered.
5. Dewater the contactor.
6. Continue the ventilation procedure.
7. Have the contactor interior tested for ozone, oxygen, and gaseous contaminants (e.g., hydrogen sulfide) by personnel wearing protective clothing and SCBAs.

TABLE 26.10 Routine operational checklist and troubleshooting guide for ozonation.

Items	What to check	Potential problems	Corrective actions
Air filter	Proper air flow	Dirt or dust clogging filter	Replace filter.
Gas compressor or blower	Proper air volume and pressure	Low air volume or pressure	Open valves and verify that air filter is clean.
Aftercooler	Compressor	Improper cooling	Recharge with refrigerant.
		Not running	Replacement probable.
	Fan	Not running	Replacement probable.
Coalescing filter	Proper air flow	Dirt or oil clogging filter	Clean or replace filter and drain trap.
Dryer	Desiccant cartridge	Spent cartridge	Replace.
	Dryer system and refrigerant	Improper drying	Recharge with refrigerant.
		Compressor not running	Replacement probable.
Inverter	Frequency output	Final thyristor or inverter	Replace unit or thyristor.
Transformer	Output voltage	Low output	Verify proper input voltage.
			Increase potentiometer setting.
		No output	Verify proper input voltage; replacement probable.
Potentiometer	Dial setting corresponds to voltmeter	No voltage control	Verify proper volunteer operation; potentiometer replacement probable.
Voltmeter	Verify readout with potentiometer setting	Meter rating too low	Verify proper potentiometer setting.
			Verify proper transformer output.
			Calibrate voltmeter.
			Replacement probable.
Ozone generator	Inlet gas-flow rate	Insufficient volume or pressure; leak	Start and increase gas flow from compressor or blower; repair leak.
		Moisture content too high	Verify proper operation of gas cooler or dryer systems.
	Inlet cooling-water flow	Insufficient flowrate	Provide proper water supply for unit size.
			Check for kinked, broken, or otherwise restricted water-supply tubing.

TABLE 26.10 Routine operational checklist and troubleshooting guide for ozonation (*continued*).

Items	What to check	Potential problems	Corrective actions
	Dielectric electrodes	Breaker tripped	Examine dielectric tube or plate closely for a defect that may result in grounding grounding arc; defect could be pinhole, crack, or break in glass.
		Excessive buildup of deposits on the exterior	Clean dielectric tube and troubleshoot the exterior air supply for failure of the gas-drying system.
Gas-flow rotameter	Gas flow to ozone reaction vessel	Gas flow too low or too high	Increase or decrease gas flow by operating needle valve.
		Gas-flow indicator not functioning	Remove ozonator from service and clean rotameter.
Pressure-regulating valve	Compare pressure-relief and gauge settings.	Pressure setting too high or too low.	Adjust to recommended setting.
Ozone destructor	Excessive ozone in ozone-destructor effluent	Leak	Repair leak.
		Catalyst black	If water on catalyst is black, heat to 212 °F*.
		Catalyst not black	Replace or consult manufacturer.
		Catalyst crushed	Replace—make certain bed is not fluidizing.

*(°F − 32) 0.5556 = °C.

8. Once working conditions are safe, allow personnel equipped with safety harness and rope to enter the contactors, using the buddy system. With this system, a second person on the deck of the contactor watches and assists the worker in the contactor. Self-contained breathing apparatuses must be kept immediately adjacent to the work area.

Because of the hazardous nature of ozone gas, security measures must be in place to ensure that only authorized personnel have access to the ozone gas-generation and -handling systems.

TABLE 26.11 Health effects of ozone.

	Concentration (ppm)	Duration of exposure	Effect
Acceptable zone	0.01– 0.04	—	Odor threshold
	0.1	—	Minor eye, nose, and throat irritation.
	0.1	8-hour average exposure limit	
	>0.1	Few minutes	Continuous headache, shortness of breath.
	0.25	2 to 5 hours	Reduced lung function and ability to do physical work (for persons with a history of heart and lung disease).
	0.3	15-minute exposure limit	
	0.4	2 hours	Reduced lung function during moderate work for all persons.
Hazardous zone	>0.6	2 hours	Chest pain, dry cough.
	1	1 to 2 hours	Lung irritation (coughing), severe fatigue.
	>1.5	2 hours	Reduced ability to think clearly. Continuing cough and extreme tiredness, maybe lasting for 2 weeks; severe lung irritation with fluid buildup.
	9	Intermittent	Severe pneumonia (arc welders).
Critical zone	10	Immediately dangerous to life and health	
	11	15 minutes	Rapid unconsciousness.
	50	30 minutes	Expected to be fatal

PREVENTIVE MAINTENANCE. Preventive maintenance, performed routinely, increases the life expectancy and efficiency of equipment. There must be no leaking connections or other leaks in or around the ozonator because this is an electrical shock hazard.

Extreme caution must be exercised when working near the dielectric tube, transformer, or other electrical-system components, because electricity in excess of 20 000 V may be encountered.

The following considerations apply to a preventive maintenance program for ozonation:

- Inspect and clean the ozonator, air supply, and dielectric assemblies on a scheduled basis, as recommended by the manufacturer.
- Collect samples of ozone gas from the sample tap and determine the percent ozone generated via an iodometric or UV monitor. If a reduction in ozone production is observed, check the air supply for proper moisture content. Also check to ensure that coolant flow (cooling water) and applied voltage are proper.
- Lubricate the compressor or blower consistent with the schedule and instructions recommended by the manufacturer. Ensure that all compressor sealing gaskets are in good condition, and replace them as necessary.
- Monitor the ozone generator operating temperature and clean the cooling-system components as necessary.
- Check the supply air (gas) for moisture content (dewpoint). If the supply gas is moist, the ozone will react with the moisture to form a highly corrosive condensate on the internal components of the ozonator.
- Clean the ozone-generation cells periodically to maintain maximum efficiency.

OTHER DISINFECTION METHODS

BROMINE CHLORIDE. Bromine chloride (BrCl), which is occasionally used for wastewater disinfection, is a mixture of bromine and chlorine. Twelve times more bromine chloride than chlorine will dissolve in water. Products of bromine chloride mixed with water are stronger oxidants and disinfectants than chlorine. Also, in the presence of amines, bromine chloride forms bromamines, which are better disinfectants than chloramines. The bromamines have a short half-life, resulting in less toxic effects in receiving water than chloramines. So, debromination to remove bromine residuals is seldom needed.

Bromine chloride mixes with water to form hypobromous acid and hydrochloric acid:

$$BrCl + H_2O \rightarrow HOBr + HCl \qquad (26.17)$$

Bromine chloride mixes with amines to form monobromamine and hydrochloric acid:

$$BrCl + NH_3 \rightarrow NH_2Br + HCl \qquad (26.18)$$

Process Description. A pressurized system using either air or nitrogen gas feeds the bromine chloride solution. The pressure forces the bromine chloride liquid from the

supply tank to the feed point. This pressurized feed system contrasts with that for chlorine, which is fed under vacuum.

Safety. Bromine chloride is a heavy, corrosive, fuming liquid with a sharp, penetrating odor. Anhydrous ammonia, saturated hypo (sodium thiosulfate) solution, lime slurry, or dry soda ash and potassium carbonate or sodium carbonate must be available for decontamination purposes. A self-contained breathing apparatus is required for all employees handling this material.

CHLORINE DIOXIDE. Chlorine dioxide (ClO_2) is a strong disinfectant that has been used in the water and pulp-bleaching industries. Because chlorine dioxide is explosive as a gas, it is used only as an aqueous solution. Chlorine dioxide is typically generated onsite and warrants the same security measures as those of chlorine gas. Effluent treated with chlorine dioxide is also subject to the problems associated with DBPs (e.g., chlorite and chlorate ions), which are toxic. Although chlorine dioxide has served effectively as a wastewater disinfectant, it has seldom been applied in the United States. *White's Handbook of Chlorination* (White, 1986) or *The Chlorination/Dechlorination Handbook* (Connell, 2002) can provide more information about this disinfectant.

PERACETIC ACID. Peracetic acid ($C_2H_4O_3$) is a mixture of acetic acid (CH_3COOH) and hydrogen peroxide (H_2O_2) in an aqueous solution. It is a stronger oxidizing agent than chlorine or chlorine dioxide and initially was used in the food processing industry as a sanitizer and disinfectant. Although it is relatively untested in the U.S. wastewater treatment industry, it has been used in Europe. It is fed in (15% active) liquid form at a rate of 5 to 8 mg/L with a 30-minute contact time. The advantages of peracetic acid include its long shelf life, its nontoxic residual in effluent, and its low level of environmental safety regulations.

WET-WEATHER TREATMENT APPLICATIONS

The development and enforcement of sanitary sewer overflow (SSO) and combined sewer overflow (CSO) regulations has emphasized the need for disinfection of wet-weather-related flows. Classical municipal secondary WWTPs are primarily biological in nature and consequently are not able to provide high levels of treatment to wet-weather flows in excess of three or four times the average dry-weather flow. As a result, more municipalities are considering split-flow physical–chemical treatment trains to accommodate these peaks. Combined sewer overflow treatment facilities intended to provide "primary-equivalent" levels of treatment also need disinfection processes capable of adequately reducing pathogens in effluents with somewhat higher pollutant

concentrations. A number of pilot studies and research projects have been conducted to address these anticipated needs.

Recent pilot studies were completed in Columbus, Georgia, through the Water Environment Research Foundation (Bonner, 2003). The demonstration project evaluated sodium hypochlorite, peracetic acid, chlorine dioxide, and UV disinfection techniques. The three chemical techniques provided consistent results when the data were normalized by ammonia, COD removed, and temperature.

Chlorine dose varied from 4 to 30 mg/L, with average concentrations between 8 and 9 mg/L. Contact times ranged from 6 to 40 minutes at peak flowrates for events tested. The predominant contact times were between 10 and 20 minutes. Contact time is not as significant a factor as water quality and chemical dose for the range of contact times tested. Contact time is most significant with sodium hypochlorite, less with peracetic acid, and did not appear at all significant with chlorine dioxide. These observations indicate that the germicidal performance depends more on satisfying the chlorine demand from substances in the water compared to conventional combined chlorine disinfection. Dosing rates that resulted in objective disinfection were typically at the breakpoint level.

Ultraviolet irradiation performance was typically correlated to other water quality parameters (e.g., TSS, ammonia, COD, and temperature). Ultraviolet disinfection of *E. coli* bacteria during winter temperatures depends on dose (product of intensity and time) and light transmittance. Light transmittance in the filter effluent was typically below 60%. At levels below 40%, the effluent bacteria was three orders of magnitude higher (thousands) than with transmittance above 40% (bacteria in the hundreds). Unfiltered light transmittance was as low as 20%.

Many of the technologies considered for wet-weather applications are summarized in *Alternative Disinfection Methods* (U.S. EPA, 1999). They include chlorine dioxide, ozonation, UV radiation, peracetic acid, and electron-beam (E-beam) irradiation.

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Task Force

Prepared by the Operation of Municipal Wastewater Treatment Plants Task Force of the Water Environment Federation

Michael D. Nelson, *Chair*

Douglas R. Abbott
George Abbott
Mohammad Abu-Orf
Howard Analla
Thomas E. Arn
Richard G. Atoulikian, PMP, P.E.
John F. Austin, P.E.
Elena Bailey, M.S., P.E.
Frank D. Barosky
Zafar I. Bhatti, Ph.D., P. Eng.
John Boyle
William C. Boyle
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Sandeep Karkal
Gregory M. Kemp, P.E.

Justyna Kempa-Teper
Salil M. Kharkar, P.E.
Farzin Kiani, P.E., DEE
Thomas P. Krueger, P.E.
Peter L. LaMontagne, P.E.
Wayne Laraway
Jong Soull Lee
Kurt V. Leininger, P.E.
Anmin Liu
Chung-Lyu Liu
Jorj A. Long
Thomas Mangione
James J. Marx
Volker Masemann, P. Eng.
David M. Mason
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Debra McCarty
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Roger A. Migchelbrink
Darrell Milligan
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Alie Muneer
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Michael W. Sweeney, Ph.D., P.E.
Chi-Chung Tang, P.E., DEE, Ph.D.
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Gordon Thompson, P. Eng.
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http://www.wef.org

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Chapters 11, 23, and 32 were not updated for this edition of MOP 11. Chapters 11, 23, and 32 included herein are taken from the 5th edition of the manual, which was published in 1996.

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M. D. Nelson
S. Rangarajan
E. P. Rothstein
A. T. Sandy
A. K. Umble
T. O. Williams
J. Witherspoon

Acknowledgments

This manual was produced under the direction of Michael D. Nelson, *Chair*.

The principal authors and the chapters for which they were responsible are

George Abbott (2)
Thomas P. Krueger, P.E. (2)
Thomas E. Arn (3)
Greg Ramon (3)
Gregory M. Kemp (4)
Roger A. Migchelbrink (5)
Melanie Rettie (6)
Michael W. Sweeney, Ph.D., P.E. (6)
David Olson (7)
Russell E. Mau, Ph.D., P.E. (8)
Peter Zanoni (9)
Louis R. Germanotta, P.E. (10)
Norman Jadczak (10)
James Kelly (11)
Richard Sutton, P.E. (12)
Alicia D. Gilley, P.E. (13)
Jorj Long (14)
Keavin L. Nelson, P.E. (15)
Ed Ratledge (16)
Kathleen M. Cook (17)
Frank D. Barosky (17)
Jerry C. Bish, P.E., DEE (18)
Ken Schnaars (19)
Donald J. Thiel (20, Section One)
William C. Boyle (20, Section Two)
Donald M. Gabb (20, Section Three)
Samuel S. Jeyanayagam (20, Section Four)
Kenneth Schnaars (20, Section Five)
Alan J. Callier (20, Section Six)
Jorj Long (20, Appendices)
Howard Analla (21)
John R. Harrison (22)
Anthony Bouchard (23)
Sandeep Karkal, P.E. (24)
Daniel A. Nolasco, M. Eng., M. Sc., P. Eng. (25)
Donald F. Cuthbert, P.E., MSEE (26)
Carole A. Shanahan (27)
Kim R. Riddell (28)
Peter L. LaMontagne, P.E. (29)
Patricia Scanlan (30)
Webster Hoener (30)
Gary Neun (30)
Jim Rowan (30)
Hari Santha (30)
Elena Bailey, M.S., P.E. (31)
Rhonda E. Harris (32)
Peter L. LaMontagne, P.E. (33)
Wayne Laraway (33)

Contributing authors and the chapters to which they contributed are

David M. Mason (3)
David W. Garrett (9)
Earnest F. Gloyna (23)
Roy A. Lembcke (23)
Jerry Miles (23)
Michael Richard (23)
John Bratby, Ph.D., P.E. (29)
Curtis L. Smalley (32)

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David A. Flowers, Cedarburg, Wisconsin
DCWASA, Washington, D.C.
Department of Biological Systems Engineering, Washington State University, Pullman, Washington
Earth Tech Canada, Inc., Markham, Ontario, Canada
Earth Tech, Sheboygan, Wisconsin
East Norriton-Plymouth-Whitpain Joint Sewer Authority, Plymouth Meeting, Pennsylvania

EDA, Inc., Marshfield, Massachusetts
Eimco Water Technologies Division of GLV, Austin, Texas
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Ministry of Environment, Toronto, Ontario, Canada
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Pennoni Associates, Inc., Philadelphia, Pennsylvania
Peter LaMontagne, P.E., New Britain, Pennsylvania
Philadelphia City Government, Philadelphia, Pennsylvania
Philadelphia Water Department, Philadelphia, Pennsylvania
PSG, Inc., Twin Falls, Idaho
R.V. Anderson Associates, Limited, Toronto, Ontario, Canada
Red Oak Consulting—A Division of Malcolm Pirnie, Inc., Phoenix, Arizona
Research and Development Department, Metropolitan Water Reclamation District of Greater Chicago, Cicero, Illinois
Rock River Water Reclamation District, Rockford, Illinois
Rohm and Haas Co., Croydon, Pennsylvania
Sanitary District of Hammond, Hammond, Indiana
Seacoast Environmental, L.L.C., Hampton, New Hampshire
Siemens Water Technologies, Waukesha, Wisconsin
Simsbury Water Pollution Control, Simsbury, Connecticut
Tata Associates International, Naperville, Illinois
Thorn Creek Basin Sanitary District, Chicago Heights, Illinois
Trojan Technologies Inc., London, Ontario, Canada
U. S. Environmental Protection Agency, Philadelphia, Pennsylvania
U.S. Filter Operating Services, Indian Harbour Beach, Florida
United Water, Milwaukee, Wisconsin
University of Wisconsin, Madison, Wisconsin
USFilter, Envirex Products, Waukesha, Wisconsin
USFilter, Inc., Norwell, Massachusetts
Veolia Water North America, L.L.C., Houston, Texas; Norwell, Massachusetts
West Point Treatment Plant, Seattle, Washington
West Yost & Associates, West Linn, Oregon
Weston & Sampson Engineers, Inc., Peabody, Massachusetts

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Chapter 27

Solids Management

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Solids management refers to the use or disposal of solids that have been removed from wastewater, processed, and are ready to leave the treatment plant. The solids in this context are typically biosolids but could also be scum, grease, screenings, grit, or ash. [The Water Environment Federation defines *biosolids* as "primarily organic solids produced by wastewater treatment processes that can be beneficially recycled." Before treatment, this material is called *wastewater solids* or *sludge*. To be classified as biosolids, the material must meet state and U.S. Environmental Protection Agency (U.S. EPA) criteria for beneficial use.]

TYPES OF SOLIDS

Wastewater treatment plants receive and generate many types of solids, including ash, scum, grease, screenings, grit, and sludge (e.g., raw, treated, primary, secondary, tertiary, combined, and chemical). Some also receive septage from onsite treatment systems and liquid sludge from other treatment plants. (For more information on solids, see Chapter 28.)

Treatment plants also generate solid wastes, including paper, garbage, automotive residuals, equipment oils and greases, chemical-impregnated rags, lab wastes, office wastes (e.g., printer cartridges and copy- and fax-machine chemicals), light bulbs, batteries, and barrels. These wastes must be disposed or recycled according to local regulations. [Given that wastewater treatment plants are supposed to protect the health of both the public and the environment, it behooves them to recycle as much of their wastes as possible (Fisichelli, 1992).]

CHARACTERIZATION

The physical, chemical, and biological characteristics of biosolids affect both its use and the public's perception of it. For example, federal and state regulators base land-application requirements on biosolids' pollutant and pathogen concentrations. A land-application site's neighbors, on the other hand, base their acceptance on the material's consistency and odor.

Biosolids should be sampled for metals and organics after they have been processed so the analytical results will describe the actual material to be used or disposed. Once the chemical and biological standards have been met, the biosolids characteristics that will affect its management options are

- nutrient concentrations, which can affect surface water quality;
- micronutrient concentrations, which can affect soils and plant growth (a certified agronomist may be needed to pinpoint the source of abnormal plant growth); and

- concentrations of various constituents (e.g., mercury and sulfur), which can affect an incinerator's air-pollution controls.

A wastewater treatment plant should keep a large database containing multiple years' worth of chemical analysis results, so staff can prove that the plant's biosolids have not contained harmful levels of constituents such as metals, organics, pathogens, dioxin, radioactive components, polychlorinated biphenyls (PCBs), and so is unlikely to contain them in the future. To be convincing, the data should show that metals and organics concentrations are stable or decreasing—no wild variations—and every result should have been promptly checked by experts and quality-control personnel.

Also, the treatment plant should have an active pretreatment program to minimize unwanted constituents in its influent. Such constituents tend to end up in the solids, and the presumption may be that the resulting biosolids should not be land-applied if these constituents might cause the soil to need remediation for certain uses. However, biosolids typically are land-applied before many test results are available, so plant staff and regulators need to be confident that the material will not harm humans or the environment. They should be able to base this confidence on historical data and a successful pretreatment program.

To demonstrate that a wastewater treatment plant's biosolids management program is based on best management practices (BMP), staff should:

- Do the sampling and analysis required to demonstrate that regulatory standards are being met;
- Do additional sampling and analysis (e.g., priority pollutant analysis, radioactivity, dioxin, and possibly others) on a regular basis (because telling the public that the plant's biosolids meet all federal and state standards does not inspire confidence; specifying how the biosolids surpass those standards does);
- Maintain an effective pretreatment program (even if only to show that there are no industries in the plant's service area) and an active pollution prevention program to help industries and the public reduce their use of pollutants;
- Develop and use a written sampling plan and chain-of-custody form;
- Review every analysis, including those done by a contract lab, to verify that the appropriate test was done, the results are accurate, the appropriate quality-control measures were taken (if the tests were done onsite, the quality-control procedures should be written based on appropriate industry protocols); and
- Ensure that the biosolids look innocuous (e.g., no pieces of fast-food wrappers, condiment pouches, or personal sanitary products should be seen in the material).

HANDLING

GENERAL. While all wastewater solids and septage must be treated to meet the relevant federal, state, and local regulations, differences in processing methods can result in biosolids with widely varying consistencies, which will affect how they can be transported and beneficially used. Handling methods, for example, can greatly affect the consistency of biosolids: Screw conveyors can turn biosolids into a paste that is difficult to apply via manure spreaders. Belt conveyors alter the material less.

For example, two modifications to the solids treatment process at the Allegheny County Sanitary Authority in Pittsburgh, Pa., had unexpected results. Originally, the biosolids were dewatered via belt presses and then mixed with lime. This produced a crumbly mixture that was easily applied via standard manure spreaders. When plant staff replaced the lime-addition equipment with mixers and screw conveyors, the biosolids became a "pudding" that was difficult to spread. However, when staff replaced the belt presses with centrifuges, the material reverted back to the crumbly, spreadable mixture. (Each treatment plant's sludge is unique, so the best process train will be site-specific.)

CHEMICAL ADDITIVES. Any compound added during wastewater treatment typically ends up in the biosolids and may affect its physical, chemical, or handling characteristics. It also may affect the biosolids' permitted use and disposal options.

Lime and sodium bicarbonate, which are added during anaerobic digestion to control pH, should not be problematic; they only increase the concentration of compounds that occur naturally in biosolids and are typically harmless. Likewise, the acids and caustics used to control pH in aerobic digesters should not affect the biosolids' ability to meet regulatory standards. Calcium, on the other hand, can change the soil chemistry and nutrient uptake at land-application sites, so agronomists may recommend occasional soil tests (e.g., once every 3 years) to check the macro- and micronutrient levels at the sites.

Some treatment plants use organic polymers or inorganic chemicals to thicken or dewater sludge. Some regulators are concerned that nitrogen-based polymers may decompose to produce amines and other intensely odorous compounds. However, research has shown that the polymer may adsorb to particulate, making it less biodegradable and significantly less reactive—effectively, an inert material (Dental et al., 2000). The portions of the polymer that do break off are typically innocuous and biodegradable. So, polymer additions should not prohibit the biosolids from being land applied safely.

Solids-conditioning chemicals [e.g., lime, ferric chloride, ferrous sulfate, ferrous chloride, and aluminum sulfate (alum)], which may be added before or after thicken-

ing or dewatering processes, should not affect the biosolids' ability to meet regulatory standards. However, if the ferric chloride solution is a byproduct of another process (e.g., spent pickle liquor from an industrial source), then the solution should be analyzed for metals and possibly organics.

Some treatment plants use potassium permanganate to control odors; this also should not affect the biosolids' ability to meet regulatory standards.

TREATMENT PROCESSES. Most sludge-stabilization methods (e.g., anaerobic digestion, aerobic digestion, composting, lime stabilization, thermal treatment, and heat drying) produce land-applicable biosolids, but their products' characteristics and required handling methods will vary. Anaerobic digestion, for example, produces biosolids with low levels of organics and bacteria. However, the material may be somewhat odorous and difficult to dewater.

Aerobic digestion, which is mostly used at small treatment plants, produces a land-applicable biosolids that may be harder to thicken than other types of biosolids.

Composting, when done properly, produces a relatively dry, biologically stable, odor-free biosolids that may be stored outside without developing odors or attracting insects. Some treatment plants sell this material, thereby reducing solids-handling costs. Composted biosolids typically look better and emit less odor than other types of biosolids.

Lime stabilization produces biosolids whose quality some state regulators question, because they are not convinced that this method produces "stabilized" solids. Also, the biosolids are likely to be odorous (primarily ammonia). Research has shown, however, that if enough alkaline (or lime and heat) is added, then the resulting biosolids meet the pathogen-reduction and vector-attraction-reduction standards for Exceptional Quality (EQ) biosolids and are less likely to be odorous because the odorous gases are driven off during processing and can be collected and treated then.

Thermal treatment processes destroy pathogens, improve the resulting biosolids' thickening and dewatering characteristics, and greatly reduce its volume. Although odors are produced during treatment, the biosolids have little odor (as long as the material remains dry). However, the biosolids may have higher metals concentrations and could spontaneously combust.

Mechanical drying methods and drying beds have potential odor problems and may be costly if covers are needed to abate odors or because of temperature extremes.

Incineration destroys organic matter, reduces the sludge volume, and produces an ash that may be beneficially used if its metals levels do not exceed regulatory standards. At temperatures well above 816 °C (1500 °F), the ash may become a hard frit

that can be used as a fill, roadbed material, or ceramics ingredient. This option may be attractive to larger wastewater treatment plants that have difficulty finding enough land for composting or land application.

Emerging sludge-stabilization technologies include a microwave technology and methods involving quicklime and heat. For more information on sludge-stabilization methods, see Chapter 32.

MANAGEMENT

USE OPTIONS. Biosolids that meet the requirements of U.S. EPA's Standards for the Use or Disposal of Sewage Sludge (40 *CFR* 503), as well as state and local standards, can be beneficially used. Metals levels in U.S. biosolids have dropped since U.S. EPA's pretreatment regulations were promulgated, and most treatment plants now have no trouble meeting 40 *CFR* 503's metals requirement, according to various studies. The pathogen and vector-attraction-reduction levels, however, depend on the processing method used.

Land Application. The most common method for using biosolids is land applying it on farmland. In 1988 (before ocean disposal stopped), 33% of sewage sludge was land applied, according to the preamble of 40 *CFR* 503. A more recent U.S. EPA study gives a rough estimate that 60% of biosolids are now land applied. Before a treatment plant can begin spreading (or injecting) biosolids on farmland, however, all federal, state, and local paperwork must be completed and approved. Some states require every site to be permitted, while others require the biosolids generator to obtain a general permit and maintain a register of individual sites.

To obtain a general permit, the biosolids generator may need the following:

- An open and ongoing relationship with regulators (they should be familiar with the treatment plant and its operations because they have toured the site at the plant staff's invitation);
- A database of biosolids test results (at least 3 years' worth, but preferably since plant startup because regulators will be more comfortable about letting a plant land apply biosolids if extensive physical, chemical, and pathogenic data demonstrate its safety);
- A history of the treatment plant's operations and a detailed description of its solids processes;
- A quality-control and quality-assurance plan, standard operating procedures for each analysis, and chain-of-custody forms or a logbook of all samples;

- A public relations plan and ongoing outreach efforts to inform the public about the biosolids management program;
- A written description of all land-application activities and personnel, along with the contact information for the treatment plant staff and regulators who should be notified if a question arises or emergency occurs;
- A spill prevention and control plan, a contingency plan, and a long-range plan for future improvements to the biosolids management program; and
- A written procedure (and form or logbook) for handling complaints from each land-application site's neighbors.

Some states have training programs for biosolids generators and land appliers. Biosolids personnel should take such programs (whether mandatory or optional) because they will learn how to interact with regulators and what their expectations are. Biosolids personnel also should become active members of biosolids-related professional organizations [e.g, the Water Environment Federation (WEF), its member associations (MAs), and regional associations], which are sources of useful information, help, and support. In addition to committees devoted to biosolids issues, WEF and its MAs also publish technical materials.

Once a treatment plant has met the general permit requirements, its personnel can establish the land-application program by doing the following:

- Find suitable farmland. The site must have enough acres to justify the expenditure of time and resources that go into obtaining a permit. The vicinity must be checked for wetlands, wind direction, remoteness, location of neighbors, local ordinances on biosolids use, and the general feeling about biosolids.
- Determine which farmers want the material, explain the approval requirements, verify ownership, obtain the necessary data and signatures, and notify the neighbors and any local officials (e.g., township or borough supervisors, county officials, conservation districts, and regional state regulators);
- Contact all of the relevant biosolids regulators; prepare the necessary paperwork; do the required field work [e.g., soil sampling every 10.1 ha (25 ac) or so] and lab tests; procure aerial photographs of the area and mark the fields, boundaries, and all water-related landmarks (e.g., waterways, wetlands, water supplies, and wells); determine the delivery truck's travel route; and complete any other work required by local agencies;
- Inform local agencies and the public about the benefits of beneficially using biosolids (especially if land application or the treatment plant is new to the area), ensure that all program-related personnel (e.g., generators, transporters,

and land appliers) understand the benefits of biosolids and can explain them properly to the public, and maintain an ongoing local outreach program for the benefit of anyone who inquires about land application; and

- Inspect the land-application sites regularly to verify that the work is done correctly (e.g., the trucks are not causing problems, mud is not tracked onto roads, odors are controlled, the site is well-maintained, and any unspread biosolids are neatly stored) and that a treatment plant representative will be able to answer all questions during regulatory inspections.

Land Reclamation. Land reclamation is similar to land application except that the biosolids-application rates are higher because the application is not just to provide nutrients for the current growing season but to establish long-term growth on disturbed and nutrient-poor soils. The land-reclamation sites are usually acidic, strip-mined areas (Sopper, 1993; Pennsylvania Organization for Watersheds and Rivers, 2003). However, biosolids also have successfully reclaimed rangeland in New Mexico by providing organic content that helps retain moisture in the soil.

Lime-stabilized biosolids work well on strip-mined ground where the pH may be low across the site—the lime content of the biosolids provides the pH adjustment needed to allow grasses to grow—but other types of biosolids are also effective as long as appropriate pH adjustments are made. The material's organic matter and slow-release nitrogen will provide a good base for most seed mixtures. However, if the seed mixture includes warm-season grasses, which develop slowly (over 2 to 3 years), they can be choked by faster-growing fescue and other grasses, so multiple applications of biosolids at lower rates may be necessary to avoid this problem.

Biosolids have also successfully revegetated capped cells at landfills. Once a cell has been filled, it is typically covered with a geomembrane, or filter fabric covered with soil to keep water from infiltrating into the cell and to minimize leachate from the cell. The biosolids are then applied in the same manner as for reclaiming strip-mined land.

Forestry. The King County (Washington) Wastewater Treatment Division has been applying biosolids to tree farms since 1987 and to state forests since 1995. The biosolids make an excellent soil amendment and source of nutrients for trees, as illustrated by tree rings from biosolids-fertilized trees, which are wider after the applications. The forestry projects help protect and enhance forests and wildlife habitat along the scenic highway that leads from Seattle to the mountains.

Commercial Products. Some treatment plants (on their own or with a private company) compost biosolids for use in landscaping and gardening. Biosolids that can be bagged and sold may be used by the public for their gardens and potted plants.

Incineration. In 1993, 381 wastewater treatment plants (2.8%) incinerated their sludge (16% of the total volume produced nationwide), and seven plants co-incinerated sludge with municipal solid waste in municipal waste combustors, according to the preamble of 40 *CFR* 503. Some treatment plants choose to incinerate biosolids because they are in colder areas and need an effective management method in winter, when land application is infeasible. Some plants in large metropolitan areas incinerate solids to avoid the odor complaints related to hauling Class B biosolids long distances through city neighborhoods. The incineration process is equipment- and energy-intensive and requires air-pollution-control devices; the leftover ash must also be used or disposed. (For more information on incineration processes, see Chapter 32.)

Some wastewater treatment plants recover the heat generated during incineration and use it to heat other treatment processes, to generate electricity, or to make steam for heating or use in other treatment processes. Incinerator ash is typically landfilled, but it could be beneficially used if its metal concentrations are within regulatory limits (all pathogens were burned off during incineration). For example, the ash could be used as

- An amendment to soil that will be dug up and sold by topsoil producers (the ash-and-soil mixture produced must meet regulators' criteria);
- A component of cement, concrete, or asphalt;
- An alkaline addition to sludge (with other alkaline additives, perhaps);
- A component of house shingles;
- A component of plastic;
- A ceramic-like material (if further treated at higher temperatures); and
- Landscaping bricks (if further processed at higher temperatures).

To qualify for most of these uses, the ash must meet certain criteria and be available on demand at specified volumes. Not all treatment plants can meet such requirements, and they must compete with other industries that produce large volumes of suitable ash.

Heat Drying and Other Themal Processes. Together, heat drying and pelletizing produce a marketable fertilizer that meets the 40 *CFR* 503 requirements for EQ biosolids, and so has fewer regulatory recordkeeping and reporting requirements if used for land application. This biosolids management option is a proven technology in which odors can be contained and controlled. The resulting biosolids pellets have much less volume and weight than the influent solids and are easily handled, conveyed, and stored. They can be delivered to consumers in bulk or in bags or other containers.

The disadvantages of heat drying and pelletizing include the dust's explosive potential and the potential for overheating and fires. Also, the equipment is expensive, complex, and maintenance-intensive, requiring qualified operators. Air-emissions-control equipment also is required, especially because drying certain types of solids can result in more odorous pellets.

Solids also may be treated via the following thermal processes:

- phased thermophilic digestion;
- heat pasteurization, which produces a marketable fertilizer;
- residuals gasification, which produces liquid, gaseous, and hydrogen-derived fuels;
- treating biomass thermo-chemically to produce a low- to medium-grade heat content gas;
- Enersligle™ (a process that produces a fuel-grade oil); and
- Cambi™ (thermal hydrolysis using temperature and pressure to heat and cool sludge).

DISPOSAL OPTIONS. Treatment plants typically decide whether to use or dispose of biosolids based on the cost of each evaluated option. Sludge that will ultimately be landfilled may need as much treatment as if it were to be land applied, so the related labor and trucking costs may be the overriding factors.

The disposal methods—"dumping", landfilling, monofilling, surface application, and co-disposal with municipal solids waste—all typically involve putting the biosolids in a hole in the ground. These holes are subject to federal, state, and sometimes local regulations, which require liners; daily and final covers; collection of leachate and methane gas; groundwater monitoring; control of odors, vectors, and nuisances; and caps and other closure methods.

DIVERSIFICATION AND CONTINGENCY PLANS. The Allegheny County Sanitary Authority's wastewater treatment plant in Pittsburgh, Pennsylvania, produces approximately 154 000 wet tonne/a (170 000 wet ton/yr) for the following purposes:

- Almost one-half is incinerated, producing steam for use in various plant processes as an energy-recovery method;
- Almost one-half is land applied on farms and strip mines by contractors; and
- The rest is landfilled.

Treatment plant staff chose this combination because the plant is within city limits, surrounded by businesses and residences, and cannot store solids onsite because of

potential odors. This diversity enables the treatment plant to operate efficiently and without odors, regardless of maintenance needs or weather conditions.

Treatment plants do not just process wastewater, and solids management is not a small part of the operation. It requires at least as much time, effort, and financial commitment as wastewater does. So, all treatment plants should have a contingency plan for unexpected events (e.g., severe weather). Planning for regulatory changes, however, is another matter. Plant staff should establish a good working relationship with regulators and keep abreast of the regulatory changes under development. Changes that will result in more solids treatment will involve more money and equipment, which can take months or years to secure, install, and start up.

FACTORS AFFECTING THE DECISION. The most important factor in choosing a biosolids management option is the applicable laws, regulations, and local ordinances. Check carefully: even if land application is technically allowed, obtaining permits and site approvals can be difficult and time-consuming. The regulators who permit generators and approve sites may have many duties and, therefore, little time for these tasks or for complaints from organizations that vehemently oppose land application. In some states, local governments have established local ordinances that impose fees and requirements doubling the cost and effort of land application. The current trend is that regulators want treatment plants to produce odorless Class A biosolids.

Another important factor is whether to treat the plant's solids to meet Class A or Class B biosolids requirements. Typically, Class A treatment processes cost more than Class B processes. Most land-application programs use Class B biosolids, which work well on farms and strip mines and are acceptable to farmers and miners. Class A biosolids have lower pollutant and pathogen levels, and can be sold or given away to the public. (The sale price typically does not cover the entire production cost, but does help defray it.)

Other factors that affect the choice of biosolids management option include:

- The treatment plant's location;
- Local weather conditions;
- Past solids-management practices (everyone is more comfortable with something they know);
- Distance from available beneficial use sites;
- The number and strength of local anti-biosolids groups;
- Support of local government officials;
- Estimated costs;

- Available funding; and
- Local landfill availability and pricing.

Each option has advantages and disadvantages, and plant staff should avoid making the decision based solely on cost. Choosing to land apply Class B biosolids, for example, may ultimately fail if the anti-biosolids groups complain daily to regulators, who then become overwhelmed with public relations efforts and cannot keep up with permit applications and site-approval requests. Also, switching from a long-used method to a new one will be stressful, especially if the old method was simple (e.g., landfilling) and the new one is complex (e.g., composting or heat drying). Treatment plant personnel also need to decide whether to manage solids in-house or to outsource the work.

OUTSOURCING. *Outsourcing* is the process of hiring another entity to perform some of an organization's work. It enables treatment plant personnel to decide how much of the solids management work they want to do and how much they prefer to let someone else do. For example, the treatment plant could produce the biosolids and then hire a contractor to land apply it (e.g., perform all the work related to permitting, transporting, land applying, reporting, and communicating with the public and regulators). Alternatively, the treatment plant could hire a contractor to handle all of the solids-management processes.

One advantage of outsourcing is that the treatment plant does not have to expand its workforce. Also, plant personnel can rely on the expertise of a biosolids management specialist rather than "starting from scratch" themselves. Nor does the plant have to invest in a fleet of specialized vehicles (e.g., tractors, spreaders, and front-end loaders) or—if the entire solids-management program is outsourced—any solids or biosolids handling, processing, or storage facilities.

One disadvantage of outsourcing is that the treatment plant is still responsible for its contractor's actions, because as far as regulators are concerned, the biosolids generator remains their owner. So, plant personnel should be familiar with all aspects of the contractor's work, monitor the operations, and confirm that the program is effective and meets all requirements. Plant personnel also should maintain a suitable public outreach program and keep in contact with contractor staff, beneficial-use site owners, and regulators.

Once treatment plant personnel have decided to hire a solids management contractor, they need to draft an agreement that covers all usual and exceptional matters affecting the services that they expect the contractor to perform. The bid specifications or request for proposal should be developed by a team that includes legal counsel, en-

vironmental scientists, engineers, and operations and maintenance staff, as well as input from regulators. (Most outsourcing treatment plants are willing to share their bid specifications.) Any contractor hired to manage a treatment plant's solids should be well-known in their field and have experienced staff, a good compliance record, and a good work history.

ODORS AND PUBLIC ACCEPTANCE. Another important factor is the problem of odor complaints. Some complaints may be justified. Others will have nothing to do with the treatment plant's biosolids; they may be the result of odors from neighbors down the road. The complaints may even be more general: "We don't want your sewage sludge here." Justified or not, these complaints will cost the treatment plant personnel much time and energy combating their effects on regulators and the news media.

Although odor complaints cannot be completely avoided, treatment plant personnel can address the problem by

- Producing as odorless a product as possible;
- Monitoring conditions at beneficial-use sites (e.g., remoteness, wind direction, possibility of inversions, humidity, topography, and occurrence of holiday weekends);
- Encouraging regulators to educate the public about biosolids;
- Supporting environmental programs in schools and teaching students about biosolids;
- Establishing and maintaining public outreach programs on biosolids;
- Inviting local government and media representatives to tour the sites so they become familiar with biosolids and their benefits for farms and strip mines; and
- Following the suggestions of biosolids organizations [e.g., WEF and the National Biosolids Partnership (NBP)] concerning the public and the media.

Making the public familiar with the beneficial use of biosolids will hopefully counteract their instinctive fear of and aversion to the material.

RECORDKEEPING. Treatment plant personnel should keep the required records for as long as the regulations dictate. All permits, lab analyses, and regulatory reports should be maintained in a well-organized file or bookshelf to help regulators or third-party verifiers when they inspect the solids facilities.

Plant personnel also should set up an archive system. For example, paper files could be copied onto new storage media (e.g., CDs or optical disks) and then stored off-

site so the hardcopies are backed up, but the data remain at staff's fingertips. (For more information on management information systems, see Chapter 6.)

REGULATORS AND INSPECTIONS. Regulators and treatment plant personnel are "in this together": both answer to the public, their supervisors, and elected officials. The regulators who inspect facilities or approve permits want a treatment plant's solids management program to succeed because it makes their jobs easier. If regulators approve a permit and the treatment plant does a poor job, then both look bad. On the other hand, if the solids management program is a success, then both look good.

So, if regulators ask for information that is not "required" by the regulations, they probably need the data to help them approve the plant's paperwork. Treatment plants will get their work done faster if their personnel are cooperative.

EMS AND ISO 14001. The National Association of Clean Water Agencies (NACWA), U.S. EPA, and WEF formed the NBP in 1997 "to advance environmentally sound and accepted biosolids management practices". For example, the NBP encourages treatment plants and solids contractors to develop environmental management systems (EMSs) to improve their production and use of biosolids. The partnership's *EMS Guidance Manual*, which is based on ISO 14001, is designed to help treatment plants develop EMSs tailored for their solids management programs. The systems will help treatment plants do a good job, develop a good reputation, and improve working relations with regulators and environmental groups. However, they may or may not help public relations efforts, because some people will never accept any material that comes from a wastewater treatment plant.

OTHER SOLIDS

Other solids separated from wastewater may be beneficially used but are typically landfilled. The use of grit is being explored; it is washed to remove rubbish and slime, and then separated by size into sand and gravel for use as aggregate in asphalt mixtures and sub-base course materials.

COSTS

The costs of various solids management options are shown in Tables 27.1 through 27.4. These costs are from estimates, demonstration projects, and full-scale operations. Most are from 2002 or later, but costs from the 1990s are included for historical comparison. To make the figures comparable, some discretion was used (judgment as to number of days of operation per week, etc.).

TABLE 27.1 Costs of various biosolids process chains.

Process	Includes	Cost ($/wet ton)	Cost ($/dry ton)	Reference
Heat drying and pelletizing	Dewatering; privatized	92.47	462.39	Frankos, 2003
Composting in-vessel Paygro	Dewatering and trucking; privatized	105.36	526.80	Frankos, 2003
Land application	Privatized	32.69	163.45	Frankos, 2003
Class A lime stabilization	Thickening		1100	Leininger and Nester, 2003
Class A lime stabilization	Dewatering		900–920	Leininger and Nester, 2003
Class A ATAD	Dewatering		900–920	Leininger and Nester, 2003
Class A ATAD	No dewatering		770	Leininger and Nester, 2003
Class A indirect steam drying	Dewatering		980–1040 1600–1700 thru land application	Leininger and Nester, 2003
JVAP™ frame press and Class A heating/drying	Dewatering		820–1335 storage and land application	Leininger and Nester, 2003
Upgrading and keeping Class B process	Aerobic digestion		750	Leininger and Nester, 2003
Class A thermal drying process	Fully allocated costs; digestion, dewatering, land application		average: 257 range: 187–328	Bullard, 2002
Land application demonstration	Dewatering through land application; centrifuges		172–220	Sloan et al., 2002
	Dewatering thru land application; belt filter press		154–160	Sloan et al., 2002
Land application current system	Dewatering thru land application; gravity belt and belt filter press		202	Sloan et al., 2002
Land application and landfill daily cover	Aerated static pile composting		405	Van Der March et al., 2002
	In-vessel composting		399	Van Der March et al., 2002

TABLE 27.1 Costs of various biosolids process chains (*continued*).

Process	Includes	Cost ($/wet ton)	Cost ($/dry ton)	Reference
	Rotary heat drying		93	Van Der March et al., 2002
	Pre-pasteurization and RDP-Cambi		224	Van Der March et al., 2002
	Chemical addition—Bioset		217	Van Der March et al., 2002
	Dedicated landfill		300	Van Der March et al., 2002
Class A lime stabilization; pre-1996 study survey of 10 facilities	Thicken-digest-dewater; En-Vessel Pasteur. (RDP-EVP)		312 – 10 mgd 228 – 20 mgd 158 – 40 mgd 139 – 60 mgd	Rothberg, Tamburini & Winsor Inc., 1996
	Thicken-digest-dewater; Biofix with lime only		~345 – 10 mgd ~250 – 20 mgd ~180 – 40 mgd ~160 – 60 mgd	Rothberg, Winsor Inc., 1996 Tamburini &
Aerated static pile composting; pre-1996 study survey of 14 facilities	Thicken-digest-dewater		360 – 10 mgd 277 – 20 mgd 204 – 40 mgd 184 – 60 mgd	Rothberg, Tamburini & Winsor Inc., 1996
Thermal drying; pre-1996 study survey of 9 facilities	Thicken-digest-dewater		493 – 10 mgd 372 – 20 mgd 276 – 40 mgd 247 – 60 mgd	Rothberg, Tamburini & Winsor Inc., 1996

ATAD = autothermal thermophilic anaerobic digestion.

TABLE 27.2 Unit cost snapshot for various processes.

Process	Cost ($/wet ton)	Cost ($/dry ton)	Comments/Reference
Belt filter press dewatering	76		3% to 23.5% total solids (Hagaman, 1998)
Belt press dewatering	30	187	to 15.9% (Lee et al., 2003)
Centrifuge dewatering	33.25	187	Lee et al., 2003
Anaerobic digestion	2.25 per gallon (4.25–1.90/gal)		Cost depends on size of digester (Potts et al., 2003)
	3.85 per gallon		Concrete egg-shaped digester (Potts et al., 2003)
	1.88–4.24 per gallon		Costs include everything but storage (Marx, 2002)
Centrifuge dewatering		172.63	Drury et al., 2002
Belt press dewatering		185.77	Drury et al., 2002
Aerobic digestion without thickening	6.07 per gallon	146	Curley et al., 2002
Aerobic digestion with thickening	6.23 per gallon	150	Curley et al., 2002
Anaerobic digestion without thickening	6.87 per gallon	165	Curley et al., 2002
Anaerobic digestion with thickening	7.31 per gallon	176	Curley et al., 2002
Composting	50 (38 after revenues)		Hogan, 2003
Heat drying and pelletizing		250–350 412	Hogan, 2003 with dewatering and bond repayment pelletizing (Hogan, 2003)
Multiple hearth incinerator		192.30	at 20.80% total solids (Leger, 1998)
Lime stabilization—RDP EnVessel process		41.33	at 22–25% total solids (Hagaman, 1998)
Composting	22-own facility 29-outside facility		Lee et al., 2003
Multiple hearth incinerator		183.78	Sherodkar and Baturay, 2003
Fluidized bed tray dryer and pelletizer		190 for O&M	Janses et al., 2003
Incinerate scum and grease		248	6-year average (Dominak and Stone, 2002)

TABLE 27.2 Unit cost snapshot for various processes (*continued*).

Process	Cost ($/wet ton)	Cost ($/dry ton)	Comments/Reference
Land application of biosolids	20/ton – by facility 25/ton – contractor 55/ton – to landfill		agriculture application; Chambersburg, Pennsylvania (Hook, 2003)
	0.055 per gallon		Class B; North Carolina (Hagaman, 1998)
		88	includes lagoon drying and subsurface injection; Calgary, Canada (Tatem, 1998)
Landfill biosolids	58	233	Hampton, New Hampshire (Berkel, 2003)
	approx. 59		by contractor; Cleveland, Ohio (Dominak and Stone, 2002)
Landfill ash		approx. 50	Cleveland, Ohio (Dominak and Stone, 2002)
Landfill grit and screenings	approx. 53		Cleveland, Ohio (Dominak and Stone, 2002)

TABLE 27.3 Sales value of biosolids.

Material	Value	Comments
Biosolids	$6–7 per percentage point of nitrogen	Florida (Maestri, 1998)
Compost	$10 per dry metric ton or $6.50 per cubic meter	Palo Alto, California (Nichols, 1998)
Bulk dry pellets	$63 per dry metric ton ($28.22 after marketing and distribution)	Palo Alto, California (Nichols, 1998)
Compost	$5.45 per cubic yard	Baltimore, Maryland

TABLE 27.4 Incineration costs.

Time	Operations and maintenance ($/dry ton)	Amortized capital installed capacity ($/dry ton)	Total ($/dry ton)	Reference
1990 actual[(1)]	70–90	100–125	170–215	Walsh et al., 1990
1990 actual[(2)]	180–200	200–230	380–430	Walsh et al., 1990
2003 estimate[(3)]	105–187	37–55	114–187[(5)]	Welp and Lundberg, 2003
2003 estimate[(4)]	135–247	37–55	144–247[(5)]	Welp and Lundberg, 2003

(1) Based on a well-operated sludge incineration system operating at capacity; starts with dewatered sludge and includes furnaces, heat recovery, air-pollution control, and ash disposal systems; includes some reserve capacity; 20 years for equipment, 40 years for buildings, and 8%.
(2) Same as 1 and also including thickening and dewatering.
(3) Does not include thickening and dewatering; fluid bed incinerator; 20 years, 6%.
(4) Does not include thickening and dewatering; multiple hearth incinerator; 20 years, 6%.
(5) Total includes $27–55 of energy credit.

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Chapter 28

Characterization and Sampling of Residuals

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INTRODUCTION

Sludges, biosolids, and other residuals typically are sampled and analyzed to ensure that various solids handling and treatment processes are performing properly. Residuals management may entail meeting a number of pollutant parameters established to protect

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human health and prevent nutrient overloading of the environment. U.S. and other regulatory requirements have increased the frequency and scope of analysis for residuals. Additionally, information obtained from sampling and analysis can improve the treatment facility's bottom line.

This chapter describes the qualitative and quantitative aspects of various residuals found in wastewater treatment plants (WWTPs). Parameters, properties, and miscellaneous analyses used to characterize residuals are also described. In addition, it notes the sampling procedures necessary for process control and regulatory purposes.

TYPES OF RESIDUALS

Residuals are produced by the removal of soluble and insoluble constituents during wastewater treatment. Of the various residuals, sludges and biosolids are composed primarily of water, but contain dissolved and suspended solids that can range from 0.5 to 7% of total unthickened solids. Thickening, stabilization, and dewatering processes are used to make these residuals acceptable for disposal (Figure 28.1). Utilities should remove as much water as possible to minimize transportation and disposal costs. (For more information on thickening, stabilization, and dewatering equipment and systems, see Chapters 29 through 33.)

Sludges can be classified broadly as primary, secondary, mixed, and chemical.

PRIMARY. Raw sludges are those that have not been chemically or biologically treated to reduce pathogens. Because the volatile solids content has not been stabilized, they tend to putrefy readily. Primary sludges are produced by sedimentation processes and consist mainly of fecal material, food wastes, fibers, silt, and, to lesser degrees, heavy metals and other trace minerals and substances. Properly settled primary sludge typically will have a total solids concentration between 1 and 3%; if gravity thickened, it can contain up to 10% total solids. This thickening can effectively cut the sludge volume in half, thereby reducing the sizing requirements (hydraulically) and costs of downstream units. Primary sludge may be easily thickened and dewatered if not allowed to become septic. This sludge is highly putrescible, generates unpleasant odors, and contains enough pathogens to cause disease in humans on contact with unprotected skin and mucous membranes, especially if the skin is cut or abraded.

SECONDARY. Secondary sludge is composed of the solids that were not readily removed via primary clarification and those produced during the consumption of soluble and insoluble organics in the secondary treatment system. Secondary sludge is either returned to the treatment process (return activated sludge) or wasted for further

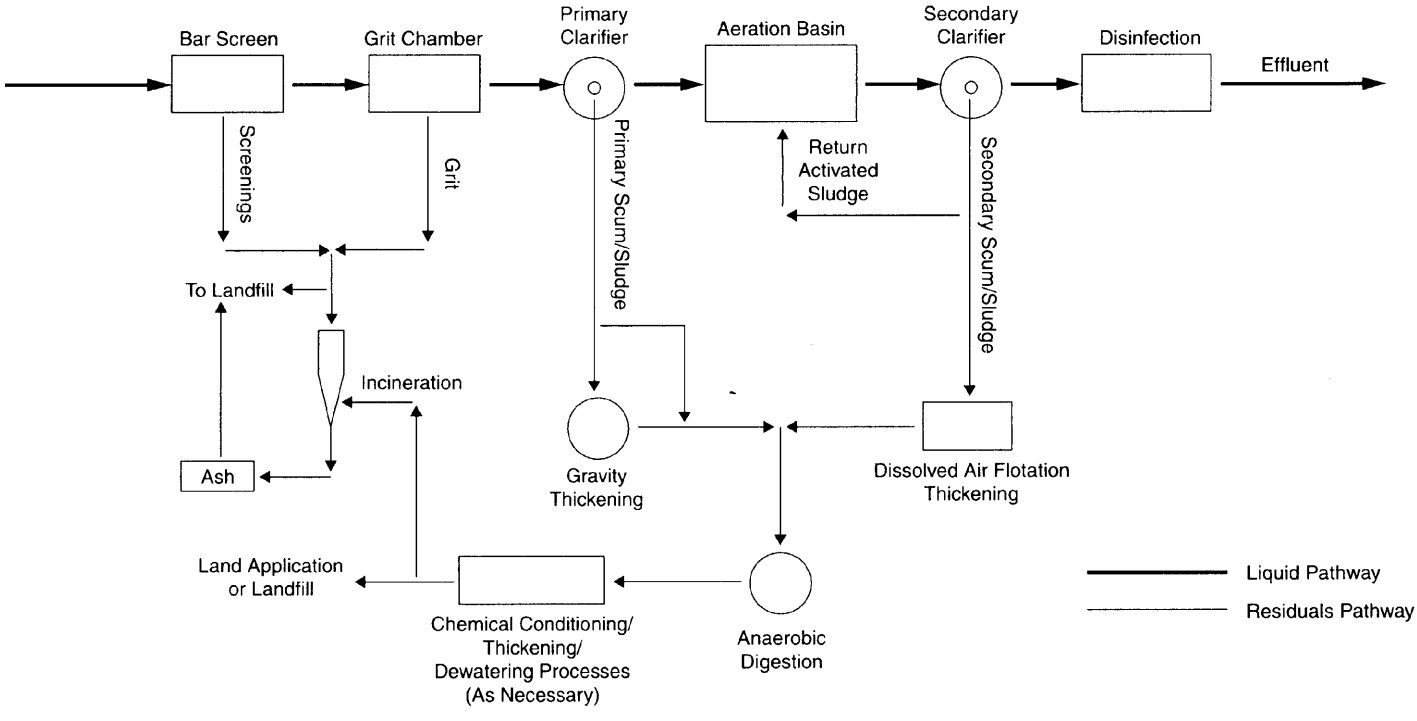


FIGURE 28.1. Residuals pathways in primary and secondary treatment systems.

treatment. Whether produced by aerobic or anaerobic decomposition, these microbial masses can account for most of the sludge volume at a treatment facility. Properly managed activated sludges will contain 0.5 to 1.5% total solids; attached growth (biofilm) sloughings will contain 1 to 4% total solids.

MIXED. Primary and secondary sludges may be combined after their respective sedimentation processes. They may be individually thickened before combination or combined first and then further processed. Secondary sludges at smaller WWTPs are sometimes wasted to the primary clarifier, thus producing a mixed sludge. Plants with no primary treatment, such as extended aeration "package plants", produce only a secondary sludge.

CHEMICAL. Chemical sludges are produced when chemicals are added to precipitate otherwise hard-to-remove substances from the wastewater. A typical form of this sludge is when lime, alum, ferrous or ferric chloride, or ferrous or ferric sulfate is used to remove phosphorus from wastewater via precipitation. These chemical sludges contain a considerable amount of primary and secondary sludges. While some chemicals improve the thickening and dewatering characteristics in downstream processes, others reduce dewaterability and have unwanted side effects (e.g., low pH and alkalinity). These effects may require the addition of alkaline chemicals (typically lime or caustic) to adjust these parameters before nitrification or discharge to the receiving stream.

STABILIZED. Sludges that have been stabilized (have reduced pathogen concentrations and vector attraction reductions) are called *biosolids* and can be used beneficially as soil amendment. Biosolids are typically land-applied, although they could be landfilled or incinerated and then landfilled. Maximal reuse of these solids is achieved through agricultural application, forest application (silviculture), land reclamation, composting, and other such applications.

Approximately one-third of the solids produced in the United States were, in some way, land-applied (U.S. EPA, 2004). More solids are expected to be beneficially used and less landfilled, as landfill sites become an increasingly expensive disposal method. Restrictions on ocean dumping in the United States and the dramatic shift in the number of U.S. plants providing secondary or better treatment by 2012 can only exacerbate the problem of landfill disposal, particularly in the most densely populated areas of the United States, according to a U.S. Environmental Protection Agency (U.S. EPA) assessment (U.S. EPA, 1993a).

Sludges can be stabilized anaerobically (e.g., in an anaerobic digester where sludge is heated; organic compounds are hydrolyzed into methane, carbon dioxide,

and water; and volatile solids are reduced). They also can be stabilized aerobically in an unheated digester, producing carbon dioxide and water, and reducing volatile solids.

Stabilization is defined by the pathogen and vector-attraction reductions set forth in 40 *CFR* 503 and the guidance document for issuance of U.S. EPA permits (U.S. EPA, 1993b, 2004). The regulations limit the amount of pathogens that sludge can contain. The agency allows pathogens to be reduced via composting, heat drying, heat treatment, thermophilic aerobic digestion, irradiation, pasteurization, reduction of fecal coliform density, anaerobic digestion, and lime stabilization (U.S. EPA, 1993b, 2004). Similarly, vector attraction reduction can be achieved by a 38% volatile solids reduction via aerobic or anaerobic digestion (U.S. EPA, 1993b, 2004). It also can be done via thermophilic aerobic digestion, reducing the specific oxygen uptake rate to less than 1.5 (mg oxygen/h)/g of total solids at 20°C, raising the percent solids concentration, or raising the pH to 12 or higher for 2 hours using alkali addition and remaining at a pH greater than 11.5 for 22 more hours without more alkali (U.S. EPA, 1993b, 2004). The U.S. EPA regulations also set land-application ceiling concentrations and cumulative pollutant loadings for nine metals that can cause adverse human or environmental effects in excessive amounts (Tables 28.1 and 28.2).

OTHER RESIDUALS. Wastewater treatment plants also produce several other types of residuals. While they have significantly less volume and weight than sludges, their disposal is by no means a small concern.

Screenings. Screenings typically are removed by bar screens or bar racks. They are relatively large debris consisting of rags, plastic, cans, leaves (especially in autumn in the

TABLE 28.1 Pollutant ceiling concentrations for selected heavy metals.

Pollutant	Ceiling concentration (mg/kg[a])
Arsenic	75
Cadmium	85
Copper	4300
Lead	840
Mercury	57
Molybdenum	75
Nickel	420
Selenium	100
Zinc	7500

[a]All concentrations are on a dry weight basis.

TABLE 28.2 Cumulative pollutant loading rates for selected heavy metals.

Pollutant	Cumulative pollutant loading rate (kg/ha)
Arsenic	41
Cadmium	39
Copper	1500
Lead	300
Mercury	17
Molybdenum	—[a]
Nickel	420
Selenium	100
Zinc	2800

[a]Limit deleted by a U.S. Federal Court action.

northern hemisphere), rocks, and similar items. Quantities vary, although they are typically small (4 to 40 mL/m^3). Screenings can be removed and disposed of either by hauling them to a landfill or by incineration. Macerating or comminuting the screenings and returning them to the liquid stream are not recommended because many downstream processes and units (e.g., aeration diffusers, mixer shafts, and electronic probes) are subject to fouling from reintroduced rags, strings, and similar debris.

Grit. Grit is composed of many heavy or coarse materials (e.g., sand, cinders, gravel, and similar inorganic matter). The organic fraction of grit may include coffee grounds, eggshells, corn, and seeds. Grit also includes any items that passed through the bar screens. Grit in downstream processes is undesirable, because it can wear out pump impellers, piping, and other equipment. It builds up in vessels with lower flowthrough velocities (e.g., channels, aeration basins, digesters, piping, and wet wells), thereby reducing their working volumes.

Grit can be removed via grit chambers (typically aerated) or centrifugal separation. It may be washed to remove organics that will readily putrefy. In aerated grit systems, cyclonic or vortex-type separators, the amount of organics in the grit can be controlled somewhat by varying the amount of air supplied to the air diffusers in a grit chamber or limiting the air to the air scour unit in a vortex. Volumes of grit removed vary (4 to 200 mL/m^3 is typical) (Metcalf and Eddy, Inc., 2003). Grit, like screenings, varies in quantity because of variations in influent flow. After a dry weather period followed by a wet weather event, both residuals typically will increase because of flushing action in the collection system. Grit is almost always landfilled. If grit is being

stored for removal, some facilities cover it with a layer of lime to reduce odors and provide a modicum of vector control.

Scum. Scum is the product of clarifier or tank skimmings. Primary clarifier skimmings are composed of fats, oils, grease, and floating debris (e.g., plastic and rubber products). It can often plug the scum trough or build up in downstream lines, thereby restricting flow and increasing pumping costs. It fouls probes, flow elements, and other instruments and equipment in the wastestream. Plants sometimes use degreasers to emulsify the fats, oil, and grease (FOG) in the wastewater, making it easier to handle in the primary system. Bioaugmentation (the addition of microbes that are genetically engineered to use FOG as their food source) can also be used to reduce the amount of FOG.

Secondary scum consists of the same substances found in primary scum, but most of it tends to be floating solids (either activated sludge or biofilm, depending on the type of secondary treatment used).

Other skimmings may include those from oil and grease separators, which are similar to the primary skimmings, but without most of the floating debris. They may include solvents that require different processing and disposal.

Scum's quantity and moisture content typically is not measured, although WWTPs that treat and dispose of it separately have more impetus to do so. Scum can be pumped directly to the digestion process; concentrated and then incinerated with other residuals; dried and landfilled; or recovered by firms that specialize in recycling and reprocessing FOG. Like screenings and grit, scum is laden with pathogens and should be handled carefully.

Ash. Ash is the product of thermal reduction processes (e.g., fluidized bed reactor, multiple hearth furnace, or wet-air oxidation). Although the volume of residuals is reduced to approximately 4% of the original volume, because of the oxidation of the organic fraction, the mass is still 20 to 50% of the original mass (digested solids produce more ash content) (WEF, 1992). Ash typically is disposed via landfilling.

In Japan, heat-dried solids are mixed with crushed stone and melted in a furnace. This produces an ash–stone slag used increasingly for construction materials (e.g., road bedding, clay pipes, water-permeable concrete blocks, and paving bricks and tiles) (Kanezashi and Murakami, 1992; Sato and Watanabe, 1994). Ash can be considered a beneficial product, although large amounts of it are still landfilled in Japan. The Japanese and the Europeans are also aggressively recovering the thermal energy expended in the incineration process and augmenting it with methane gas combustion produced in the anaerobic digestion process (Kaneko, 1992; Sato and Watanabe, 1994). While incineration is declining as a disposal alternative in many countries, it is increasing in Japan, which has little usable land.

CHARACTERIZATION

Residuals can be characterized by their physical, chemical, and biological properties. The tools used to measure these residuals range from physical testing (e.g., capillary suction time and settled volume) to biological testing (e.g., biochemical oxygen demand and coliform counts). Chemical testing is used to ascertain the major and minor constituents in the residual. Most of the testing methods referred to below can be found in *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 2005). Some of these methods are controversial; residuals vary and are truly unique to every plant. *Standard Methods* (APHA et al., 2005) and 40 *CFR* 503 (U.S. EPA, 2004) are exceptional references. For questions about the use of these methods for a specific application, contact the appropriate U.S. EPA representative.

PHYSICAL PROPERTIES. A substance's physical properties relate to the human senses (touch, sight, and smell). Some physical properties of residuals include temperature, viscosity, thickness (or ability to be thickened via physical means), color, settleability, volatile and nonvolatile solids, and odor. Odor is highly subjective and discussed more extensively in Chapter 13. Several other parameters are interrelated (e.g., temperature, viscosity, and settleability). Physical solids processes (e.g., gravity, gravity belt, or dissolved-air-flotation (DAF) thickening; and belt filter presses, pressure filters, and centrifugation) focus on primary and secondary sludges. Their goal is to increase the sludge's solids content by removing water. For example, settling primary sludge can increase the total solids to between 4 and 7%; additional gravity thickening can further increase the total solids. Secondary sludge can be thickened via rotary drum concentrators, gravity thickeners, DAF units, or centrifuges. These units typically use polymers to increase both the total solids concentration and solids capture rates. Secondary sludge can be thickened from 0.5 to 1.5% total solids to approximately 4 to 7%, assuming it is not septic or has some other thickening-inhibiting characteristics. Recently, membranes have begun to be used to thicken sludge, achieving mixed-liquor suspended solids (MLSS) concentrations in excess of 20 000 mg/L.

Tests have been established to determine the degree to which sludge has been thickened or dewatered. Septicity can greatly affect the sludge's dewatering characteristics. Improperly conditioned sludge also can give undesirable results. So, the following tests are offered as indicators of sludge quality.

Settled sludge volume and sludge volume index are typical thickening tests used not only to evaluate an activated sludge's settling quality, but also to analyze gravity thickening. The 30-minute settling test provides the best data on the sludge's settling

characteristics. A settleometer (2-L graduated cylinder) is typically used for this test. The average settled sludge volume (SSV) is 100 to 300 mg/L (the higher the result, the poorer the sludge will settle). The results of this test can be combined with the MLSS to obtain the sludge volume index (SVI):

$$\text{SVI} = \text{SSV} \times 1000/\text{MLSS}$$

This test indicates the sludge's ability to settle properly (the lower the SVI, the better the settling quality). Sludge with an SVI of 100 or less is typically considered to be a good settling sludge (WEF, 2002). Capillary suction time and the related time-to-filter tests are used to determine the rate that water is released from sludge. The procedures for conducting these tests are presented in *Standard Methods* (APHA et al., 2005).

Sludges typically are conditioned with inorganic chemicals or polymers before dewatering. Standardized methods of determining chemical and polymer doses are presented in the manual *Sludge Conditioning* (WPCF, 1988). For belt filter presses, centrifuges, pressure filters, and vacuum filters (now largely obsolete), tests measuring the sludge's specific resistance, capillary suction time, centrifuge (bench-scale), penetrometer, and floc strength are also discussed in detail in *Sludge Conditioning* (WPCF, 1988).

CHEMICAL PROPERTIES. The major chemical constituents of sludges and biosolids are total nitrogen; total Kjeldahl nitrogen (TKN); organic nitrogen; ammonia nitrogen; total phosphorus; alkalinity; volatile acids; and other typical parameters (e.g., biochemical oxygen demand, chemical oxygen demand, total organic carbon, and pH). Related analytical methods can be found in *Standard Methods* (APHA et al., 2005) and similar documents.

The moisture content in residuals can be determined by calculating the percent solids and subtracting it from 100%. Likewise, the volatile solids in content in residuals can be found by determining the percent ash and subtracting it from 100%. Tracking solids through various treatment processes can help utility staff establish solids balances and inventories, which are useful in managing treatment efficiencies. For example, an increase in inert solids may indicate a buildup of WWTP solids because of higher recycle loadings as a result of poor solids capture in the thickening and dewatering processes.

Digester controls typically focus on volatile solids, volatile acids, alkalinity, pH, and temperature. Increasing volatile acids, decreasing alkalinity and pH, or poor volatile solids reduction indicate poor digester performance (WPCF, 1987).

Residuals also contain small amounts of organic and inorganic chemicals. These chemicals are present in such small quantities that sophisticated instruments are required to measure them. The inorganic substances that typically are monitored include

both metals (e.g., arsenic, cadmium, chromium, copper, lead, mercury, molybdenum, nickel, selenium, zinc, and iron) and nonmetals (e.g., calcium and potassium).

Nitrogen, phosphorus, calcium, and potassium can substantially raise crop yields, so they are important constituents in biosolids. Nitrogen typically is present in three forms: ammonia, nitrate, and organically bound. Nitrite concentrations are typically low. The organic fraction of nitrogen in biosolids is simply equal to the TKN concentration minus the ammonia. Exposure to air will convert some ammonia to nitrate, but most is in the form of ammonium bicarbonate. Much of the ammonia is lost when biosolids are dried especially if the pH is elevated to 12 or more in postliming operations. Much of the ammonia volatilizes when biosolids are surface-applied to land (rather than added via subsurface injection). The odor associated with ammonia volatilization should be a major concern when deciding which disposal method to use. Phosphate is present as orthophosphate or total phosphate (including polyphosphates). Total phosphate enhances the fertilizer value of biosolids.

Although beneficial in small dosages, metals typically are considered indicators of potential harm when using or disposing of ash and biosolids. They are particularly harmful to anaerobic digestion and are often the rate-limiting parameters in land application. For example, if the chromium concentration is higher than that of other regulated metals, it will be used to establish the residual's maximum disposal rate and maximum cumulative loading rate. There is little a typical secondary treatment plant can do to reduce metal concentrations. The best and most economical approach typically is to categorize the sources of metals and reduce or eliminate them. Conducting a pretreatment program to reduce influent sources of metals and other undesirable wastewater constituents can help meet applicable regulatory requirements for residuals use or disposal.

Residuals contain minute amounts of organic constituents. These organics originate at both industries and households. Some are refractory, like insecticides (e.g., aldrin, eldrin, heptaclor, lindane, malathion, dichlorodiphenyldichloroethane, dichlorodiphenyldichloroethylene, dichlorodiphenyltrichloroethane, and chlordane) (WEF, 1999). Polychlorinated and polybrominated hydrocarbons (e.g., hexachlorobenzene and bromodichloromethane) are potential health and environmental hazards and largely resistant to biological decomposition (WPCF, 1990). Other hazardous compounds (e.g., phenols, benzenes, and toluenes) are more easily degraded by biological systems (WEF, 1999). The U.S. Environmental Protection Agency is likely to begin regulating organics at WWTPs, starting with dioxin and polychlorinated biphenyls (WEF, 1995). The agency does not currently require annual dioxin analysis of biosolids, but regulators highly recommend it. Some states (e.g., Ohio) do require dioxin testing and reporting. A typical WWTP has neither the laboratory equipment nor the technical

expertise to analyze the metals and organics in its wastestreams. So, independent laboratories analyze wastewater and residuals samples for most U.S. treatment facilities.

Chemical processing plays an important role in sludge treatment. The use of polymers in thickening and dewatering has increased in recent years, especially as gravity belt thickeners, belt filter presses, and centrifuges have gained popularity. Utility staff should periodically test polymers to select the proper type for a given sludge because what works well for one sludge may not be suitable for another. Also, as sludge characteristics change over time, so might the chemical requirements.

Lime is also important at many WWTPs. It is used to adjust alkalinity in activated sludge (especially before nitrification) and "postlime" biosolids. Lime consumption depends on the type and dryness of the solids being adjusted. The pH of the liquid slurry can be measured easily by an electrode.

BIOLOGICAL PROPERTIES. All residuals (except ash) contain appreciable numbers of biological constituents (e.g., pathogenic bacteria, protozoan cysts, helminthic organisms, and enteric viruses). Indicator organisms (e.g., fecal coliform and fecal streptococci) help wastewater treatment professionals track pathogenic organisms. U.S. regulations address fecal counts in both wastewater and residuals. [For more information on pathogenic reduction requirements for biosolids, see *Standards for the Use and Disposal of Sewage Sludge* (U.S. EPA, 2004).]

Most treatment facilities rely on biological processes. Anaerobic and aerobic digestion are the most typical forms of solids treatment. U.S. regulations require that WWTPs reduce the volatile content of solids by at least 38% unless other control parameters (e.g., specific oxygen uptake rate) are measured. Analytical procedures can be found in the current edition of *Standard Methods* (APHA et al., 2005).

Solids characteristics can affect thickening and dewatering. For example, septic sludge tends to thicken and dewater less readily than fresh sludge and cause the recycle flows from these processes to be less efficient in capturing solids, thereby increasing recycle solids loadings. Anaerobically digested solids tend to dewater more readily than waste activated sludge or aerobically digested solids. Temperature, pH, polymers, conditioning chemicals, and other parameters also affect thickening and dewatering characteristics (see References and Suggested Readings at the end of this chapter).

SAMPLING

Utilities take samples for two reasons: regulatory compliance and process control. Following is a discussion of representative sampling, sample collection, chain-of-custody procedures, sample preservation, quality assurance, and quality control.

REPRESENTATIVE SAMPLING. The goal of a sampling program is to obtain samples that best represent the flow being analyzed. Otherwise, any decision based on analysis of these samples is more likely to be erroneous.

Grab samples are taken for rapid analysis. They typically are used for process control, but because of the holding time requirements of certain analyses, may be used for reporting purposes. For example, fecal coliform samples are typically grab samples. Grab samples are also quick and effective tools to help adjust a chemical dose or study the effects of a process modification. For a grab sample to be representative, operators should ensure that the sample is taken in a well-mixed area and obtained in the same place each time it is taken.

Composite samples consist of a mixture of grab samples taken over a period of time (e.g., 24 hours) from the same sampling point. Composites of influent and effluent typically are collected by automated samplers to save labor and ensure accurate sampling intervals, but automated samplers can only be used on low-viscosity sludges. Compositing can be time-, flow-, or concentration-paced. Time-interval composites have been discussed. Regulations often require flow pacing, in which the grab samples (aliquots) are proportional to the flow. Concentration pacing uses a sampling system to try to maintain a predetermined concentration that is not directly correlated to flow. When collecting composites of higher viscosity sludges, which cannot be sampled via automated samplers, utility staff should develop a good standard operation procedure (SOP) that should be followed each time the sample is obtained.

Although less common than grab or composite samples, integrated sampling is useful in categorizing wastestreams that may significantly affect treatability (APHA et al., 2005). An example of this might be an industrial treatment system where two process streams are combined. An integrated sample would help utility staff study the effects of this combination.

SAMPLE COLLECTION. Samples should be collected methodically. A set of procedures has been developed that ensures sampling reliability. The procedures include instructions on sampling methods, container preparation, chain of custody, sample preservation, and storage. Unless utilities adhere to these procedures, results of the sample analysis could be disputed. For example, containers must always be clean and free of previous sample residues. *Standard Methods* (APHA et al., 2005) lists the type of material suitable for sample containers (which is based on the type of test required).

Typically, compliance testing will specify the location, frequency of analysis, type of sample (grab, composite, etc.), parameters to be measured, and method of measurement. It also typically requires that chain-of-custody procedures be used. Chain-of-custody procedures; which are required for any litigious actions, are similar to those

used by law enforcement agencies to preserve evidence for trial. The major points of a chain-of-custody procedure are sample labeling (time, date, and identification number); sealing of the sample container; and a chain-of-custody sheet that includes the sample volume, type, location, time, date, person collecting the sample, person relinquishing the sample, person analyzing the sample, what parameters are to be tested, and the signatures of persons involved in the transaction. After arriving at the laboratory, the analyses are checked for accuracy, a signature attesting to the procedures used for each analysis is affixed to the custody sheet, and a report is issued. Completed custody and analysis reports are kept on file for inspection and reference.

Sample preservation may be required. Some samples (temperature, dissolved oxygen, etc.) require immediate analysis. Others (e.g., selected metals), if properly preserved and stored, can be analyzed up to 6 months later. Knowing the proper preservation and storage techniques can make the difference between a meaningful and meaningless analysis.

Sample storage is important; improperly stored samples are worthless from a legal standpoint and possibly misleading from a process control standpoint. Sample-handling requirements (e.g., sample volume required, container type, preservation required, and maximum time interval between storage and analysis) can be found in *Standard Methods* (APHA et al., 2005).

QUALITY ASSURANCE AND QUALITY CONTROL. Quality assurance and quality control (QA/QC) programs are established by laboratory personnel to confirm the reliability of the results they generate and report. Recordkeeping provides the verification of QA/QC efforts. A typical QC program will include, at a minimum, files of all raw data, calculations, QC data, and all reports. Additionally, regulations may require a written manual that includes procedures for all tests performed, instrument (pH meters, analytic balances, thermometers, and spectrophotometers) calibration frequencies with certification dates attesting to them, and other internal control mechanisms. Typically, the QC records are kept for a specified period of time—at least 3 years in some U.S. jurisdictions (State of West Virginia, 1992). Computerized records are particularly helpful in maintaining organized files of all reports and QA/QC records, but paper documentation of verification must still be maintained.

The QC data will include a record of test results for all blanks, duplicate (replicate) samples, precision analysis (spike and percent recovery results), and standardization curves (e.g., atomic absorption analysis). Information on QC data is given in extensive detail in *Standard Methods* (APHA et al., 2005). Examples of typical data-reporting sheets, with simplified test procedures and standard analytical calculations, can be found in *Basic Laboratory Procedures for Wastewater Examination* (WEF, 2002).

As part of QA/QC programs, some U.S. states require certification of laboratory personnel (State of West Virginia, 1992). These requirements stipulate specific levels of education and experience for laboratory managers, supervisors, and technicians. Certificates are issued where applicable, following successful inspection and completion of all the requirements contained in the governing code of regulations.

In sum, these internal and external controls are designed to ensure that reported results are reasonably accurate and reliable. However, the analytical results cannot ensure the quality and reliability of the sample taken.

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Chapter 29

Thickening

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INTRODUCTION

DEFINITION OF THICKENING. The removal of water from biosolids is a continuum. Although there is no technical definition of *thickening*, at around 50 000 centipoises we are at a point where most biosolids are a heavy paste and no longer pour from a cup.

PURPOSE OF SLUDGE THICKENING. Biosolids enter a plant at ±350 ppm (0.035% suspended solids). To remove these solids, they have to be concentrated and separated from the fluids. Concentrating takes place at several points during the treatment process and the basic goal is to reduce the process volume, which, in turn, will reduce the costs of downstream sludge processing. For example, in feeding an anaerobic digester, a plant may require 20 days residence time in the digester. If the plant is producing 100 000 gpd of 2.0% sludge, they will need 20 days times 100 000 gpd, or 2 million gallons of digester capacity. If the sludge can be thickened to 3%, the daily volume is only 66 000 gal and the resulting digester volume is 1.3 million gallons, which represents a considerable savings.

Similarly, a plant may wish to concentrate sludge before transport or disposal. The Deer Island Wastewater Treatment Plant in Boston, Massachusetts, thickens digested sludge before pumping it several miles under Boston Harbor to the dewatering facility. This reduces pumping costs and also reduces the volume of centrate produced at the dewatering site; both of these factors represent significant cost reductions after thickening.

THICKENING MODES

There are several points in the treatment process where thickening is commonly done. The most common are thickening before sludge stabilization or dewatering. The clarifier underflow is often quite thin and, as mentioned earlier, preconcentrating it will reduce the amount of process equipment downstream.

Recuperative thickening is also occasionally used. Recuperative thickening is where the sludge is withdrawn from a process (typically digestion), thickened, and returned to the digester.

The last stage in the treatment process is when the sludge is thickened after stabilization and before beneficial reuse, which is a common practice when the biosolids are disposed of as a liquid.

ANCILLARY EQUIPMENT

This section addresses equipment needed to support thickening equipment.

GRINDERS, PUMPS, AND FLOW METERING. Some devices are easily damaged or plugged by oversized materials. There are three sources of oversized particles: those that somehow slipped by bar screens; those that are generated within the plant, such as rag and string balls; and miscellaneous debris, such as wrenches, mop heads, and construction materials.

Grinders or screening devices are used whenever there is a likelihood of oversized particles causing damage. Although grinders are usually less expensive than screens, either device will suffice in terms of removing oversized particles. At one time, there were high-speed grinders available that caused a lot of shear and low-speed grinders that did not. However, the high wear rates of high-speed grinders drove them out of the market, leaving only the low-speed grinders.

There are two broad categories of pumps: centrifugal and positive-displacement. As a rule, positive-displacement pumps create less shear on the sludge. Because shear is presumed to be detrimental to thickening and dewatering, positive-displacement pumps are preferred. However, the cost of positive-displacement pumps poses a problem. As the volume pumped increases, the positive-displacement pump cost-per-volume pumped goes up. Therefore, centrifugal pumps usually are used to move very large flowrates. When the sludge is concentrated the volume is less, and the pump is more likely to be a positive-displacement type.

In recent years, the price of variable-frequency drives has dropped, and it is practical to install variable-speed centrifugal pumps. This allows a flow meter to control the

pump speed, which greatly reduces both the power consumption and shear imparted to the sludge.

Another consideration is flow pulsing. A thickening or dewatering centrifuge has a liquid residence time of fewer than 2 seconds. Pulsations in flow are not dampened out very much in the centrifuges, so the clarified liquid will reflect the peak flow, not the average flow. Along those lines, most mechanical thickening devices require polymer to operate. Assuming the polymer flow is constant, pulsing feed sludge will result in variation in the polymer dosage. Pulsation dampeners are a valuable addition to the pumping system but must be maintained to avoid failure.

The following are positive-displacement thickened sludge pumps listed in order of increasing pulsation:

- Progressing cavity,
- Double disc,
- Rotary lobe,
- Diaphragm, and
- Plunger.

The last two pumps create very large pulsations and should not be used in instances where this will be a problem.

Although older plants used a variety of variable-speed devices, variable-frequency drives are presently the least costly. One advantage of variable-frequency drives is that they are easily programmed to provide a "soft start". This reduces the wear and tear on the pump drives. These drives also provide a readout of the motor speed at no additional cost. For a positive-displacement pump, the fluid flow is proportional to the pump's revolutions per minute. This provides a flowrate readout at no cost. Unfortunately, as the pump wears, the actual flowrate drifts off of the new pump calibration. The result is that a year or so after start-up, no one knows what the flowrate is on any of the pumps. As such, pump speed is a poor substitute for flow meters.

POLYMER ADDITION. In water and wastewater treatment, all filtration processes are dependent on polymers to work. In contrast, although they can perform much better with polymer, sedimentation processes can work without polymer. Polymer selection and application is covered in depth in Chapter 33.

GRAVITY THICKENING

Prior to nitrification requirements (circa 1980), gravity thickening was the principal method used for mixed sludges (both primary and secondary). Dissolved air floatation

(DAF) was occasionally used for thickening secondary biological sludges due to their light, diffuse nature.

With nitrification, gravity thickening of mixed sludges became difficult due to zero dissolved oxygen in the thickener, which allowed nitrates to be broken down, nitrogen to be released, and the sludges to float rather than be thickened. Larger plants then used gravity thickening for primary sludges and DAF for secondary biological sludges.

Gravity belt, rotary drum, and centrifuge thickening have virtually replaced gravity and DAF thickening due to their relatively low capital cost, ease of operation, relatively low odor generation, and small size. The major problem with these three methods is thickening the sludge to too high a concentration, which can cause downstream pump failure. Six to eight percent solids are normal discharges from these units (with polymer) and 12 to 14% solids can also be achieved. Process control instruments are beginning to be used to control the solids load going to thickening devices and to control the thickened solids from the operation.

The following three methods are typically used to thicken at various points in the treatment stream:

- Gravity thickening concentrates through the use of sedimentation. The normal acceleration of gravity provides the driving force for the separation. The most typical configuration for gravity thickeners is circular, as shown in Figure 29.1; however, rectangular systems are also used. The physical processes governing gravity thickening vary according to the nature of the solid being thickened. Sedimentation and thickening occur in different modes depending on the concentration and flocculent nature of the solids being handled. Three basic types of sedimentation include discrete settling (unhindered), hindered or zone settling, and compression or compaction settling. Gravity thickening can be aided by mechanical stirrers (pickets) and by chemical addition.
- Flotation thickening concentrates through sedimentation. The attachment of microscopic air bubbles cling to the suspended solids, thereby reducing their specific gravity to less than that of water. The air-attached particles then float to the surface for removal. This method is well-suited to wastes containing high amounts of finely divided solids. The most common thickener in this category is the DAF thickener.
- Centrifugal thickening uses centrifugal force to enhance the sedimentation of suspended solids. The centrifuges generate ± 2000 times the force of gravity; it is this acceleration that causes suspended solids to migrate through the suspending liquid, away from the rotation axis, and to concentrate on the bowl wall.



FIGURE 29.1 Typical open tank gravity thickener.

- Gravity belt thickening concentrates through filtration. Water filters through the conditioned solids, driven by gravity separation of water and solids on a continuously moving, porous, horizontal belt.
- Rotary drum thickening concentrates solids through filtration, much like the gravity belt thickener, except that instead of a belt it uses a rotating perforated drum or screen.

Conditioning agents, typically polyelectrolytes (polymers) specific to the waste stream being treated, may be required to enhance the separation of free water from the charged particles in all of the aforementioned thickening methods. Conditioning agents are discussed in Chapter 9 and Chapter 30.

DESCRIPTION OF PROCESS. Gravity thickening characteristics vary according to the nature of the solids being thickened. Settling and thickening will occur in different modes depending on the concentration and flocculent nature of the solids being

handled. Three basic types of settling occur: discrete settling, hindered or zone settling, and compression or compaction settling. These are described as follows:

- Discrete settling occurs in dilute suspensions in which particles maintain their own characteristic settling rates. Although these rates may be affected by the presence of neighboring particles, the settling rate of a particle depends primarily on its size and density. Discrete settling is characteristic of very low solids loading rates and, for this reason, does not apply to most gravity thickeners.
- Zone settling occurs as the loading rates increase and individual particles become increasingly influenced by neighboring particles. Particles maintain position relative to one another as they settle, forming a porous matrix supported by the displaced fluid as the solids settle. Zone settling is characterized by an easily identified interface between the solids-laden liquor and adjacent supernatant. The solids concentration, fluid viscosity, and rate of underflow withdrawal dictate the zone settling rate.
- Compression settling occurs when flocculent particles develop a structure in which they are supported by adjacent particles rather than the displaced fluid. The compression settling rate is determined by channel formation in the floc structure that allows water to escape while the solids mass settles and compresses into itself.

Prevailing theory on gravity thickener design is based on zone settling, with the settling rate ideally depending on solids concentration alone. Downward solids transport in a gravity thickener stems from settling because of gravity and bulk movement resulting from pumping from the tank bottom. The sum of these two transport mechanisms provides the total solids flux.

Supernatant from a gravity thickener recycles through the treatment facility. Supernatant clarity is maintained to limit the recycled solids and biochemical oxygen demand (BOD) through the plant to minimums, thus limiting increased system solids and organic loading rates. Overflow from a smoothly operating gravity thickener, typically with less than 350 mg/L suspended solids, may be sent as influent to the secondary treatment process (Metcalf and Eddy, 2003). Supernatant from a gravity thickener with operational difficulties should be recycled to primary clarifiers (because it can be a source of strong odors). Diluting thickener influent sludge with "fresh" secondary effluent, chlorinated effluent, or waste activated sludge (WAS) can enhance the reliability of gravity thickening.

Gravity thickener loadings may be expressed both in terms of solids loading rates, the most useful parameter, and overflow rates. Typical gravity thickener loading rates

for primary sludge range from 100 to 150 kg/m^2·d (20 to 30 lb/d/sq ft), whereas typical loading rates for activated sludge range from 20 to 40 kg/m^2·d (4 to 8 lb/d/sq ft). Gravity thickener overflow rates typically range between 16 and 32 m^3/m^2·d (390 and 780 gpd/sq ft). The overflow rate reduces as the proportion of secondary sludge increases.

The following list includes various sludge feed characteristics and their expected thickening effects:

- Primary sludge
  - Readily gravity-thickened,
  - Tends to settle quickly, and
  - Forms thick sludge without chemical aids;
- Waste activated sludge
  - Low settling rates,
  - Resists compaction, and
  - Tends to stratify causing flotation;
- Temperature
  - 15 to 20 °C (59 to 69 °F) acceptable if secondary-to-primary sludge ratio ranges from 4:1 to 6:1 and
  - Higher temperatures may require additional dilution of sludge feed;
- Upstream grinder pump
  - Breakup of oversized material to enhance settling;
- Chemical addition
  - Improves thickener efficiency; and
- Separate scum-handling procedures
  - Reduces odors and improves aesthetics of thickeners.

DESCRIPTION OF EQUIPMENT. Gravity thickeners (Figure 29.2) typically are circular tanks with side water depths of 3 to 4 m (10 to 13 ft) and diameters of up to 25 m (82 ft). Thickener bottoms are designed with a floor slope between 1:6 and 1:3. Occasionally, gravity thickeners may be rectangular units; however, their performance typically has been unsatisfactory.

Gravity thickener mechanisms tend to be of stronger construction than clarifier mechanisms because of the higher torques involved. Gravity thickeners may be designed as an integral part of a clarifier when the clarifier includes a central, deep well with a raking mechanism for thickening. If very high solids concentrations or high viscosities are anticipated, a lifting mechanism may be supplied to raise the thickener mechanism (rake) above the sludge blanket when torques are extremely high. This has

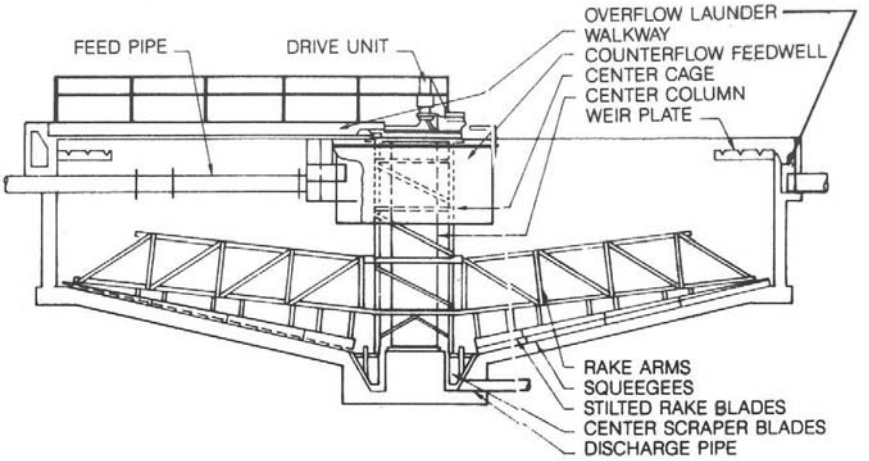


FIGURE 29.2 Typical gravity thickener.

been used with lime solids or other chemically precipitated sludges. As solids are removed from the tank and the torque is reduced, the lift will lower the mechanism back into the sludge blanket until it reaches its original position. Typical mechanism tip speeds are 0.08 to 0.1 m/s (15 to 20 ft/min).

Gravity thickeners may include the following equipment:

- Pickets, vertical pipes, or angles may be attached to the thickener arm to aid in releasing gas and preventing rat-holing or coning. However, pickets may cause difficulties in wastewater treatment plants (WWTPs) without effective screening for removal of rags and fibrous materials.
- Variable-speed drives may be used to increase rake speed to agitate the sludge blanket and release trapped gas bubbles, and to prevent rat-holing or coning. Prolonged operation at high speeds will reduce the ultimate solids concentration and reduce the life of the thickener drive mechanism.
- Scum removal equipment may include a skimmer and scum box.

The ancillary equipment should include positive-displacement pumps (plunger, rotary lobe, diaphragm, or progressing cavity pumps). Process control equipment includes sludge blanket indicators (light path, sonic, or variable-height taps), online process monitors on the feed or underflow, torque readouts on the rake drive, and timers to vary the pump on–off (or speed) sequences. In cold weather areas or areas where odors are a problem, thickeners are typically covered (most commonly by a dome, although they can be a more traditional form as shown in Figure 29.3).

START-UP. It is important to ensure that all guards and covers are properly secured on the machine and that lockout/tagout is not in place. The following procedures apply during start-up:

- Following confined-space entry protocol, check the mechanism to ensure that there are no obstructions in the tank (e.g., ice or tools).
- Check the drive mechanism alarm switch and cutout switch to ensure they are operating properly. Do not attempt to adjust these switches. Alarm and cutout switches are set by the factory; therefore, avoid field adjustment unless performed by a manufacturer's service representative.



FIGURE 29.3 Enclosed gravity thickeners (City of Boulder, Colorado, Wastewater Treatment Plant).

- Avoid starting a thickener that contains accumulated solids. To avoid overload, the solids should be disposed of before starting the mechanism.
- Depending on your configuration, start your thickener first with fresh dilution water, then apply sludge flow. This will maintain freshness and proper overflow rates.
- Before pumping from the system to downstream processes, allow sufficient solids to accumulate in the thickener to completely seal the hopper feeding the underflow discharge pipe.
- Check and adjust the skimming mechanism to increase the amount of scum drawn into the scum box and to reduce the amount of supernatant carried with the skimmings.
- Always avoid starting a thickener with ice in the unit. The system, including the feed (stand) pipe, should be drained to prevent freezing whenever it is taken out-of-service.

SHUTDOWN. The following procedures apply during shutdown:

- If shutdown is for a short period of time (from 1 to 6 hours), continue the fresh or chlorinated dilution water. This action will keep the sludge "fresh".
- Continue the programmed withdrawal of solids until you are down to 50% of the typical sludge blanket depth (measured from the floor) or the top of the cone, whichever is greater.
- Reduce the overflow of "fresh" dilution water to approximately 25% of normal flow for the length of the shutdown. If the shutdown is only for between 1 and 6 hours, do not shut the drive off.
- If the shutdown is for longer than 6 hours, or if you need to service tank internals, remove the remaining sludge to another online thickener or slowly return it to the primary clarifier. You may leave the tank full of chlorinated effluent unless you plan to keep the thickener out-of-service for a length of time.
- Follow lockout/tagout procedures to secure the unit before conducting any maintenance or inspection. Lockout is a method of keeping equipment from being set in motion and endangering workers. The *Code of Federal Regulations* (1991) 29 *CFR* Part 1910.147 covers the servicing and maintenance of machines and equipment in which the unexpected energization or start-up of the machines or equipment or release of stored energy could cause injury to employees. Tagout occurs when the energy isolation device is placed in a safe condition and a written warning is attached to it. Typically, the employee signs and dates

the tag. Removal of the tag and lockout device is done by the same individual when the equipment is safe for restart.

- If freezing is a possibility, drain the tank and all exposed piping, including the feed stand pipe and scum wells.

PROCESS CONTROL. Ideally, feed to a gravity thickener should be screened or shredded to prevent the entry of rags or fibrous materials, and it should be pumped continuously. If continuous pumping is impractical, the feeding schedule should closely approach continuous feeding. Continuous feeding not only promotes a stable sludge blanket, but it also tends to reduce gasification and resultant floating sludge. Successful gravity thickener operation depends on low-feed-rate pumping during long periods.

When practicing combined primary and secondary thickening, the sludge should be mixed and combined with makeup water (often called *elutriation*) before introduction to the gravity thickener. Makeup water, which is added to maintain a constant hydraulic load, can also be used as an oxidizing source. This practice produces a feed with more uniform characteristics and "freshness" that will resist the tendency to stratify. Primary sludge is most easily thickened using gravity. It tends to settle quickly and form a thick sludge that is easily pumped without chemical aid. For these reasons, primary sludge is frequently thickened separately. Unfortunately, primary sludge generation varies greatly during 24 hours. Operators are now beginning to take notice of this in programming pumping rates to the thickener.

Greater attention to the thickener is required when thickening WAS because it has a large surface area per unit mass, resulting in low settling rates and a resistance to being compacted. Sludge tends to stratify in the gravity thickener while continuing biological activity, which includes the production of gases that can cause accumulated sludge to float.

Studies have shown that when the ratio of secondary to primary sludge varies between 25 and 59%, the resultant underflow concentration remains essentially unchanged. At some point above this range, an increase in the ratio of secondary solids to primary solids will cause a decrease in underflow concentration.

If activated sludge begins to gasify and rise despite wasting from the aeration tank, a bacteria side such as chlorine, potassium permanganate, or hydrogen peroxide may be applied to the feed to reduce biological activity, thereby reducing gas and odor production. Chlorinated WWTP effluent is often used as dilution water; this tends to "sweeten" the sludge.

The gravity thickening process is pH-sensitive, and treatment facilities have been found to react differently to pH shifts. Observation of the thickening process and

experimentation seems to offer the only method of determining the effects of pH shifts and how they can be handled.

Gravity thickener operation responds to changes in process temperatures; therefore, loading rates should be reduced to values at the lower end of the range when temperatures exceed 15 to 20 °C (59 to 68 °F), depending on the ratio of primary to secondary solids. Higher temperatures will require additional dilution.

High-temperature recycle streams, such as anaerobic digester supernatant or decant tank supernatant, will cause thermal stratification in gravity thickeners and reduce settling rates. In addition, recycled centrate or filtrate may contain biologically active solids, causing gasification and a rising sludge blanket. Effects of recycle streams can be reduced by slowly metering recycle flows into the gravity thickener or by introducing recycle flows at another point, causing fewer negative effects.

Scum handling procedures can significantly affect thickener cleanliness. A large scum buildup on a gravity thickener is unsightly and causes odor and fly problems. There are two methods of in-house scum handling. The first is to treat skimmings immediately after they are removed from clarifiers in the facility. The second is to pump skimmings to a thickener and consolidate them for subsequent handling. The difficulty with the second alternative is that gravity thickeners are rarely equipped with skimming equipment capable of handling large amounts of scum, particularly scum that has accumulated and possibly congealed and hardened.

Because thickening is dependant on the weight of the solids, one on top of the other, a blanket of solids in the thickener is necessary to promote compaction thickening. The blanket also reduces rat-holing or coning as well as the need for intermittent feeding of the gravity thickener. The depth of the allowable sludge blanket varies with temperature. Higher temperatures require more shallow blankets. Typically, a sludge blanket between 0.3- and 1.5-m (1- and 5-ft) deep at the tank periphery should be maintained, with greater depths for cooler temperatures and deeper tanks. At one time, the blanket readings were taken by the operator. Current practice is to use a blanket detector, and display the sludge blanket on the supervisory control and data acquisition system. Either way, the location where the blanket level is measured is important. If done manually, sampling must be from the same point each time. Depending on tank access and operator preference, measurement of blanket depth is often taken at the ⅔ radius point (measured from the center on a circular tank) off the catwalk (walkway). The key here is consistency; therefore, it may be beneficial to permanently mark the railing where depths are obtained. The sludge blanket depth at the point of sludge discharge definitely affects the ultimate solids concentration. To take advantage of this phenomenon, the operator should experiment to determine the range of depths that optimize ultimate solids concentration. The results will depend on temperature. After the opti-

mum depth is determined, pumping should be modulated to maintain the blanket within the optimal range. Sludge depth can be determined a variety of ways—with an electronic depth finder; a "sludge judge," or circular plastic tube called a *coretaker*; or with an airlift pump. Increased retention times may cause deterioration of other aspects of the gravity thickening operation. Under no circumstances should the blanket reach the bottom of the thickener feedwell.

Retention time for sludge in the gravity thickener should range between 1 and 2 days for primary sludge, depending on temperature. The retention time for mixtures of primary and secondary sludge should range from 18 to 30 hours, depending on temperature. Longer retention times may cause thickener upsets, such as gasified sludge, and increase chemical requirements in downstream dewatering operations.

Like sludge feeding, thickened sludge pumping must be as continuous as possible. Pumping rates may be adjusted to conform to the concentration of the solids being pumped. The traditional controls are usually on–off pumping, which, of course, are not continuous. Recently, the low cost of variable-speed drives has offered excellent control of pumping rates, representing a significant improvement over the earlier operation. The best means of developing a regular, optimum pumping schedule requires varying the duration of pumping and cycle times while checking solids concentration until the best schedule is found. As this requires a good deal of time and effort, it is commonly not done, much to the detriment of operations. As a result, the operations manager should schedule time to do this on a regular basis or consider automating the process. Underflow pumping velocities of at least 0.75 m/s (2.5 ft/sec) are needed to prevent solids deposition. When pumping highly concentrated sludge, the increased viscosity will increase operating head. Small increases in concentration above an 8% level produce large increases in operating head requirements.

For thickening, makeup water consisting of plant effluent (mixed-liquor suspended solids [MLSS] direct from aeration or secondary effluent) can offer several benefits. The dissolved oxygen in the recycled liquid helps reduce anaerobic biological activity that would otherwise cause the sludge to gasify, float, and produce odors. In addition, the elutriation process tends to remove soluble carbohydrates, ammonia nitrogen, phosphates, fats, oils, and fine particulates. Chlorination of elutriation water may be used to reduce the biological activity that causes gasification of sludge. A disadvantage, however, is that elutriation will remove salts and thus may increase conditioning requirements. Too much elutriation flow will be detrimental by expanding the sludge (thinning) and recycling wastewater unnecessarily. The key is moderate use. With anaerobic digestion, wide fluctuations in underflow concentration caused by elutriation should be avoided to maintain digester stability. As with all dilution, the added water in effect dilutes the overflow. If the incoming feed is 3000 mg/L and you

measure 300 mg/L suspended solids in the overflow in round numbers, you are achieving 90% capture. If you change operations, and begin to add elutriation water equal to the feed rate, you would be doubling the overflow rate and, as a consequence, the overflow rate would have to contain about 150 mg/L to achieve the same 90% capture.

Viscous drag between the thickened sludge and the rakes creates a load on the rake drive, usually measured as amperage on the rake drive motor. Should the sludge become thicker and more viscous or something jam the rake, the amperage will rise until it sounds an overload alarm. Ideally, this will not happen with modern controls, where increasing rake amperage results in automatic increasing of the underflow pumping rate. Increasing underflow pumping reduces the cake blanket, thinning out the underflow solids and thus reducing the torque on the rake.

If the rake drive does shut off in overload, discontinue the feed to the thickener to keep the problem from worsening. Do not turn the drive mechanism on and off or "jog" it because that could overload and possibly damage the drive before the drive cutout can operate. In addition, do not wire around the drive overload protection because that would likely damage the mechanism. Unfortunately, the thickener may have to be drained to remove the cause of the torque overload (possibly a foreign object or very viscous sludge). If for some other reason the thickener is out-of-service for more than 1 hour, flow to the device should be discontinued to prevent a torque overload. If the thickener is to remain out-of-service for 1 day or more, sludge should be removed and replaced with chlorinated plant effluent.

SAMPLING. At a minimum, gravity thickeners should be sampled and analyzed as follows:

- Influent for dissolved oxygen (if thickening activated sludge), total suspended solids (TSS), total solids, and flow.
- Effluent for TSS, total solids, and flow.
- Underflow (bottom sludge withdrawal) for total solids and flow.
- Depth of blanket (DOB) by way of sampler, either "bomb" or other thief method, sonic or light path, or with variable-height taps (using an air-lift arrangement). The DOB is reported as the height above the bottom of the tank at the ⅔ radius point (sample point measured from the center of the tank outward ⅔ of the distance on the catwalk for circular tanks).

TROUBLESHOOTING. This section describes typical operational problems and methods of handling these problems. Table 29.1 presents a troubleshooting guide that identifies problems and presents possible solutions. Each of several pervasive prob-

TABLE 29.1 Gravity thickener troubleshooting guide.

Indicators/ observations	Probable cause	Check or monitor	Solutions
Septic odor, rising sludge	Thickened sludge pumping rate is too low	Check thickened sludge pumping system for proper operation	Increase pumping rate of thickened sludge
		Check thickener collection mechanism for proper operation	Increase collection speed, repair mechanism
	Thickener overflow rate is too low	Check overflow rate	Increase influent flow to thickener; a portion of the secondary effluent of MLSS may be pumped to the thickener (if necessary) to bring overflow rate to 400 to 600 gpd/sq ft[a]
	Septicity in thickener	Check thickener DO[b]	Add oxidizing agents to influent sludge (0.5–1.0 mg/L)
Thickened sludge not thick enough	Overflow rate is too high	Check overflow rate	Decrease influent sludge flow rate
	Thickened sludge pumping rate is too high	Check sludge concentration	Decrease pumping rate of thickened sludge
	Short-circuiting of flow through tank	Use dye or other tracer to check for circuiting	Check effluent weirs, repair or relevel; check influent baffles, repair or relocate
Torque overload of sludge-collecting mechanism	Heavy accumulation of sludge	Probe along front of collector arms	Agitate sludge blanket in front of collector arms with water jets; increase sludge removal rate
	Foreign object jammed in mechanism	Probe with big magnet on rope	Attempt to remove foreign object with grappling device; if problem persists, drain thickener and check mechanism for free operation
	Improper alignment of mechanism	Alignment	Realign mechanism
Surging flow	Poor influent pump programming	Pump cycling	Modify pump cycling; reduce flow and increase time

TABLE 29.1 Gravity thickener troubleshooting guide (*continued*).

Indicators/ observations	Probable cause	Check or monitor	Solutions
Excessive biological growths on surfaces and weirs (slimes)	Inadequate cleaning program		Frequent, thorough cleaning of surfaces Apply chlorination
Oil leak	Oil seal failure	Oil seal	Replace seal
Noisy or hot bearing or universal joint	Improper alignment	Alignment	Align joint or bearing as required
	Lack of lubrication	Lubrication	Lubricate
Pump overload	Improper adjustment of packing	Check packing	Adjust packing
	Clogged pump	Check for trash in pump	Clean pump
Fine sludge particles in effluent	Waste activated sludge (WAS)	Portion of WAS in thickener influent	Better conditioning of the WAS portion of the sludge Thicken WAS in a flotation thickener

[a] gpd/sq ft × 40.74 = L/m^2·d.
[b] Dissolved oxygen.

lems often experienced with gravity thickeners and the likely remedies for each problem are described herein.

Excessive scum is frequently caused by prolonged sludge retention times in the thickener. Wasting sludge directly from an aeration tank to keep it fresh may reduce scum. Maintaining lower sludge blanket levels or increasing elutriation may also remedy the problem. In some cases, scum removed from clarifier surfaces enters a gravity thickener for accumulation. Because the thickener's scum disposal system is often not equipped to handle large amounts of scum, this practice should be discouraged. One scum disposal aid includes a spray system covering a portion of the tank near the scum box to keep the scum soft and suitable for pumping. Spraying with chlorinated water is particularly effective for scum caused by *Nocardia* foaming. Substantial scum accumulations may be broken up with high-pressure hosing so that the skimming mechanism can remove the scum. In severe cases, scum accumulations may be vacuumed into a hauling truck and disposed of properly.

Grease buildup in underflow lines may disrupt sludge handling. High-pressure water should be used to backflush underflow lines and dislodge grease accumulations.

One means of combatting grease accumulations requires filling underflow lines with digested sludge and allowing the sludge to remain undisturbed for at least 1 day before removing the digested sludge and dislodged grease. If the line can be isolated and cleanouts are provided, steam cleaning can reduce stoppages. In severe cases, a self-propelled hydraulic rodding device known as a *jet rodder* or hydro may be used to clear blockages. As a last resort, a specially designed plug or "pig" may be inserted in the line and propelled by the sludge pump or water pressure to clean the line.

Sludge septicity is characterized by floating solids, solids carryover in the overflow, foul odors, and reduced underflow concentrations. Storing sludge too long in either the gravity thickener or in upstream clarifiers causes septicity. This condition can be resisted temporarily by chlorine or hydrogen peroxide. Aeration of thickener feed or elutriation to provide some dissolved oxygen may reduce the problem. If secondary effluent is recycled through the gravity thickener to elutriate, the overflow rate must not exceed approximately 32 $m^3/m^2 \cdot d$ (780 gpd/sq ft).

Sludge bulking is indicated by a rising sludge blanket. The blanket disperses, resulting in poor supernatant and dilute underflow. Sludge bulking provides evidence of problems elsewhere in the WWTP; therefore, only the symptoms of sludge bulking may be dealt with in the gravity thickener. The problem must be solved at its source. Control of bulking should receive high priority to avoid excessive chemical costs and reduce other process upsets throughout the facility. Any attempt to deal with bulking at the gravity thickener should be undertaken only on a short-term basis because of the expense involved. Chlorination or the addition of hydrogen peroxide to incoming sludge may reduce the gelatinous extracellular materials characteristic of some bacteria that cause bulking. Weighting agents such as bentonite may be used to capture sludge that would not otherwise settle. Polymers are sometimes used against bulking. In worst cases, the thickener contents may be pumped to a drying bed to rid the facility of poor-quality sludge if improved sludge characteristics are expected.

Rat-holing or coning occurs when clear supernatant is pumped through the sludge blanket to produce a low underflow concentration. An increase in the sludge blanket depth will reduce the chance of rat-holing. Sludge pumping at a high flowrate for short durations leads to rat-holing. There are two solutions: replacing the pump motors with variable-speed drives or replacing the pumps and drives. Both solutions will increase the duration of sludge pumping.

PERFORMANCE. Gravity thickeners typically produce underflow sludge ranging from 4 to 8% when thickening primary sludge alone. The percentage of sludge is reduced to between 3 and 6% when a combination of primary and secondary sludge is gravity-thickened. Table 29.2 indicates various sludge sources with their corresponding

TABLE 29.2 Sludge source and total solids characteristics.

Sludge source	Low-viscosity TS, %	High-viscosity TS, %
Raw primary sludges	<6	6–12
Raw secondary sludges	<2	2–6
Raw primary and secondary sludges	<3	3–8
Digested sludges	<4	4–10
Chemical sludges		
Lime	<15	15–40
Alum and ferric sludges	<2	2–6
Chemical slurries	1–30	—
Incinerator ash slurries	5–20	—

anticipated solids characteristics. The literature shows little correlation between the percentage of solids in the sludge fed to a gravity thickener and the concentration of the thickener underflow. Anticipated solids capture ranges between 90 and 95%. Thickeners are often a major source of solids recycle within the plant (Figure 29.4). Recycle is often ignored as a cost on the notion that "the place is full of sludge, so what's a little more?" However, this is misguided thinking. The cost of recycle is, at a minimum, the cost the wastewater authority charges a customer to dump solids into the plant.

PREVENTIVE MAINTENANCE. Regular maintenance is a must. Daily maintenance items include

- Checking the drive units for overheating, unusual noise, or excessive vibration; and
- Checking for unusual conditions, such as loose weir bolts.

Weekly maintenance items include

- Checking all oil levels and ensuring that the oil fill cap vent is open,
- Checking all condensation drains and removing any accumulated moisture,
- Examining drive control limit switches, and
- Visually examining the skimmer to ensure that it properly contacts the scum baffle and scum box.

Monthly maintenance items include

- Inspecting skimmer wipers for wear and
- Adjusting drive chains or belts.



FIGURE 29.4 Thickeners as a significant source of solids recycle within the plant.

Yearly maintenance items include

- Disassembling the drive and examining all gears, oil seals, and bearings. Gears and bearing surfaces should be examined for abrasive wear, scoring, pitting, and galling. Balls should be inspected and those that are scored or cracked should be replaced.
- Checking the oil for the presence of any metal that might be a precursor to future problems. The thickener should be drained and all submerged portions of the mechanism should be checked. Particular attention should be given to the adequacy of the coating system, flexible piping connections, bolted connections, and "squeegees," if used.

- Replacing any part that has an expected useful life of less than 1 year. It is far easier to replace these items during scheduled maintenance than during a breakdown (WPCF, 1987).

Other routine maintenance items include the following:

- Use corrosion-resistant materials when possible to resist the thickener's hostile environments.
- Install kick plates on the gravity thickener bridge to prevent objects from falling into the tank. An object lodging in the underflow discharge pipe or under the mechanism will quickly halt operation of the thickener.
- If objects fall into the tank, immediately halt thickener operation to prevent torque overload.
- During plant rounds, regularly observe and record the drive torque indicator, the best signal of mechanical problems.
- Regularly check the underflow pump capacity because pumps wear rapidly in a thickened sludge operation.
- Follow the manufacturer's recommended lubrication schedule and use recommended lubricant types. Oil should typically be changed after the first 250 hours of operation and every 6 months thereafter.

SAFETY. Good safety practices include the following procedures:

- When working on the thickener, disconnect the power by following lockout/tagout procedures. Lockout is a method of keeping equipment from being set in motion and endangering workers. The *Code of Federal Regulations* (1991) 29 *CFR* Part 1910.147 describes servicing and maintenance of machines and equipment in which the unexpected energization or start-up of the machines or equipment or release of stored energy could cause injury to employees. Tagout is when the energy isolation device is placed in a safe condition and a written warning is attached to it. The employee typically signs and dates the tag. Removal of the tag and lockout device is done by the same individual when the equipment is safe for restart.
- Do not disconnect the drive if the torque indicator registers any torque. If energy is stored in the springs that activate the torque indicator, releasing the springs could cause injury. This must be part of the lockout/tagout procedure.
- When working on the thickener, follow the safety procedures of Chapter 5, including those for confined space entry to areas where the toxic gases hydrogen

sulfide and methane may be present as well as areas where oxygen deficiency or an explosive atmosphere may exist.

DISSOLVED AIR FLOTATION THICKENING

PROCESS DESCRIPTION. A DAF system essentially consists of a flotation unit and a saturator (Figure 29.5). The flotation unit serves to separate the solid phase from

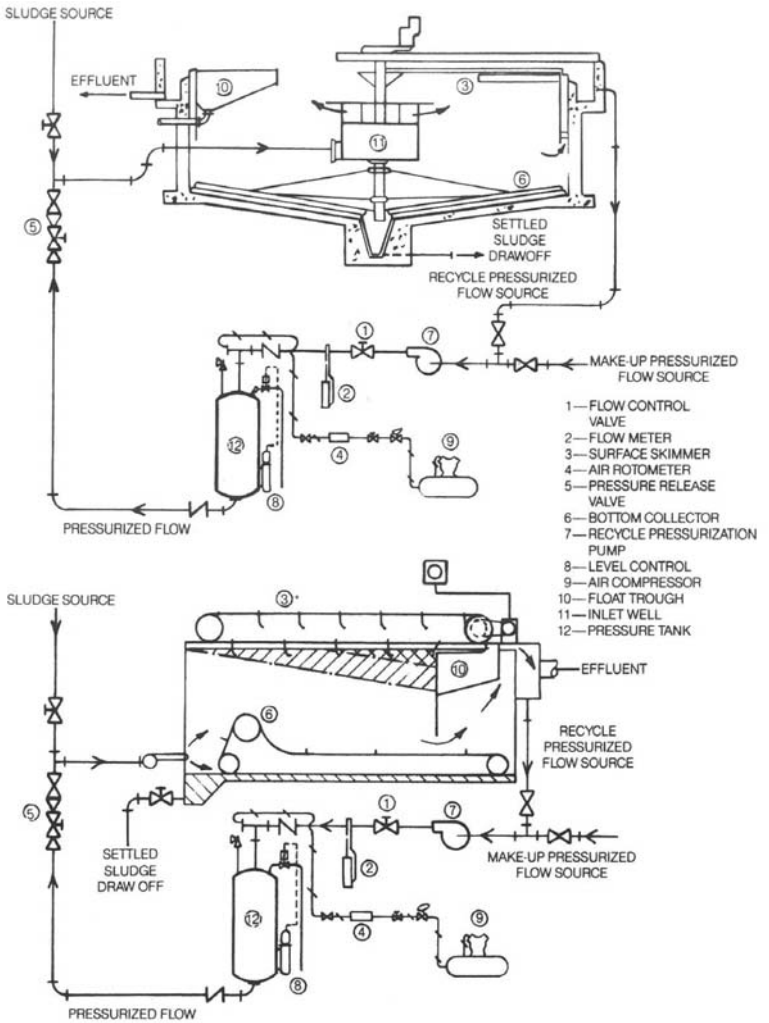


FIGURE 29.5 Detailed schematics of typical circular and rectangular DAF thickeners.

the liquid phase and the saturator dissolves air into water under pressure. Pressure-saturated water (from the saturator) is introduced to the flotation unit through a reducing valve. Just downstream of the valve, the pressure is virtually atmospheric and the saturator feed becomes highly supersaturated with air. The air precipitates out of solution in the form of very small bubbles. Just downstream from the reducing valve, the saturator feed is blended with the wastewater feed. The precipitated bubbles become attached to wastewater particles, forming bubble-particle agglomerates with a density lower than water.

If chemical aids such as polymers are used, they typically enter at the mixing point of the saturator feed and the sludge feed. Proper mixing to ensure chemical dispersion, while avoiding excessive shearing forces, produces the best aggregation of sludge particles and air bubbles. Experience has shown that introduction of polymer just downstream of the point of blending of the sludge feed and the precipitating saturator feed produces the best results.

Particular advantages of DAF systems include the following (Bratby et al., 2004):

- Ability to successfully co-thicken primary and secondary sludges;
- Amenability of thickening scum from both the primary and secondary scum collection systems;
- Allowing scum and sludge to be transported to the thickening process with maximum water flow;
- Allowing the separation and capture of grit from a continuous bottom sludge removal system when co-thickening primary and secondary sludges;
- Continuously producing a homogeneously mixed thickened sludge product that is of ideal quality for feeding digesters;
- Allowing all solids processing recycle loads to be concentrated into one stream; and
- Achieving a significant soluble BOD reduction in the DAF liquid stream.

In the flotation unit, buoyancy causes the bubble-particle agglomerates to rise to the water level and accumulate as a float. In this fashion, separation of the solid phase from the liquid phase is achieved. Because of the difference in density between the float and the water, a stage is reached where the top of the float, continuously rising above the water level, reaches the top of the unit where solids are continuously removed by scraping. Drainage of interstitial water from the float above the water level increases the solids concentration. This stage of the process is termed *thickening*.

Flotation, then, has basically two functions: (1) clarification or separation of the solid phase from the liquid phase and (2) thickening or dewatering of the separated (accumulated) solids. Figure 29.6 is a schematic of a DAF thickener.

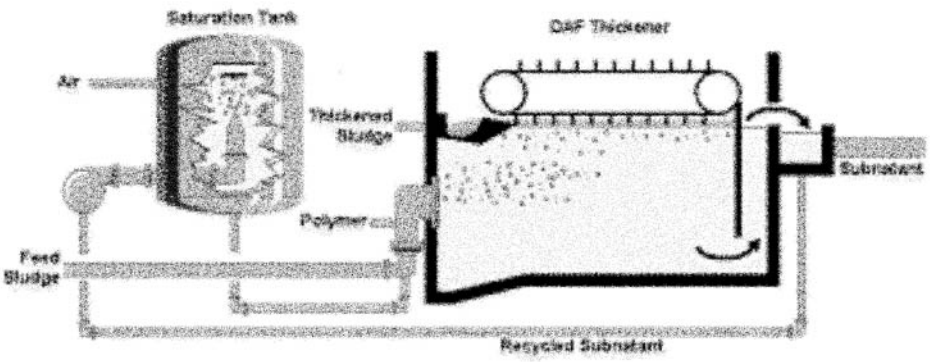


FIGURE 29.6 Dissolved air flotation thickener schematic.

Principal process variables influencing the clarification aspect of DAF are the downflow rate and the air-to-solids ratio. The downflow rate is analogous to the overflow rate used for sedimentation tanks and is defined as the total flow into the unit divided by the effective plan area of the flotation unit. The air-to-solids ratio is defined as the mass of air precipitated per unit time divided by the mass of solids introduced per unit time. The downflow rate and the air-to-solids ratio are related by the following empirical expression (Bratby, 1978):

$$v_L = K_1 \cdot (a_S)^{K2} - K_3 \tag{29.1}$$

where

K_1 through K_3 = empirical constants for a particular waste or sludge,
v_L = the downflow rate (m/d or gpd/sq ft), and
a_S = the air/solids fraction.

Principal process variables influencing thickening are the solids loading rate and the height at which the float extends above the water level. Thickening of float solids occurs principally by drainage of interstitial water from the float above the water level.

Both the solids loading rate and the height of float above the water level directly influence the time allowed for drainage of the float. The solids loading rate, defined as the mass of solids introduced per unit area of flotation unit per unit time, governs the rise rate of the float above the water level. The height of float above the water level governs the distance through which the float travels before being removed from the unit.

The following empirical relationships describe thickening by DAF (Bratby, 1978; Bratby and Ambrose, 1995):

$$C_F = K_4 \cdot (d_W)^{K5} \cdot (Q_S)^{-K6} \tag{29.2}$$

$$d_T = (d_B + d_W) = d_W[(a_S)^{K7} + K_8] \cdot a_S^{-K7} \tag{29.3}$$

where

K_4 through K_8 = constants for a particular waste or sludge;
C_F = float solids concentration (percent) at the top of the unit (i.e., where float solids are removed from the unit);
Q_S = solids loading rate ($kg/m^2 \cdot d$);
d_W = height of float above water level (m);
d_B = depth of float below the water level (m); and
d_T = total float depth (m).

Note that for a given set of parameters, adjusting the air-to-solids ratio does not influence the float solids concentration. However, the air-to-solids ratio does affect the total depth of float solids.

The accuracy of the expression for total float depth ($d_B + d_W$) becomes uncertain at air-to-solids ratios below a certain value. At lower air-to-solids ratios, the float depth, in practice, tends to be greater than predicted by Equation 29.3. With activated sludge, with or without the use of polymers, the limiting air-to-solids ratio is about 0.02; with raw wastewater, using metal coagulants such as alum, the limiting air-to-solids ratio is about 0.06; with stabilization pond algae separation, using metal coagulants, the limiting air-to-solids ratio is about 0.03; and with flotation applied to thickening the sludge from highly colored waters, using polymer, the limiting air-to-solids ratio is about 0.03.

The aforementioned expressions were extended by Bratby and Ambrose (1995) to take into account the actual time spent by the float above the water level, before it is removed to the sludge hopper by the sludge scraper mechanism. Parameters that are controllable by the operator in this regard are the speed of the scraper and its periodicity of operation.

An effective time, t_E, spent by the float above the water level is defined as follows (Bratby and Ambrose, 1995):

$$t_E = (t_C / t_{ON}) \cdot (L / v) \tag{29.4}$$

where

t_C = float scraper cycle time = $t_{ON} + t_{OFF}$;
t_{ON} = time that the scraper is on during a given cycle (minutes);
t_{OFF} = time that the scraper is off during a given cycle (minutes);
L = effective length of rectangular dissolved air flotation thickening (DAFT), or periphery of circular DAFT (m or ft); and
v = velocity of travel of scrapers (peripheral speed for circular units) (m/d or ft/d).

Therefore, the following relationships incorporate the effects of t_E (Bratby and Ambrose, 1995):

$$C_F = K^* \cdot t_E^{[K5/(1+K5)]} \tag{29.5}$$

$$d_T = (d_B + d_W) = Q_S \cdot t_E^{[1/(1+K5)]} \cdot (1 + K_8/a_S^{K7})/(10 \cdot K^*) \tag{29.6}$$

where

$$K^* = [K_4/(Q_S^{(K6-K5)} \cdot 10^{K5})]^{[1/(1+K5)]}$$

At long effective times, t_E, more opportunity is provided for interstitial water in the float solids to drain and, consequently, the float solids concentration will be higher. However, there is a practical upper limit to the value of t_E. For a given d_W, there is a greater value of d_B required to supply the buoyancy to support the height of float above.

Therefore, just as increasing t_E increases d_W, at the same time it also increases the total float depth. The limitation in t_E is to avoid increasing the float depth to the extent that float solids are dragged through with the underflow, causing a deterioration of effluent quality.

From the aforementioned discussion, the parameter that is manipulated by the operator to control the performance of a thickener is the effective drainage time, t_E. This parameter is controlled by

- Adjustment of scraper on-time,
- Adjustment of scraper off-time, and
- Adjustment of scraper speed.

The preceding discussions have pointed out that the principal mechanism affecting thickening during flotation is drainage of float layers above the water level. For this reason, float solids concentration profiles through the float depth will exhibit a maximum at the top of the float, decreasing markedly with depth down to the position of the water level, then at a reduced rate through subsequent float layers until a minimum is reached at the bottom of the float. This is illustrated in Figure 29.7(a) and (b) (Bratby, 1978).

Figure 29.7(a) shows results obtained in a pilot flotation unit where float solids concentrations were taken at various depths through the float. In this case, the solids loading rate was set at 55 kg/m^2·d (11.2 lb/d/sq ft) and the air-to-solids ratio at 0.036. The pilot-scale unit was fitted with a horizontal action scraper at the top of the unit. Very minimal disturbance of the float occurred and concentration profiles presented in Figure 29.7(a) are those obtained under ideal conditions. In contrast, results obtained with a full-scale proprietary flotation unit with the same sludge are presented in Figure 29.7(b). In this case, the solids loading rate was approximately 60 kg/m^3·d (12.3 lb/d/sq ft) and the air-to-solids ratio was 0.036 to 0.10. A marked difference is evident in the profile. There is no evidence in the full-scale unit of the sharp decrease in concentration achieved in the pilot-scale unit operating under similar conditions.

The float solids concentration achieved in the pilot unit was about 6.5%, whereas in the full-scale unit it was about 5%. The difference in results is due to differences in

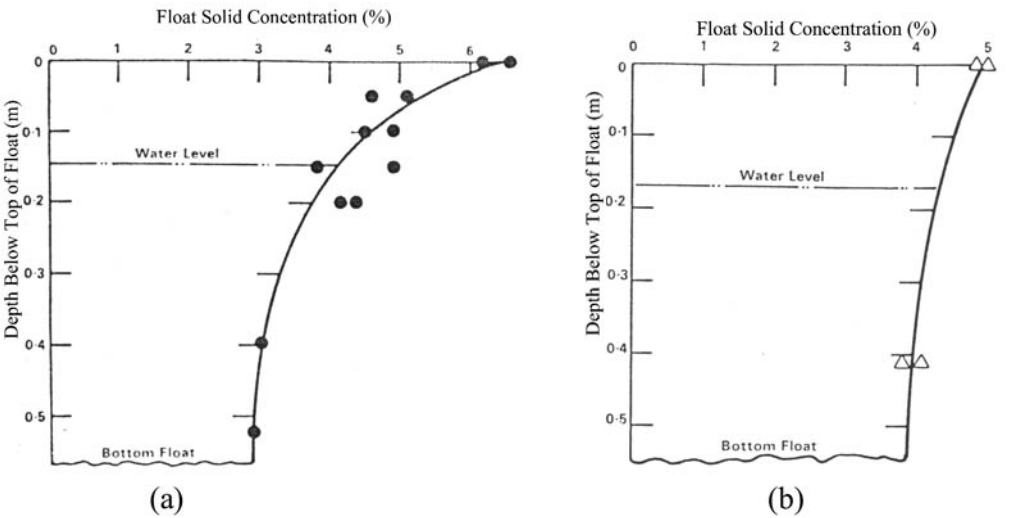


FIGURE 29.7 Float solids concentration profiles.

the methods by which float solids are removed from the two units. In the case of the pilot unit, the float scraper removes only the top-most slivers of float solids that reach the top. In the full-scale unit, the scraper blades dig into the float to a depth of about 178 mm (7 in.). This arrangement typifies most DAFT units.

In the case of the full-scale unit, the scraper arrangement had two effects. First, it maintained the top of the float at the level of the float take-off weir (i.e., it fulfilled its function of removing float solids from the unit). Second, however, it had the undesirable function of mixing the float. The influence of this disturbance will extend beyond the scraper depth. The effect of this mixing action is to replace the upper layers of the float that have attained maximum drainage by lower, wetter layers.

From this discussion it is evident that a float scraper should disturb the float as little as possible and remove only the topmost layer of the float because float solids concentration decreases markedly with depth. This requires that the bottom of the scraper be situated above the water level as far as practicable, but also that float solids do not build up excessively in front of the scraper as it travels around or along the top of the unit.

EQUIPMENT DESCRIPTION. ***Flotation Thickener Tanks.*** Flotation thickeners constructed of steel or concrete are either rectangular or circular tanks (Figure 29.8). Typically, the smaller rectangular units up to 2- to 3-m (8- to 10-ft) wide are steel and the larger units are concrete. Only very small circular units in municipal plants are constructed of steel (WPCF, 1980).

Flotation thickeners are equipped with both surface skimmers and floor rakes. The surface skimmers remove floating material from the thickening tank to maintain a constant average float blanket depth. Floor rakes are essential for removing the nonfloatable heavier solids that settle to the bottom of the flotation thickener.

Most units are baffled and equipped with an overflow weir. Clarified effluent passes under an end baffle (rectangular units) or peripheral baffle (circular units) and then flows over the weir to an effluent launder. The weir controls the liquid level within the flotation tank with respect to the float collection box and helps regulate the capacity and performance of the flotation unit.

A complete flotation thickener system includes a number of appurtenances to the thickening tank. These appurtenances include sludge and conditioning chemical feeding equipment and various control elements.

Saturation System. The heart of a DAFT system is the saturation system, where air is dissolved into water under pressure then released at essentially atmospheric pressure in the form of microscopic bubbles.



FIGURE 29.8 Circular DAF thickeners (Littleton/Englewood Wastewater Treatment Plant, Colorado).

The saturation system typically includes a recycle pressurization pump, an air compressor, an air saturation tank, and a pressure release valve. Although the flow through the pressurization pump typically is recycle flow, it can be makeup water. The pressure release valve controls pressure loss and distributes the gas-saturated pressurized flow into the feed sludge as dissolved air emerges from solution. The rapid reduction in pressure causes dissolved air (under pressure) to emerge from solution or "effervesce" into minute bubbles.

An alternative system that lost favor several years ago but appears to have renewed interest recently is an aspirating pumped system. Recent systems appear to have overcome the air binding problem common with older systems. To date, performance data is lacking. However, an apparent advantage is that the saturation vessel is not required, and the system is generally simpler.

The following principles are important to the saturation system (Bratby et al., 2004):

- Dissolution of a gas into a solute is a simple and straightforward process that is dependent on pressure, temperature, the solubility of the gas in question in the solute (in this instance, water), and the surface area of the liquid available for gas transfer.

- The solubility of nitrogen in water is roughly half that of oxygen.
- At 78% nitrogen and 21% oxygen, the water will more readily absorb oxygen, leaving the volume represented by the oxygen left for addition of more gas in the unvented headspace commonly provided in standard saturation tank designs, plus the volume represented by the nitrogen absorbed by the water during the critical contact period in the headspace.
- With an unvented headspace, the saturation efficiency, as measured by the volume of gas absorbed in the pressurization flow stream, rapidly deteriorates to approximately ⅔ that if the headspace gas is at or near atmospheric concentrations. Essentially, this represents a 33% loss of process capacity. It follows, then, that it is necessary to vent excess nitrogen continuously to maintain process efficiency. Because more than 80% of the energy consumed by the DAFT process is the power required for pressurizing the saturation system pumps, this also represents an opportunity to fine-tune the process to reduce energy consumption.

Other important equipment that forms part of a DAFT system is the float handling and pumping system. After removal of the float from the DAFT unit, float solids are deposited in a hopper and then pumped for further processing. This aspect of the operation requires special considerations because of the following characteristics of float solids:

- They float on the surface of the liquid; and
- They do not flow easily on flat or gently sloping surfaces, especially if the surfaces lack a smooth surface that reduces skin friction.

Adding to these characteristics, conventional sump level controls make the situation that much more difficult because pumps are typically controlled on a high/low-level basis, with the former used to start the pumps and the latter used to stop the pumps. The effect of this control scheme is to concentrate the floating material by decantation rather than pumping the solids away. If left on the surface of a sump for a protracted period and exposed to air, the solids dry out and become a dry cake, making the task of trying to move the solids toward the pump intake that much more difficult. Operators are frequently forced to spend considerable time directing high-pressure hose streams to the floating mass trying to force the material under, thereby wetting it (and decreasing its concentration) until the material can find its way into the pump.

A preferable arrangement, however, is to position the pump intake connection in a confined sump located well below the nominal floor of the sump to concentrate the

floating solids in a small surface area right over the pump inlet. The pump is then controlled to shut down not on level, but rather when the pump breaks suction, guaranteeing that the floating material has reached the pump inlet (Bratby et al., 2004).

PERFORMANCE. Through experience with specific flotation thickening units, operators may determine the optimum ranges of performance for their systems. Tables 29.3 and 29.4 provide operating data from several WWTPs to compare system performance.

A float total solids content of 4% represents a typical minimum for flotation thickeners handling solids without primary sludge. Under optimum conditions, however, a 5 to 6% solids content can be expected. At least one plant routinely and successfully operates at loadings as high as 580 $kg/m^2 \cdot d$ (120 $lb/d/sq\ ft$), thickening a mixture of conventional and high-purity-oxygen WAS, and achieves more than 4% thickened solids concentration.

One factor influencing the float solids concentration is the sludge volume index (SVI) of the activated sludge. However, this is probably not the principal factor influencing the thickened concentration achieved. Other factors such as design and operation of the float scraper and proper drainage of the float layers are probably more important.

A float total solids content of 6% approximates a typical minimum for flotation thickeners handling a 50:50 mixture of secondary and primary sludge. Under optimum conditions, minimum solids contents ranging from 6 to 8% can be expected from thickening such mixtures (Bratby et al., 2004).

PROCESS CONTROL. Proper operation requires reducing variations of the feed rate and concentration. A feed sludge holding and mixing tank helps with intermittent operation. Most units are operated continuously. Some are operated with a short period shut-down during weekends, while others are operated only during certain hours of the day.

The hydraulic throughput for flotation thickening includes feed plus recycle. Flotation units are designed hydraulically to reduce entrance velocities, thereby reducing potential shearing of flocculated sludge particles.

Process control considerations include

- Operating the skimmer so that float is only skimmed above the water level, as described previously (Bratby et al., 2004).
- The speed of the float skimmer arms and the number of arms controls the rate at which floated sludge is pushed into the sludge trough, as explained earlier.

TABLE 29.3 Operating data for plant-scale dissolved air flotation units.

Location	Feed[a]	Influent SS,[b] mg/L	Subnatant SS, mg/L	Removal, %	Floatable solids, %	Loading, lb/hr/sq ft[c]	Flow area, gpm/sq ft[d]	Remarks[e]
Bernardsville, N. J.	ML	3 600	200	94.5	3.8	2.16	1.2	Standard
Bernardsville, N. J.	RS	17 000	196	98.8	4.3	4.25	0.5	Standard
Abington, Pa.	RS	5 000	188	96.2	2.8	3.0	1.2	Flotation aid after 12-hour holding
Hatboro, Pa.	RS	7 300	300	96.0	4.0	2.95	0.8	Flotation aid
Morristown, N. J.	RS	6 800	200	97.0	3.5	1.70	0.5	Standard
Omaha, Nebr.	RS	19 660	118	99.8	5.9	7.66	0.8	Flotation aid after 24-hour holding
Omaha, Nebr.	ML	7 910	50	99.4	6.8	3.1	0.8	Flotation aid
Belleville, Ill.	RS	18 372	233	98.7	5.7	3.83	0.4	Flotation aid
Indianapolis, Ind.	RS	2 960	144	95.0	5.0	2.1	1.47	Flotation aid after 12-hour holding
Warren, Mich.	RS	6 000	350	95.0	6.9	5.2	1.75	Flotation aid
Frankenmuth, Mich.	ML	9 000	80	99.1	6.8	6.5	1.3	Flotation aid
Oakmont, Pa.	RS	6 250	80	98.7	8.0	3.0	1.0	Flotation aid
Columbus, Ohio	RS	6 800	40	99.5	5.0	3.3	1.0	Flotation aid
Levittown, Pa.	RS	5 700	31	99.4	5.5	2.9	1.0	Flotation aid
Nassau Co., N. Y.								
Bay Park Sewage Treatment Plant	RS	8 100	36	99.6	4.4	4.9	1.2	Flotation aid
Bay Park Sewage Treatment Plant	RS	7 600	460	94.0	3.3	1.3	0.33	Standard
Nashville, Tenn.	RS	15 400	44	99.6	12.4	5.1	0.66	Flotation aid

[a]ML = mixed liquor from aeration tanks; and RS = return sludge.
[b]Suspended solids.
[c]lb/hr/sq ft × 4.88 = k/m^2·h.
[d]gpm/sq ft × 0.679 1 = L/m^2·s.
[e]Standard = no flotation aid and no holding before sampling; flottation aid = use of coagulation-flotation aid.

TABLE 29.4 Additional operating data for plant-scale dissolved air flotation units.

Location	Sludge	Loading lb/hr/sq ft[a]	Thickened sludge concentration, %	SS[b] capture, %	Air: solids ratio
Albany, Ga.	Primary and WAS[c]	0.82	6–9	88	0.013
Mankato, Minn.	Primary and WAS	0.50	5–8	90–95	0.013
Menomonie, Wis	Primary and WAS	0.67	4.8–6.7	97	0.013
Waukesha, Wis.	Primary and TF[d]	1.3	6–8	85	0.013
Hagerstown, Md.	Primary and O_2 WAS	0.96	6	97	0.016
Scranton, Pa.	Primary and WAS	1.3	5–6	85	0.016
Oconomowoc, Wis.	WAS	0.4–0.6	4.0	95	0.150
Marshalltown, Iowa	WAS	0.41	4.0	98	0.030
	WAS with chemical	0.8	4.3	99	0.018
York, Pa.	O_2 WAS	0.56	5.8	91	0.010
San Jose, Calif.	WAS	0.42–0.62	3.5–5.5	99	0.015
	WAS with chemical	1.0	3.5–5.5	99	0.015
Huntington, Ind.	WAS	0.38	4.5–5.0		
Glenco, Minn	WAS	0.22	4.0	9.5	0.015
Ocean City, Md.	O_2 WAS with chemical	0.8–1.2	4.5	99	0.013
Erie, Pa.	WAS with chemical	2.25	6.5–7.5	99	0.013
Albany, N. Y.	WAS with chemical	0.52	4.5	99	0.034
Brewer, Maine	WAS with chemical	3.25	3.5	97	0.010
Middletown, N.J.	WAS with chemical	1.25	4.5	99	0.030

[a] lb/hr/sq ft × 4.88 = k/m^2·h.
[b] Suspended solids.
[c] Waste activated sludge.
[d] Trickling filter.

- The speed and the on–off times of the float skimmers should be set to maximize the float solids concentration, but not too slow to cause excessive float-depth accumulation.
- Controlling pressure within the 350 to 590 kPa (50 to 85 psig) range—find the lowest pressure that allows optimum operation—but do not operate at less than 350 kPa (50 psig). Pressures much below 350 kPa cause disproportionate increases in total float depth (see Bratby [1978] and Bratby and Ambrose [1995]).
- Controlling the saturator feed rate to maintain the required air-to-solids ratio.
- Periodically removing bottom sludge is necessary to prevent septicity, gasification, and general deterioration of float density and overall DAF efficiency.

The air-to-solids ratio (pound air/pound solids) affects the sludge rise rate and, as importantly, the total float depth. The necessary air-to-solids ratio, typically between

0.02 and 0.04 (Bratby et al., 2004), depends mostly on sludge characteristics, as explained earlier.

Dilution reduces the effect of particle interference on the rate of separation. Concentration of the sludge increases and the concentration of effluent suspended solids decreases as the sludge blanket detention time increases.

START-UP. Typically, an operator should follow these steps for routine start-up of a DAF:

- Fill the tank with screened final effluent or plant nonpotable water until overflowing.
- Start the collection mechanism for both float and underflow. Ensure that they are operating properly and then place into the normal automatic mode of operation.
- Continue plant nonpotable water flow to the DAF unit and engage the recycle system, including the compressor, if applicable. Adjust to proper pressures and flow. After functioning properly, proceed.
- Ensure that the float and underflow pumps are functional by pumping some water.
- Prepare the polymer, if applicable, and engage the polymer addition at proper flow or as jar tests have indicated if starting after prolonged shutdown, start-up, or process changes.
- Phase the nonpotable plant water out and start WAS flow to the DAF. Make process adjustments as necessary to maintain float depth as described herein.

SHUTDOWN. Typically, an operator should follow these steps for routine shutdown of a DAF:

- Stop polymer flow, if applicable, and at the same time stop WAS feed.
- If only down for a short time (30 minutes or so), there is no need to shut down the recycle system, including the compressor. If down for longer than this, shut down the recycle system.
- The float rake timer can be left on until most of the float is removed into the hopper and pumped to further processing.
- If the unit is going to be down for more than 24 hours, displace the tank contents with nonpotable water or drain and clean the tank, all troughs, and pipelines.
- In a typical operation, only the recirculation pump and retention tank discharge valves are closed when stopping a unit's operation. All other valves remain open, with the exception of valves on drain lines.

SAMPLING AND TESTING. At a minimum, DAF thickeners should be sampled and analyzed as follows:

- Influent for TSS, total solids, and flow;
- Effluent for TSS, total solids, and flow;
- Float (sludge withdrawal) for total solids and flow;
- Depth of blanket by way of sampler, either "bomb" or coretaker (sludge judge). Sample location should be near the beach where sludge is raked into the float trough;
- If applicable, determine the total solids of the polymer or whatever quality assurance tests you deem necessary for the coagulant; and
- Occasionally determine the mass of precipitated air in the saturator feed to evaluate the operating air-to-solids ratio. The methodology has been documented elsewhere (Bratby and Marais, 1975, 1977).

TROUBLESHOOTING. Table 29.5 provides causes and solutions for the most common flotation thickener problems (U.S. EPA, 1978).

PREVENTIVE MAINTENANCE. An effective preventive maintenance program will reduce equipment stoppage and breakdown. Daily maintenance items include

- Checking the drive units for overheating, unusual noise, or excessive vibration, and
- Checking for unusual conditions, such as loose weir bolts.

Weekly maintenance items include

- Checking all oil levels and ensuring that the oil fill cap vent is open;
- Checking all condensation drains and removing any accumulated moisture;
- Examining drive control limit switches; and
- Visually examining the skimmer to ensure that it properly contacts the scum baffle and scum box.

Monthly maintenance items include

- Inspecting skimmer wipers for wear and
- Adjusting drive chains or belts.

TABLE 29.5 Troubleshooting guide for flotation thickening.

Indicators/ observations	Probable cause	Check or monitor	Solutions
Floated sludge too thin	Skimmer speed too high	Visual inspection	Adjust as required
	Unit overloaded	Rise rate	Turn off feed sludge to allow unit to clear or purge the unit with auxiliary recycle
	Polymer dosages too low	Proper operation and calibration of polymer pumps	Adjust as required
	Excessive air : solids ratio	Float appears very frothy	Reduce air flow to pressurization system
	Low dissolved air	See "Low dissolved air"	
Low dissolved air	Reaeration pump off, clogged, or malfunctioning	Pump condition	Clean as required
	Eductor clogged	Visual inspection	Clean eductor
	Air supply malfunctioning	Compressor, lines, and control panel	Repair as required
Effluent solids too high	Unit overloaded	Rise rate	Turn off feed sludge to allow unit to clear or purge the unit with auxiliary recycle
	Polymer dosages too low	Proper operation and calibration of polymer pumps	Adjust as required
	Skimmer off or too slow	Skimmer operation	Adjust speed
	Low air : solids ratio	Poor float formation with solids settling	Increase air flow to pressurization system
	Septic sludge on bottom		Periodically remove settled sludge
Skimmer blade leaking on beaching plate	Skimmer wiper not adjusted properly	Visual inspection	Adjust as required
	Hold-down tracks too high	Visual inspection	Adjust as required
Skimmer blade binding on beaching plate	Skimmer wiper not properly adjusted	Visual inspection	Adjusted as required

TABLE 29.5 Troubleshooting guide for flotation thickening (*continued*).

Indicators/ observations	Probable cause	Check or monitor	Solutions
High water level in retention tank	Air-supply pressure low	Compressor and air lines	Repair as required
	Level control system not operating	Level control system	Repair as required
	Insufficient air injection	Compressor and air lines	Repair as required
Low water level in retention tank	Recirculation pump not operating or clogged	Pump operation	Inspect and clean as required
	Level control system not operating	Level control	Repair as required
Low recirculation pump capacity	High tank pressure	Backpressure	Adjust backpressure valve
Rise rate too slow	Unit overloaded	Rise rate	Turn off feed sludge to allow unit to clear or purge the unit with auxiliary recycle
	Low dissolved air	See "Low dissolved air"	
	Polymer dosages too low	Proper operation and calibration of polymer pumps	Adjust as required

Semiannual inspections of major elements for wear, corrosion, and proper adjustment include

- Drives and gear reducers;
- Chains, belts, and sprockets;
- Guide rails;
- Saturation systems—eductors (if used) or nozzles should be inspected for wear or cleaned whenever the efficiency begins to decline, or on a semiannual basis;
- Polymer feed system; and
- Mechanical systems, including shaft bearings and bores, bearing brackets, baffle boards, flights and skimming units, suction lines and sumps, and sludge pumps.

SAFETY. The following safety considerations apply to DAF equipment:

- Comply with the applicable general safety considerations in Chapter 5, including procedures for confined-space entry to areas where the toxic gases, hydrogen sulfide and methane, may be present;

- Require the presence of at least two people when working in areas not protected by handrails;
- Keep walkways and work areas free of grease, oil, leaves, and snow;
- Keep protective guards in place unless mechanical or electrical equipment has undergone lockout/tagout. Lockout is a method of keeping equipment from being set in motion and endangering workers. The *Code of Federal Regulations* (1991) 29 *CFR* Part 1910.147 covers the servicing and maintenance of machines and equipment in which the unexpected energization or start-up of the machines or equipment, or release of stored energy, could cause injury to employees. Tagout occurs when the energy isolation device is placed in a safe condition and a written warning is attached to it. Typically, the employee signs and dates the tag. Removal of the tag and lockout device is done by the same individual when the equipment is safe for restart;
- Keep the pressure of the retention tank under its working pressure rating; and
- Ensure that the tank relief valve functions; inspect it regularly for corrosion.

GRAVITY BELT THICKENING

DESCRIPTION OF PROCESS. Gravity belt thickeners (Figure 29.9) work by filtering free water from conditioned solids by gravity drainage through a porous belt. The gravity drainage area is usually horizontal but may be inclined under some circumstances. Chemical conditioning is generally required to flocculate the sludge and separate the solids from the free water. Chemical conditioning may be accomplished by injecting the chemical through an injection ring and mixing it with the sludge. After chemical injection, the sludge velocity is reduced in a retention tank and the sludge is allowed to fully flocculate before overflowing by gravity onto the moving belt. As the moving belt carries the sludge, plows (chicanes) clear portions of the belt for the filtrate to drain through and gently turn over the solids, thereby exposing more free water. Prior to the discharge, most gravity belt thickeners have some type of dam or an adjustable ramp. This forces the solids to either crest the ramp or to go under the dam. In either case, the solids will tend to roll backwards due to shear forces. This force further assists in obtaining maximum performance. Thickened solids that pass the dam are discharged from the gravity belt thickeners. Any residual solids still on the belt are scraped off by a scraper (doctor) blade. The belt then continues through a high-pressure wash water spray system to clean the belt. The filtrate and the wash water are both collected for further processing or returned to the head of the plant. In some instances, the wash water may be recycled to improve capture efficiency.

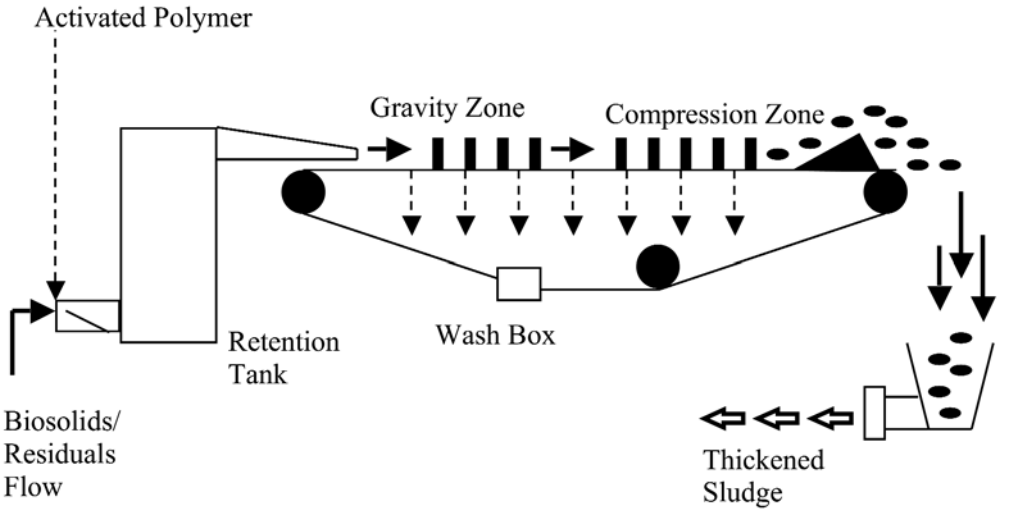


FIGURE 29.9 Gravity belt thickener process.

The hydraulic capacity of the equipment is determined by multiple factors including sludge type, sludge concentration, polymer type and polymer dosage, belt speed, belt type, as well as the obvious machine width and length.

DESCRIPTION OF EQUIPMENT. Typical gravity belt thickener systems are described herein.

Polymer Addition. Polymer addition usually occurs via injection through a multiport injection ring; it is mixed with the sludge as it flows through an inline mixing device. In some cases, the polymer may be mixed mechanically in the retention tank. However, this generally results in higher polymer consumption.

Flocculation Tank. The flocculation tank allows the incoming sludge velocity to be reduced so that flocculation can fully occur before the sludge overflows onto the moving belt. Design of the tank is critical to prevent short-circuiting within the tank.

Belt and Supports. Belts are typically woven from polyester fiber. High pH and other unusual conditions may require special materials. The belt is supported on grid strips that also serve as wipers on the bottom of the belt. This wiping action increases the drainage capacity of the belt.

Belt Tensioning. Unlike a belt press, the performance of the belt thickener is not dependent on belt tension. Once the dewatering belt on a thickener is tight enough to

prevent slippage on the drive roller, additional tension is unnecessary. Additionally, the belt tension on a thickener is not dependent on the type or amount of sludge loading. As such, the requirements for belt tension are much lower on a gravity belt thickener compared to belt filter presses. Typically, 20 lb of tension force/linear inch of belt width is sufficient. All belt tension is a result of moving one roller closer to or further away from the other roller(s). This displacement may be through hydraulic, pneumatic, or mechanical actions. Once the belt is tensioned, it is not necessary to relax the tension until the belt is replaced.

Belt Drive. All belt thickeners have a variable-speed belt drive (Figure 29.10) with a typical speed range of 8 to 40 m/min. The belt speed may be either mechanically or electrically varied with speed controls at the local control panel. Typically, the belt drive is attached to a rubber-coated drive roller.

Belt Tracking. During operation of a belt thickener, the belt should more or less remain centered and not move laterally on the machine. Although the belt should not move, some type of belt tracking device will be included on most machines. The most common devices are hydraulic cylinders, pneumatic cylinders, and pneumatic bellows. Other, less common types include mechanical guides built into the machine

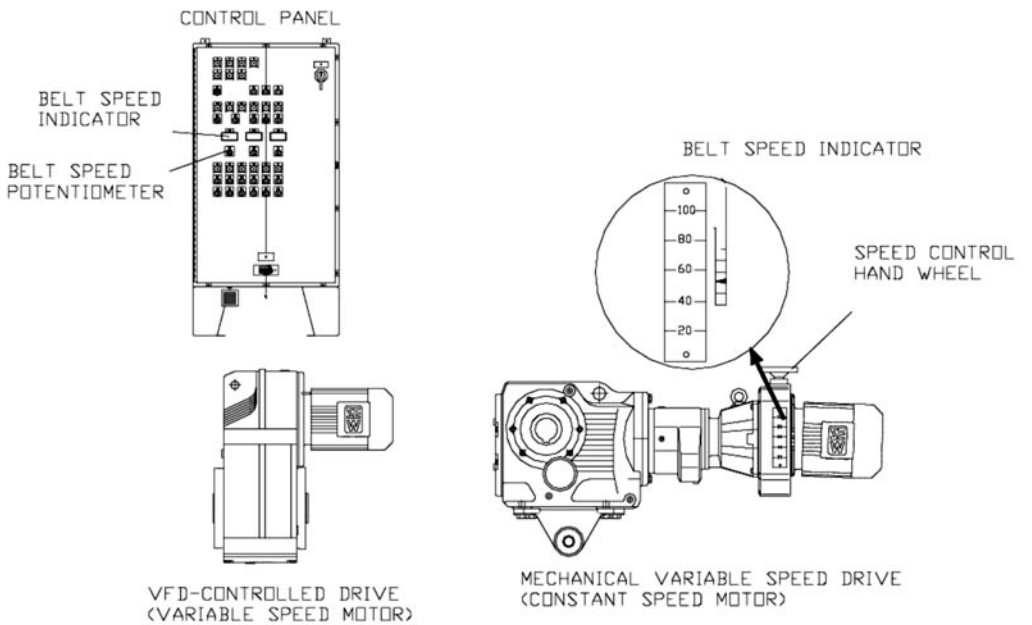


FIGURE 29.10 Basic controls for belt thickeners.

frame or rollers, jack bolts built into the bearing housing on one roller, as well as a roller that is repositionable to adjust the belt tracking. Comparatively, the belt on a belt thickener is similar to a conveyor belt; all of the tracking devices have some roots in the conveyor or papermaking industries.

Chicanes. The chicanes (Figure 29.11), or plows, on a gravity belt thickener serve several functions. As sludge first enters the gravity deck, the solids are very thin and dispersed. The chicanes clear a path on the moving belt for the filtrate to drain through. As the solids thicken, the plows start turning over the rows of solids similar to a plow making wind rows. This turning action exposes more filtrate to the moving belt and helps eliminate ponding on the gravity deck. Some plows also cause the solids to roll backwards on the deck, which creates a shearing action on the solids. This shearing action is the same force as a ramp on the machine, which greatly increases the performance of the thickener.

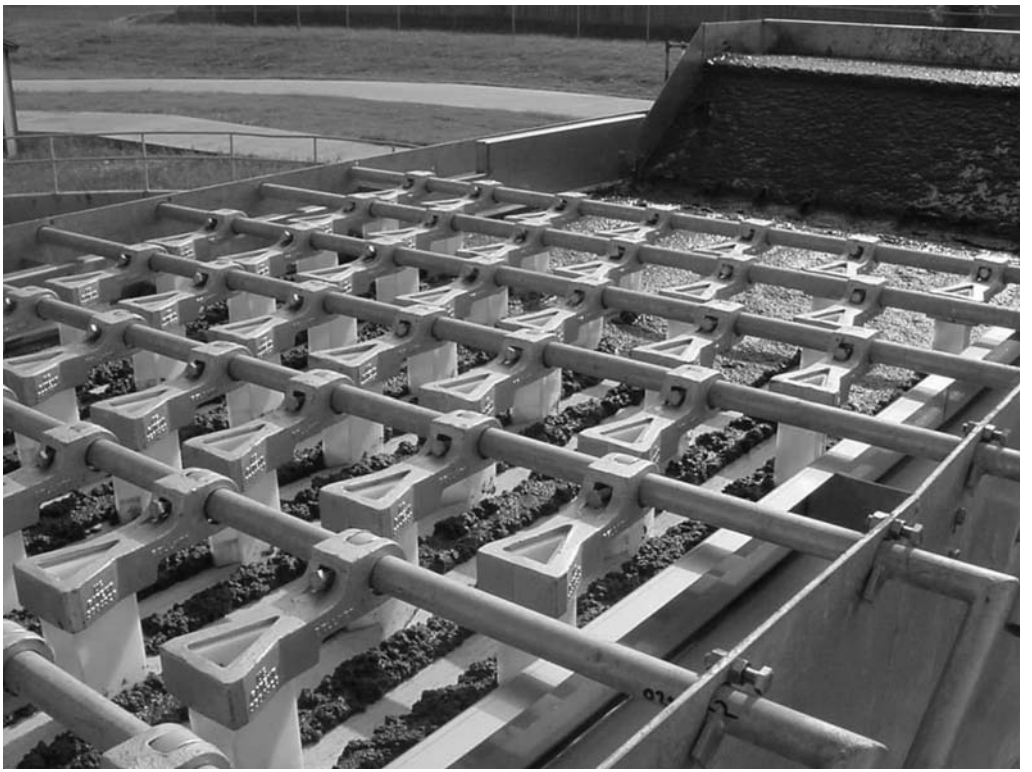


FIGURE 29.11 Chicane placement.

Adjustable Ramp. Most high-performance gravity belt thickeners will have some type of ramp (Figure 29.12) at the end of the gravity deck. It is an advantage for the ramp to have a method of adjustment with the solids either flowing over or under the ramp. The purpose of the ramp is to cause the solids to slightly pond on the gravity table. This ponding holds the solids longer on the moving belt, which increases the amount of filtrate removed. It also can cause the solids to roll backward against the ramp, which, again, improves the efficiency of the process.

Doctor Blade. When the system is operating properly, most of the thickened solids should drop off the end of the gravity table; however, a small amount of solids may stick to the dewatering belt. The doctor blade aids in removing these solids by gently scraping the belt to prepare it for cleaning in the high-pressure wash station.

Belt Wash. Most gravity belt thickeners will have one high-pressure wash tube. The typical requirements are 110 m^3/d (20 gpm) per meter of belt width at 585 to 620 kPa



FIGURE 29.12 Discharge ramp.

(85 to 90 psig). Although the wash water should be relatively clean, it could include final effluent or even filtrate from the gravity belt thickener. If filtrate is used, a strainer should be used to reduce the possibility of solids in the filtrate clogging the wash water nozzles. The typical installation will spray the belt on the cake side, but it is also possible to wash the belt from the non-cake side. In some applications, washing is carried out from both sides of the belt or washing is aided through the induction of a soap solution or other cleaning agent. With proper washing, the belt should last 3000 to 4000 hours in most applications.

Sludge Pumping. Sludge pumping is critical to the proper operation of any dewatering device and the gravity belt thickener is no exception. Sludge flocculation will generally rely on the head pressure from the sludge and polymer pumps for mixing of the sludge and polymer. As such, it is important to select pumps with enough head pressure to overcome the minor losses associated with this mixing. The pumps should also be such that surging or pulsing in the flow is eliminated. Although some installations will use mechanically variable speed drives on the sludge pumps, the more common approach is to have the speed of the pumps variable through a variable-speed drive controlled at the gravity belt thickener local control panel. Flow indication should also be provided at the local control panel.

Additionally, the thickened sludge may either be pumped or conveyed to the next part of the process. The thickened sludge pump will generally be controlled by the level of the sludge in the hopper and should not be controlled from a fixed-speed setpoint.

Controls. Typical controls for a gravity belt thickener provide either manual or automatic control depending on the level of plant automation. At a minimum, the following functions should be included:

- Belt drive start/stop,
- Wash water pump start/stop,
- Sludge feed pump start/stop,
- Thickened sludge pump start/stop,
- Hydraulic power unit start/stop (or air-compressor start/stop), and
- Polymer system start/stop.

Optionally, the following items are recommended:

- Belt drive speed controller,
- Sludge pump speed controller,
- Polymer pump speed controller,
- Thickened sludge pump speed controller, and
- Emergency stop push button/pull cord.

The following alarms should also be included:

- Belt misalignment,
- Belt broken,
- Low wash water pressure,
- Low hydraulic pressure/low air pressure,
- High sludge level (on the gravity deck),
- High thickened sludge level, and
- Low thickened sludge level.

PROCESS CONTROL. Numerous variables affect the overall thickening process. Listed below are most of these variables and their interrelationship with the other variables.

Sludge Feed. The sludge flowrate can be determined by the desired solids loading, the amount of feed solids per hour per meter of belt width (lb/hr/m), and the feed slurry solids concentration (%). The feed solids should be characterized to determine inorganic (ash) content, biosolids content, and solids chemistry. As a quick reference, the following types of municipal sludges are listed along with their applicable solids loading limits (lb/hr/m):

- Raw primary, 100%—2000–3000
- 50% primary, 50% waste activated—1500–2000
- Anaerobically digested blend (50% primary)—1300–1750
- Anaerobically digested blend (50% primary, 50% waste activated)—1300–1750
- Aerobically digested waste activated—1100–1500
- Waste activated, 100%—660–1200

Polymer. To accomplish optimum thickening, it is important to select the proper polymer. Regardless of the type of polymer selected, plant personnel should verify that the polymer system specified can handle the type of polymer selected for the application. Poor mixing, activation, and aging of the polymer are some of the most common causes of excessive polymer consumption. The recommended final polymer solution concentration range to condition the sludge is the following:

- Dry polymers (0.05 to 0.2% by weight),
- Emulsion/dispersion polymers (0.1 to 0.5% by volume), and
- Mannich polymers (1 to 3% by volume).

It is important to note that if the polymer solution is prepared at concentrations that are considerably higher than the solution concentrations recommended then polymer-thickening costs would increase because the polymer cannot be dispersed efficiently into the slurry. Polymer overdosing will deteriorate the sludge thickening process as well.

Polymer Dosage. For a given type of sludge, polymer dosage is generally solids-dependent (i.e., the lower the percent feed solids, the higher the chemical dosage required). Put another way, sludges that are difficult to gravity-settle will require more polymer than sludges that settle easily. Polymer should be injected into the sludge at the minimum amount required for thickening. All excess polymer is wasted and goes down the drain with filtrate. This is not cost- or process-effective.

Polymer selection and dosage are best determined by jar tests and bench-scale simulation tests, followed by a trial on the gravity belt thickeners.

There are a number of ways to automate the polymer dosage using different instruments and control systems. Information on various control options is available from most instrument manufacturers or process equipment manufacturers.

Mixing Energy. Mixing energy is the energy required to instantaneously mix the polymer with the suspended solids of the slurry. The optimum mixing energy is usually determined on-site by adjusting the throat opening inside the variable orifice mixer. For example, to increase the mixing energy, reduce the throat opening of the mixer by increasing the adjustable counterweight and turn up the adjustable bolt on the valve stop handle to allow the weight arm to move further down. Too little or too much mixing energy results in less than optimum floc formation that adversely affects thickening action.

Retention Time. Retention time is the time required for the polymer reacting with the biosolids/residuals suspended in the slurry to complete the flocculation process. Most thickening applications require 15 to 20 seconds to complete the flocculation process. With too little time, the flocs will be very small and, with too much time, the result is large, clumpy flocs. Both of these conditions lead to reduced thickening. For ideal thickening, large, uniform-sized flocs are desired.

Belt Speed. There are two changes an operator can make to belt speed: making it faster or making it slower. The slower the belt speed, the greater the residence time in the gravity section because, as the belt slows, the sludge has more time for the free water to drain. This translates into increased cake dryness. Conversely, the faster the belt speed, the greater the process throughput (assuming the sludge feed rate is increased). The belt speed should be slowly adjusted until the optimal balance between process

throughput and cake dryness is achieved. The belt speed range is 8 to 40 m/min. There are two different types of belt drives offered on most gravity belt thickeners: a variable-frequency drive (VFD)-controlled, variable-speed motor drive and a mechanical variable-speed drive with a constant speed motor. Typically, the VFD-controlled belt drive speed can be adjusted by a belt drive speed potentiometer or controller located on the control panel. A belt drive indicator shows the belt speed in percent (0 to 100%). For the mechanical variable-speed drive, the speed control hand wheel can be turned to adjust belt speed.

Belt Tension. Belt tension should be set at 20 pli initially by adjusting the pressure valve on the hydraulic power unit. Because sludges vary from plant to plant, the optimum pressure should be determined once the gravity belt thickener is operating. The belt tension needs to be only high enough to obtain good traction without slipping at the drive roller. The belt tension also helps keep the belt straight and flat. Excessive belt tension will decrease belt life.

Belt Type. The opening-size weave of the belt and belt material determine the thickening characteristics of that belt. The initial belt supplied by the manufacturer should have been selected based on their experience with similar processes.

Ramp Angle. The adjustable ramp is provided to cause additional dewatering of the sludge before it is discharged from the gravity deck. This is accomplished by creating a dam across the discharge end of the gravity deck, forcing the sludge to be pushed up the ramp, turning and tumbling on itself, while additional water is caused to separate from the solids. For drier sludge, the ramp will be raised to a steeper angle. It is also possible to retract the ramp away from the belt and allow the sludge to pass under it when no further dewatering is desired.

Upstream Variables. There are other items upstream of the gravity belt thickener that can affect its performance. The information presented here is designed to illustrate some of the variables that may affect the overall performance of the gravity belt thickener with the plant slurry

Slurry Pump Selection. Positive-displacement pumps are recommended for sludge thickening applications. The preferred pumps for these applications include progressing cavity, rotary lobe, and gear pumps. These pumps allow even flow of the slurry along the pipeline to allow good dispersion of the polymer with the suspended solids of the slurry as well as a constant pressure drop across the variable orifice mixer. Other pumps that are commonly used include self-priming centrifugal pumps; however, the pressure drop across the inline polymer mixer must be carefully considered.

Sludge Characteristics. The sludge characteristics described herein should be considered in sludge thickening processes.

Solids Concentration. Solids concentration level influences the selection of a slurry conditioning program. Increasing feed solids concentration will cause lower polymer conditioning requirements. It is extremely important that the characteristics of the sludge being thickened remain relatively constant to maintain good process control of the gravity belt thickener. For example, if the feed solids concentration increases by 30% (i.e., from 2 to 2.6%), one of the following variables have to be adjusted to keep the gravity belt thickener running satisfactorily:

- Polymer dosage,
- Belt speed, and
- Slurry flowrate (to maintain constant solids loading).

Biological Sludge Content. Biological sludges usually have high cationic polymer requirements. When thickening waste activated biosolids, it is critical to understand that the specific resistance for activated sludge increases when the biological process is experiencing short mean cell residence time, low dissolved oxygen, low temperature, and high food-to-microorganism ratios to control the population of filamentous bacteria in the aeration basin(s) to prevent poor gravity belt thickener performance. Blooms of filamentous bacteria increase the polymer dosage and reduce the solids loading and cake solids during the thickening process because water is stored inside the cells of the bacteria. Higher polymer requirements usually result from high dissolved solids in sludge.

Inorganic (Ash) Content. Higher ash content usually yields higher dry cake solids. Biological sludges have ash contents ranging from 15 to 35%. Ash contents of digested biological sludge can increase to 30 to 50%. Higher ash contents are occasionally encountered from lime-stabilized sludges or chemical treatment waste sludges. In these cases, it is not unusual to have an anionic or nonionic conditioning program work best with the sludge.

Sludge Storage Time. Extended storage of raw primary and waste biological sludges before polymer conditioning increases conditioning requirements. Aeration improves the sludge thickening characteristics.

Wash Water Characteristics. The wash water used to clean the belt needs to have the following qualities to prevent poor performance of the gravity belt thickener:

- The TSS concentration should be $\leq$50 mg/L,
- The total dissolved solids concentration should be 1000 mg/L,

- The pH of water should be 6 to 8,
- The temperature should be 10 to 50 °C, and
- The wash water pressure should be ≥586 kPa (85 psig).

Occasionally, if the TSS concentration reaches 200 mg/L, the unit can operate marginally if the nozzles in the spray tubes are cleaned frequently with wire brushes (these are actuated by opening and closing the manual valve). If the wash water pressure drops considerably, the solids that are embedded in the belt during the filtration process cannot be dislodged, causing belt blinding after a period of time.

START-UP. After ensuring that all of the guards and covers are in place and that the unit has not been locked out/tagged out, the unit may be started. Each manufacturer will have specific instructions that should be followed. However, the basic start-up sequence for a gravity belt thickener is as follows:

- Ensure that the belt is clear of debris and that the plows/ramp/scraper are properly positioned on the belt.
- Start the hydraulic unit (or air compressor) and allow the belt to tension.
- Start the belt drive and use an initial setting of approximately 20 m/min belt speed.
- Start the wash water pump and allow the belt to pre-wet.
- Start the polymer pump and allow the fresh polymer to reach the polymer injection point
- Start the sludge pump.
- After thickened sludge is available, start the thickened sludge pump (or thickened sludge conveyor).
- After the system is running, begin fine-tuning the process by adjusting the sludge flow, polymer dose, mixing energy, belt speed, and so on until the results are within the desired process parameters. It is critical to only adjust one item at a time and to allow time for the adjustment to take effect before making another change.

SHUTDOWN. The basic shutdown sequence is as follows:

- Shut down sludge feed pump.
- Shut down polymer feed pump.
- As the thickened sludge hopper empties, shut down thickened sludge pump (or thickened sludge conveyor).

- Drain the flocculation tank on the machine.
- Wash the machine down from top to bottom.
- Allow the belts to be completely washed (this could take 15 to 45 minutes) without sludge or polymer.
- Shut down the wash water pump.
- Shut down the belt drive.
- Shut down the hydraulic unit/air compressor.

SAMPLING AND TESTING. At a minimum, gravity belt thickeners should be sampled and analyzed as follows:

- Sample influent feed for total solids, TSS, total volatile solids, pH, and flow;
- Sample wash water for TSS and flow;
- Sample thickened solids for total solids and flow;
- Sample filtrate for TSS and flow;
- Measure flow and quantity of polymer used; and
- Measure any dilution water used to make up polymer.

Samples should be collected and sealed in airtight containers until they can be analyzed. Analysis should be conducted in accordance with the latest edition of *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 2005). Table 29.6 provides a sample log sheet for tracking the performance of a gravity belt thickener.

TROUBLESHOOTING. Each gravity belt thickener process consists of a system of integrated components and each component may have an effect on another portion of the system. It is important to hold as many variables constant as possible while troubleshooting other portions of the system. Troubleshooting starts with the process and then works down into the individual components of the system (Tables 29.7 through 29.12).

PREVENTIVE MAINTENANCE. Maintaining the gravity belt thickener will not only extend the life of equipment but also decrease the operational cost through increased operational efficiency such as lower polymer doses, increased throughput, and so on. For simplicity, the preventive maintenance tasks are broken down into basic tasks depending on the frequency of the activity. In all cases, the manufacturer should be consulted for additional steps or procedures for the equipment.

TABLE 29.6 Typical log sheet for thickener operations.

Operating data for month of_____, 19_____

	Feed sludge data				Flocculant feed data		Thickened sludge data		Belt wash data		
Day of month	Belt or drum speed, rpm	Feed rate, gpm or gal[a]	Feed solids,[b] % TSS	Solids throughput,[c] lb/hr[a]	Polymer, gpm[a]	Dosage,[d] lb/ton[a]	Dilution water flow, gpm[a]	TS, %	Wash water flow, gpm[a]	TSS in filtrate, %	Solids recovery,[e] %
1											
2											
3											
4											
.											
.											
.											
30											
31											
Total											
Average											
Minimum											
Maximum											

[a]gpm $\times (6.308 \times 10^{-5}) = m^3/s$; gal $\times (3.785 \times 10^{-3}) = m^3$; lb/hr $\times$ 0.126 0 = kg/s; lb/ton $\times$ 0.500 = g/kg.
[b]Percent TSS (total suspended solids), TS (total solids) recorded as 4% = 40 000 mg/L.
[c]Solids throughput: lb/hr = feed rate $\times$ % TSS $\times$ 0.25 or total volume fed $\times$ % TSS $\times$ 8.34 = lb fed.
[d]Flocculant dosage: lb flocculant/ton of sludge solids = flocculant feed rate $\times$ concentration $\times$ 500/throughput tons/hr or flocculant volume fed $\times$ concentration/(throughput tons $\times$ 1 000).
[e]Solids recovery: 100-(thickened sludge TS) (feed sludge TSS return flow TSS)/(feed sludge TSS) (thickened sludge TS return flow TSS).

TABLE 29.7 Process troubleshooting guide.

Problem	Probable cause	Remedy
Sludge does not flocculate	Polymer is not flowing	Verify polymer system is on
		Verify polymer is flowing through plastic hoses at mixer
	Insufficient amount of polymer	Increase polymer dosage
	Wrong polymer type	Contact manufacturer or polymer representative
	Old/nonreactive polymer	Make up new polymer
	Insufficient polymer mixing	Increase polymer mixing energy
		Increase retention time in piping
Sludge does not de-water on gravity deck	Belt is blinded	Clean belts
	Poor flocculation	Increase polymer
	Wrong polymer type	Contact manufacturer or polymer representative
	Loading rate too high	Decrease sludge feed rate
Capture is poor/filtrate is dirty	Seals are worn on restrainers	Replace seals
	Insufficient polymer	Increase polymer dosage
Low cake solids	Insufficient polymer	Increase polymer dosage
	Too much polymer	Decrease polymer dosage
	Wrong polymer type	Contact manufacturer or polymer representative
	Loading rate is too high	Decrease sludge feed rate
	Belt speed is too fast	Decrease belt speed
	Ramp is too low	Increase ramp angle
Solids adhere to belt	Polymer dosage is too high	Decrease polymer dosage
	Insufficient mixing	Increase mixing energy
Sludge buildup in pans	Upset process	Clean pans and optimize process

Daily Actions.

- Clean belt by running belt drive and wash system without sludge or polymer for a minimum of 45 minutes.
- Clean spray nozzles on wash box by rotating hand wheel to a fully open position and then rotating it back to a fully closed position.

TABLE 29.8 General troubleshooting guide.

Problem	Probable cause	Remedy
Thickener does not run	Sludge pump not operating	Check sludge pump
	Polymer system not operating	Check polymer system
	Belt drive not operating	See Table 29.10
	Hydraulic unit not operating	See Table 29.9
	Water pump not operating	See Table 29.11
Scraper blade not cleaning belt	Blade is out of adjustment or requires replacement	Adjust or replace blades
	Buildup of fibrous material, such as hair, at the knife edge of the blade	Open blade and clean
Scraper blade wears quickly	Blade tension too tight	Reduce blade tension; optimize process for good belt release
	Belt speed too fast	Reduce belt speed
Roller sticking	Bearing is worn	Replace bearing
Bearing losing excessive grease	Bearing seals are blown	Replace seals
Machine runs in a jerky motion at roller bearings	Gear train is damaged	Inspect gear reducer and replace as required

- Check the oil level in the hydraulic unit; fill as required.
- Check the oil level in the air compressor (if applicable) and fill as required.
- Manually extend and retract the tension cylinder to clean and oil the rods. This will greatly extend the life of the seals.
- Cycle the steering cylinder in both directions by holding the steering paddle first one way and then the other. This will clean and oil the rods and greatly extend the life of the seals.
- Inspect all alarms and manually trip and reset the trip cord.
- Inspect the machine for any loose or worn parts such as seals, belts, and so on that need to be replaced.

Monthly Actions.

- Clean belt with a soap/bleach mixture. To prepare the soap/bleach mixture, use 1 cup of detergent and 3 cups of bleach to mix with 5 gal of water. The soap can be any laundry-type liquid detergent and the bleach can be any generic brand bleach containing 5.25% sodium hypochlorite. The water can be tap

TABLE 29.9 Hydraulic system troubleshooting guide.

Problem	Probable cause	Remedy
Hydraulic power unit fails to energize when control push button is pressed	Control panel feeder circuit in off or "tripped" position	Set breaker to "on" position
	Motor starter overload protectors in tripped position	Depress overload reset button on motor starter
Belt steering erratically, requiring constant automatic correction	Improper roller alignment, valve alignment, valve sensitivity, or belt defects	Carry out check and adjustment procedures as appropriate
Hydraulic unit operational but fails to build pressure	Incorrect motor rotation direction	Ensure that rotation is correct; if not, have a qualified electrician revise motor wiring at motor starter
	Pressure regulator is not properly adjusted	Correct adjustment
	Pressure regulator clogged by foreign material causing fluid bypass back to reservoir	Disassemble and clean valve and check for worn or broken parts; if particles are found in valve, drain and clean reservoir, refill as recommended in lubrication schedule
	Belt steering valve bypassing fluid directly back to power unit reservoir	Remove and clean belt steering valve of any foreign material; if cleaning does not improve operation, contact a qualified hydraulic repair center or contact manufacturer
	Hydraulic pump worn or damaged	Have pump serviced by a qualified hydraulic repair center; contact manufacturer if a replacement pump or part is required
Belt tension slacks when sludge is applied	Tensioning cylinder is bypassing oil internally	Repair or replace cylinder
	Pneumatic cylinder/bellow has an air leak	Repair air line or replace cylinder/bellows

TABLE 29.10 Belt drive troubleshooting guide.

Problem	Probable cause	Remedy
Main drive fails to start and drive the belt when energized	Control panel interlocks prohibit belt drive energizing until appropriate ancillary equipment is operational	See sequence of operations and control diagrams for design interlocks; energize appropriate equipment
	Belt drive speed potentiometer (or controller) set at zero	Increase setting to desired speed
	VFD electronic controller tripping chassis mounted overload protector or feeder voltage fuses burnt out	Reset overload and check fuses for continuity, and renew or reset as required; check for dried sludge or other obstructions on the belt that would put unusual starting load on belt drive
	If check out fails to show problem and incoming voltage to VFD is proper, the VFD has failed	Take VFD controller to repair center for reconditioning or replacement; contact manufacturer for service

water. Use a power wash system to spray the soap/bleach mixture on the belt surface for cleaning. The spray pressure should be about 7000 kPa (1000 psig) and not to exceed 10 300 kPa (1500 psig).

- Inspect the belt seam wires for breaks; replace if broken.

Semiannual Actions.

- Clean (or replace) hydraulic filter screen.
- Check oil level in drive unit gear box.
- Lubricate all bearings.
- Inspect polymer mixer/injection ring assembly and clean as required.
- Replace the belt seam wires.

Annual Actions.

- Replace drive unit oil.

TABLE 29.11 Belt wash water system troubleshooting guide.

Problem	Probable cause	Remedy
Water pump does not run	Pump motor not running	Verify switch is ON
		Verify power is ON
		Motor is burned out or needs to be repaired
Low pump pressure	Bypass valve at press is open	Close hand wheel valve at wash box
	Impeller is worn	Replace impeller
	Suction pressure too low	Correct suction pressure problem
	Pressure switch fault	Restart system and verify pressure is above 340 kPa (50 psi)
		Verify pressure switch is functioning by bypassing switch and restarting system
Low pressure at wash box	Line is blocked	Check piping and remove obstruction
	Bypass valve at press is open	Close hand wheel valve at wash box
	Nozzle is missing	Replace nozzle in wash tube
No water at wash box	Valve is closed	Open valves
Water bypassing shower	Valve is open	Close hand wheel valve
	Seals on wash tube are worn	Replace seals
Appearance of dirty strips	Wash water nozzles clogged	Clean or replace nozzles
	Water pressure too low	Increase pressure
	Solids lodged under scraper blade	Clean scraper blade

SAFETY. As with any process in a WWTP, there are inherent hazards that can be minimized with proper precautions. Some general hazards are

- Polymer spills creating slip hazards;
- Lubricant spills creating slip hazards;
- Sludge spills creating slip hazards;
- Chemical exposure from caustics or acids in some processes;

TABLE 29.12 Belt tracking troubleshooting guide.

Problem	Probable cause	Remedy
Belt will not track	Poor distribution of sludge	Correct distribution on gravity section
	Sludge is built up on rollers	Clean rollers
	Steering paddle not following belt	Spring on valve is worn or broken; replace spring
		Valve is sticking or frozen; repair or replace valve
		Paddle is out of adjustment; adjust paddle
	Belt is cut out of square	Remove the belt from the machine, rotate it 180 degrees, and re-install. If the belt is bad, it will go off on the opposite side; if it steers off the same side, the belt is not at fault.
	Roller has been knocked out of alignment	Check all rollers for parallel. Run a 100-ft[a] flat tape along the belt path on both sides near the end of the roller. Each side should be the same (0.5-in. tolerance)[a]; if not, call manufacturer
	Hydraulic/air pressure is low	Increase pressure
	Cylinder is stuck	Manually move steering paddle to see if cylinder responds; if not, repair/replace cylinder

[a]ft × 0.3048 = m; in. × 25.4 = mm.

- Waterborne bacterial hazards;
- Exposure to gaseous hazards such as hydrogen sulfide;
- Material handling hazards from lifting polymer, belts, and so on; and
- Electrical hazards around the controls, motors, and so on.

Another, more specific hazard associated with a gravity belt thickener is

- Exposure to the moving dewatering belt although pinch points are guarded.

All of these hazards should be minimal with a proper health and safety plan and by following safety procedures such as the *Code of Federal Regulations* (1991) 29 *CFR* Part 1910.147 as well as applicable provisions from the Occupational Safety and

Health Administration and other relevant entities. It is essential to maintain health and safety items such as machine guards, emergency stop push buttons, emergency stop pull cords, gas monitors, and so on, as well as having a detailed lockout/tagout procedure.

THICKENING WITH A CENTRIFUGE

PROCESS DESCRIPTION. Decanter centrifuges are centrifuges that have a screw conveyor inside that transports the settled solids along the bowl and out of the centrifuge (Figure 29.13 and Figure 29.14). Decanter centrifuges are the only devices where the same piece of equipment can both thicken and dewater sludge. To the centrifuge, the process is the same, varying only in degree. Centrifuges use the principle of sedimentation to separate liquids from solids—the same principle as the clarifiers and thickeners in the wet end of the plant. With sedimentation, it is the difference in density between the solids and the surrounding liquid that drives separation. On the surface of the earth, we experience the acceleration of gravity (9.8 m/s^2). In convenient shorthand, we refer to 9.8 m/s^2 as "one g." A centrifuge might generate 2000 $\times$ g on the bowl wall, meaning the acceleration was the equivalent of 2000 times the earth's gravitational acceleration. In very real terms, a one pound weight on the bowl wall would generate a 2000-lb eccentric force and cause the centrifuge to vibrate on it's isolators. In any case, where the gravity clarifiers have only 1 $\times$ g to settle the solids, the centrifuge has thousands of times the acceleration of gravity and, therefore, carries the

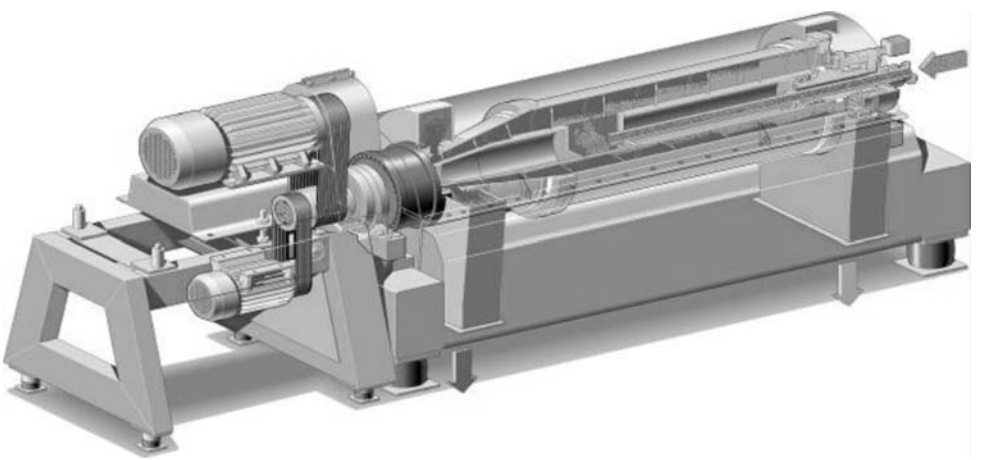


FIGURE 29.13 Thickening centrifuge (courtesy of Westfalia Separator, Inc., Northvale, New Jersey).

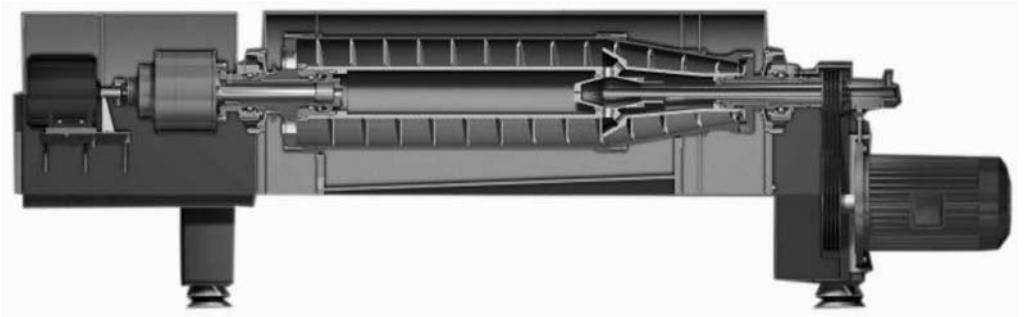


FIGURE 29.14 Cutaway of a typical centrifuge (courtesy of Alfa Laval, Inc., Richmond, Virginia).

separation farther. As it happens, the centrifuges that thicken sludges usually operate at somewhat lower speeds than dewatering centrifuges.

EQUIPMENT DESCRIPTION. Feed material enters the centrifuge through a stationary feed tube (Figure 29.15), where it then drops into the center of the conveyor that is rotating at a speed only a few revolutions per minute different from the bowl speed. This difference in speed between the bowl and the conveyor is called *differential revolutions per minute* (ΔRPM). The feed material flows along the inner surface of the pool of liquid above the compacting solids until it reaches a weir, called a *dam* (Figure 29.16). The liquid dam level is an important process adjustment on all centrifuges. The dam setting controls the liquid level in the centrifuge and is adjusted for each installation and each application. As with a clarifier, the dams must be set at the same radius to prevent short-circuiting.

Just as with a clarifier, the weir ensures the flow is evenly distributed, with no short-circuits, and controls the liquid level inside the centrifuge. As the solids travel from the feed zone to the liquid discharge end, the solids settle out of the moving layer toward the bowl wall. The screw conveyor scrapes these solids along the bowl, up the tapered beach, where they are discharged over a fixed solids weir. The difference in radius between the solids weir and the dam radius is called the *differential head* (ΔH). In most centrifuges, operators periodically adjust the ΔH by removing the dam plates and installing another set with a slightly different radius. Figure 29.15 shows how this process works. It also includes a baffle at the beach bowl intersection, sometimes called a *hydraulic lift disc*. Once a patented device, it is now commonly used on many centrifuges.

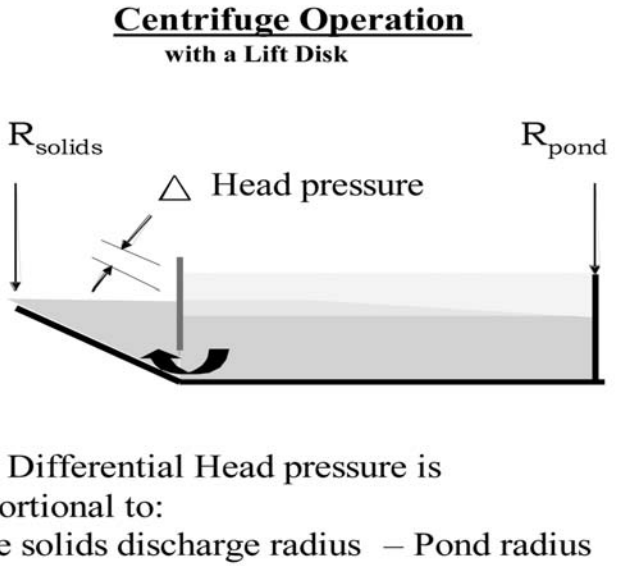


FIGURE 29.15 Centrifuge diagram showing ΔH.

In a gravity thickener, the underflow pumping rate controls the depth of the blanket of settled solids. Increasing the pumping rate reduces the solids blanket, resulting in thinner underflow. This is the same as with the centrifuge. Increasing the rate at which solids leave the centrifuges reduces the thickness of the cake. With most thickening centrifuges, the solids discharge rate (underflow pumping rate) is a function of

$$Cake\ rate = \Delta RPM + \Delta H \tag{29.7}$$

where

ΔRPM = the difference in speed between the bowl and the conveyor and
ΔH = the difference in radius between the pond weir and the solids discharge weir.

For many centrifuges, operators periodically change the dam plates so that the differential revolutions per minute stays in mid-range (i.e., between 10 and 15 rpm). This ensures that the thickened cake can be adjusted upwards and downwards as necessary. All centrifuges control the cake rate by changing either the differential revolutions per minute, the differential head, or, for greatest flexibility, both. One centrifuge manufac-



FIGURE 29.16 Complete skid-mounted centrifuge system.

turer has perfected a dam that can be adjusted while the centrifuge is operating. This gives operators maximum flexibility to optimize performance.

Some centrifuges can thicken homogeneous sludges without polymer flocculents. Because the particles of a homogeneous sludge are all of the same composition, they have the same density and, more or less, the same particle size. The centrifuge can then treat the thickening process as a liquid/liquid separation.

Plants that have primary clarifiers followed by secondary aeration generate a WAS that is the principle example of a homogeneous sludge. The primary clarifiers remove the larger and heavier particles, and the cines and colloidal solids going to the aeration are all of a similar density. Even though the centrifuge can thicken these sludges without polymer, adding polymers increases the floc size and, therefore, the capacity of the centrifuge. The savings in buying and operating fewer centrifuges usually outweigh the cost of the polymer.

If the sludges are blends of primary solids and biological solids, they are, by definition, not homogeneous. Primary solids are denser than WAS, which means that either the capture will be poor or polymers are needed to bind the disparate bits of sludge into flocs.

Design Criteria. Centrifuges come in two general design versions: dewatering centrifuges that can also thicken sludges and thickening centrifuges that may or may not be able to dewater sludges.

Dewatering Centrifuges that Will also Thicken. The centrifuge is very useful if the plant intends to thicken sludges prior to hauling as a liquid some of the time and dewater the sludge for an alternate disposal method at other times. It costs very little to design in such versatility and the centrifuge does either at no extra cost; as such, the only added expense is a method to get thickened sludge to a storage tank or hauling vehicle (Figure 29.16). Just as the centrifuge can dewater all of the sludges generated in the plant, it can also thicken all of the sludges. Dewatering centrifuges often operate in torque control mode (sometimes called *load control* mode) when dewatering sludge. The benefit of dewatering in the torque control mode is that cake dryness is more or less proportional to the torque. With torque control, cake dryness is constant. Unfortunately, thickened sludges generate very little torque; as such, torque control does not work when thickening sludges. Thickening centrifuges normally operate in differential control mode (or in pond control mode).

Automation. There are two ways to automatically control the thickened cake, either of which uses an instrument to measure the suspended solids or the viscosity of the thickened cake. Generally, the downstream processes such as anaerobic digestion or liquid injection of the biosolids are dependant on viscosity; as such, viscosity is the more useful parameter. Figure 29.17 presents a chart of cake viscosity versus solids. Below 4 to 5%, viscosity does not change much with cake solids and control in this area is more difficult. Above 5%, the curve becomes quite steep, which gives very stable control. Alternately, there are suitable suspended solids meters that can measure the suspended solids. Whatever the method, the instrument output changes either the ΔH (pond setting) or ΔRPM to maintain the setpoint.

Specialized Centrifuges for Thickening. Centrifuge designs are driven by cost. The least costly change is to reduce the solids discharge diameter, thereby increasing the pool depth. Initially, this was done for thickening centrifuges, but now it is common for dewatering centrifuges as well. Reducing the solids diameter reduces power consumption while, at the same time, the larger volume increases the residence time in the centrifuge. Both benefits make for a more efficient centrifuge. Additionally, because thickened sludge results in very little drag on the conveyor, the back-drive device (electric gear box or hydraulic) can be smaller and, therefore, less expensive. Some centrifuges have internal vanes or inclined plates that enhance thickening. Because thickened sludges are soft, plugging the vanes is not much of a problem; however, their sus-

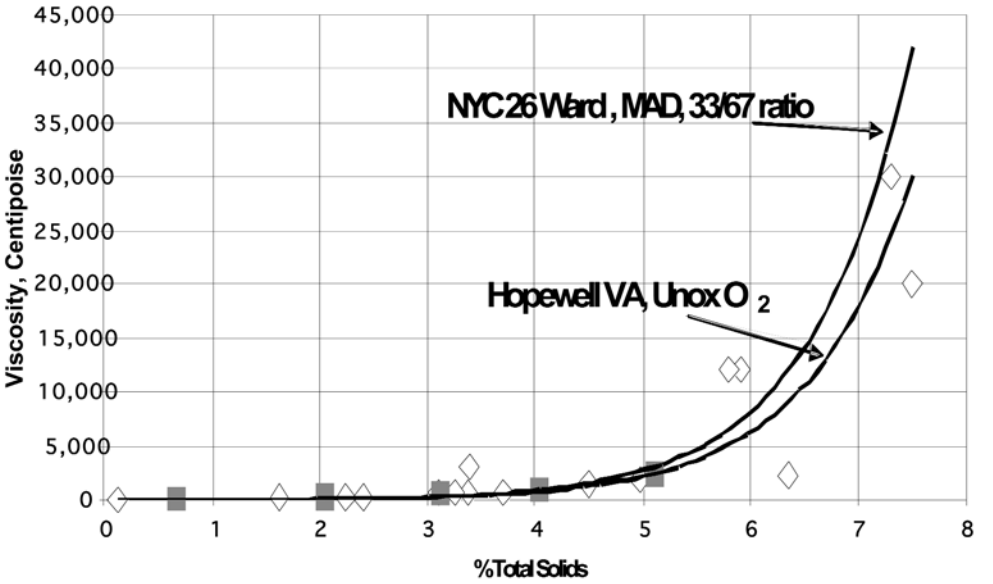


FIGURE 29.17 Viscosity versus concentration of thickened sludge.

ceptibility to plugging also prevents the use of this type of centrifuge for dewatering. Centrifuges designed just for thickening are more often chosen for larger installations where centrifuges are also used for dewatering. Although equipment selection is based on economic analysis, one noneconomic reason to favor centrifuge thickening is that the operation and maintenance procedures are the same for thickening and dewatering centrifuges and using the same device for both applications simplifies operations.

EQUIPMENT DESCRIPTION. As with other decanter centrifuges, the stationary feed tube carries the feed material into the centrifuge, depositing it at one end of the cylindrical bowl or the other. The screw conveyor, or scroll, acts as a rake to move the solids toward the solids discharge, up the inclined beach, and out of the centrifuge. The centrate flows across the surface of the pond toward the dams, or weirs, in the liquid hub.

As with dewatering centrifuges, it is a good idea to have several polymer addition points on the centrifuge. Unlike dewatering centrifuges, relatively little polymer is needed to achieve good performance. The polymer is most commonly added as close to the centrifuge as possible. Some designs, such as those depicted in Figure 29.18,

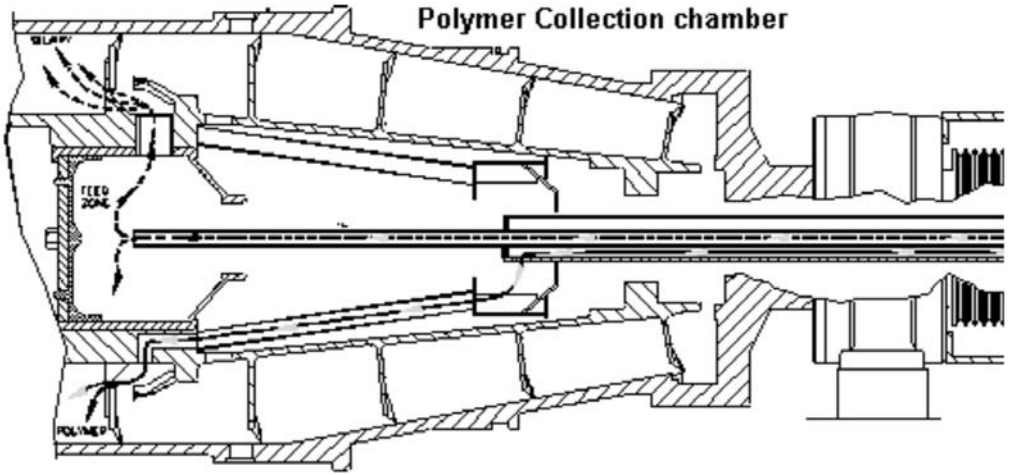


FIGURE 29.18 Internal polymer addition (courtesy of Alfa Laval, Inc., Richmond, Virginia).

have an internal polymer feature where the feed tube has an annular space between the inner and outer tube. The polymer enters what looks like a tee, but in fact flows down the annular space and ultimately mixes with the sludge after it is accelerated up to bowl speed. A poor man's version is to fit a hose down the feed tube so that when the polymer is pumped into the centrifuge it first mixes with the sludge in the feed zone.

PERFORMANCE. It is difficult to honestly describe performance, as it is coupled to the sludge properties, centrifuge design, and plant operation. Generally, thickening centrifuges requires less polymer than is required to dewater the same sludge, and there are numerous installations where little or no polymer is used. Because centrifuge performance is a continuum from about 4% up to 25 to 30% solids, the centrifuge is unique in that it can produce whatever an operator needs.

PROCESS CONTROL. ***Feed Characteristics.*** All process devices benefit from a constant feed quality, and centrifuges are no exception. Common problems are varying rations of primary to secondary solids or feed material that has become septic. For very complicated reasons, septic sludge is more difficult to thicken than fresh sludge. Holding feed material in storage tanks under uncontrolled conditions is poor practice. When in doubt, measure the pH drop through the tankage.

Hydraulic Loading Rate. Centrifuges are available to process feed rates from 6 to 340 m^3/h (25 to 1500 gpm). Although there is no intrinsic lower limit to how thin the feed can be, very viscous feedstocks are difficult to thicken, probably because the polymer does not mix well with viscous sludge.

It is also worth noting that changes in the feed rate will change the crest height over the dams and, thus, the differential head pressure. As a result, a modest change in feed rate may cause an abrupt change in process performance. It is common to run thickening centrifuges at a constant rate, and to add or drop centrifuges offline as needed to keep up with plant production. If the feed rate does change, then it is likely that the pond will have to be changed as well.

Bowl Speed. The manufacturer generally sets the bowl speed and it is rarely changed thereafter. Assuming the present speed was the correct speed several years ago is not proof that it is the best speed now. The owner should adjust the speed periodically, if only to confirm that it is correct and to remind operators that it is, indeed, a variable. It is good policy to consult the manufacturer before the bowl speed is changed.

Pond Depth (Weir Adjustment). Thickening centrifuges react to very small changes in pond height. A fair size change in a pond is 1.5 mm (1/16 in.). The goal is to set the pond so that good operation occurs with the differential revolutions per minute somewhere in its mid-range. If the differential revolutions per minute is ±5 rpm, then the pond should be reduced slightly to bring the differential revolutions per minute up to 9 to 15 rpm. Changing the feed rate substantially will require a change in pond setting. For example, increasing the feed rate will increase ΔH, which, in turn, will thin out the thickened cake. If reducing the differential revolutions per minute does not correct the problem, then the pond will have to be reduced to reduce the differential head pressure. There is one commercial design available to allow the operator to change the pond setting while the centrifuge is online. Westfalia Separator (Oelde, Germany) has a patented device called Vari-pond™. The principle is simple: Three screw motors push a nonrotating plate against the liquid discharge. As the plate nears the rotating centrifuge, the diminishing gap restricts the flow of centrate, much as restricting any weir causes the liquid level behind the weir to rise. While pond and differential revolutions per minute are, to some extent, interchangeable, in fact, changing the pond causes an immediate reaction, whereas changing the differential revolutions per minute results in a slow change in process.

Polymer Dose. Using polymer, the centrifuge can achieve very good capture of solids, which reduces the recycle of solids within the plant. It is often difficult to put a cost on recycle, but a reasonable figure is what the plant charges an industrial customer for sending suspended solids to the plant. Increasing the polymer dosage increases both

the capture and the cake solids. To maintain a particular cake solids, the differential revolutions per minute or the pond must be increased at the same time. Experienced operators can change the dosage and the differential at the same time, but less experienced operators will have to go back and forth to balance everything out. As a result, it is difficult to have automatic polymer control without also having automatic cake thickness control.

START-UP. Basic start-up sequence is more or less the same as for dewatering centrifuges. Most modern centrifuges have a one-button start. Manual systems take a few minutes, but are not onerous. When the centrifuge is up to speed, the controls unlock the feed and polymer pumps, and the operator begins to put the centrifuge online. The start-up sequence is as follows:

- Turn on the feed and polymer to about one-third of the normal rate.
- Reduce the differential revolutions per minute and/or pond to minimum.
- When the cake thickness reaches normal, begin increasing the differential and the polymer feed rate. Some plants can jump directly to the normal operating conditions as soon as the cake is sealed, while others have to ramp up more slowly.

SHUTDOWN. The basic shutdown sequence is similar to that of dewatering centrifuges. Again, modern centrifuges have a one-button stop. The shutdown sequence is as follows:

- Shut off the feed and polymer and turn the flushing water on.
- When clear water exits both ends of the centrifuge, push the centrifuge stop button.
- At some point, as the centrifuge slows down, flush water will come around the feed tube or around the casing seals. Note how long it took between engaging the stop button and the water gushing out. Next time, shut the water off a minute or two sooner.
- With the flush water off, the centrifuge can usually coast to a stop without operator intervention.

SAMPLING AND TESTING. Sampling and testing should include TSS and/or total solids for the feed, total solids for thickened sludge, and TSS, ammonia, and/or phosphorus (under some conditions) for centrate.

TROUBLESHOOTING, PREVENTIVE MAINTENANCE, AND SAFETY. There are no problems or procedures inherent to centrifuges placed in thickening applications that are different for dewatering applications. Please see sections on dewatering centrifuges in this manual for these topics.

ROTARY DRUM THICKENING

DESCRIPTION OF PROCESS. Rotary drum thickeners use rotating drums of varying sizes to capture solids with wedge wires, perforated holes, stainless steel fabric, or a combination of stainless steel and synthetic fabric. The drum has either a center shaft mounted on a steel frame or four trunnion wheels supporting its outside perimeter. A variable-speed drive unit rotates the drum at approximately 5 to 20 rpm.

Conditioned sludge enters the drum and free water (filtrate) drains through the openings into a trough underdrain. A continuous internal screw or diverted angle flights convey sludge along the drum length to the exit through the discharge chute. Wash water, periodically applied to the inside and outside of the drum, cleans solids from the screen openings. This periodic washing helps maintain high solids capture and dewatering efficiency.

DESCRIPTION OF EQUIPMENT. A rotary drum thickener, shown in Figure 29.19, Figure 29.20, and Figure 29.21, consists of an internally fed rotary drum with an internal screw, lubricated trunnion wheels, a variable- or constant-speed drive, an inlet pipe, a filtrate collection trough, a discharge chute, and an optional drum cleaning rotating brush. Figure 29.21 shows the wash water system, while Figure 29.20 shows the gear box and drive assembly.

Auxiliary equipment includes sludge feed pumps—either thickened sludge pumps or a conveyor belt—and a polymer mixing and feed system.

START-UP. Ensure that all guards and covers are properly secured on the machine and that lockout/tagout is not in place. The following sequences apply to starting up the equipment after a relatively short shutdown period:

- Inspect the unit and ensure that all of the guards and screen wash covers are in their proper place. Visually inspect the interior of the screen(s) from the discharge side without touching the equipment or getting close to any rotating assembly. Look for tools, dried sludge, or other foreign objects in the screen of influent troughs.

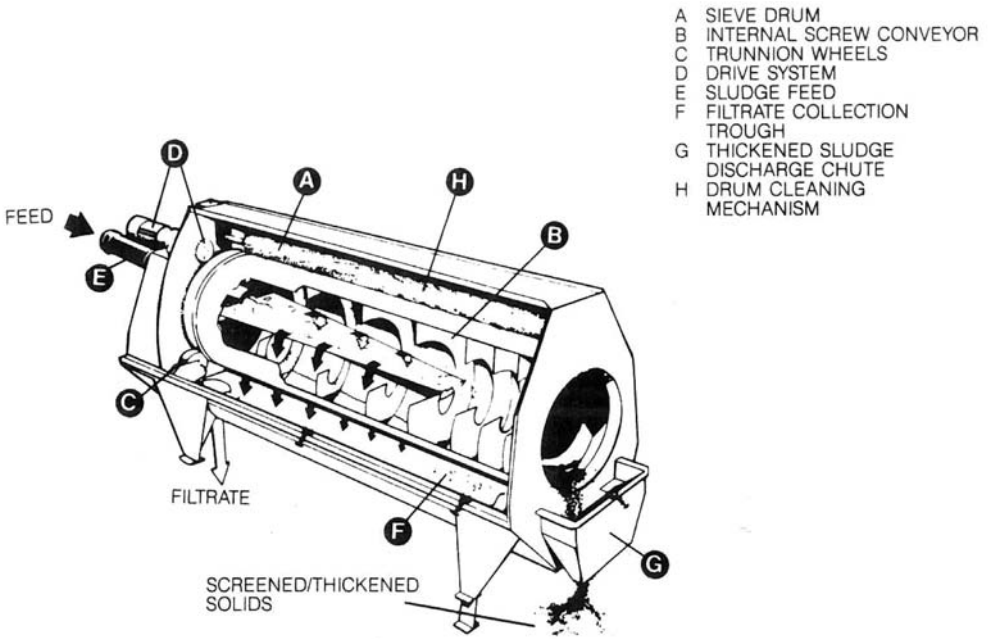


FIGURE 29.19 Drum screen thickener.

- Visually check the chain oilers and ensure that lubricant is present.
- Ensure that the floc or mixing chamber drain is open (back to the head end of plant).
- Start the spray washes.
- Start the drum rotation.
- Start the polymer pump and the dilution system after ensuring that a fresh polymer batch is prepared.
- Immediately after polymer flow begins to enter the floc tank, start the sludge flow. Operate both at 25% of normal flow until stable.
- As soon as sludge flow starts entering the floc tank, close the drain and start the mixer, if applicable. (Most floc tanks do not have mechanical mixers; they have static mixers.)
- Observe and adjust polymer and sludge flow as necessary to achieve desired results. Ramp the flowrate upward until you achieve desired results.
- Adjust drum speed as necessary.

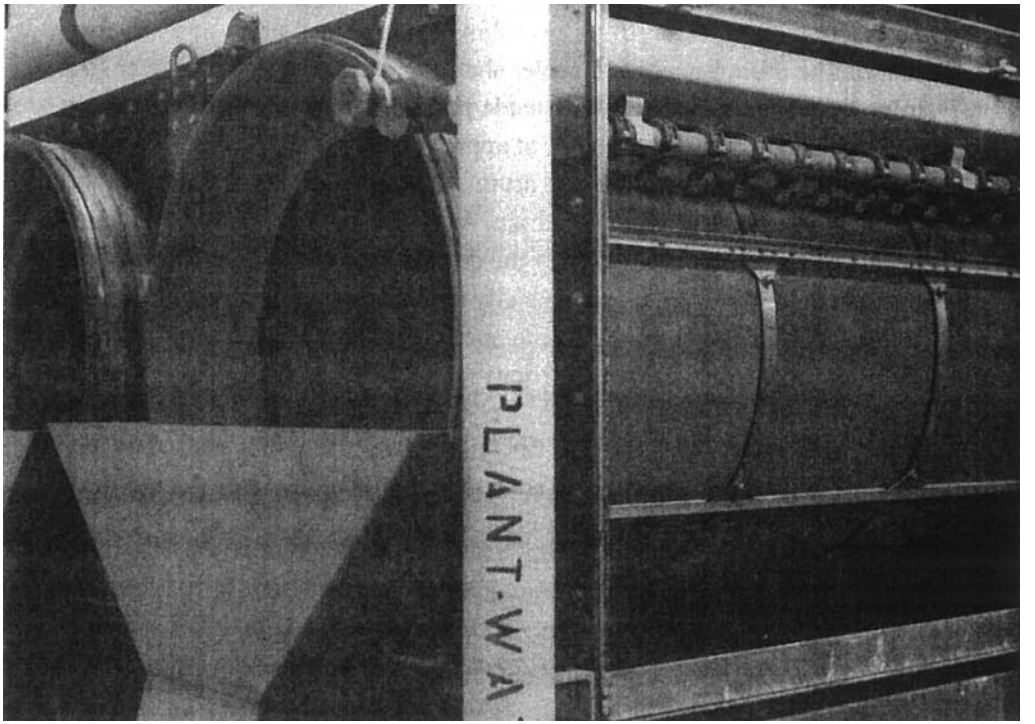


FIGURE 29.20 Rotary drum thickener (side panel removed).

SHUTDOWN. The procedures described herein should be followed for a typical shutdown. It is important to note that the units can easily be stopped on an emergency basis and cleaned soon thereafter. Shutdown procedures are as follows:

- Shut off the sludge and polymer flow.
- Flush the sludge feed piping with nonpotable plant water and allow the polymer dilution water to continue for several minutes until flushed of polymer.
- Stop the flushing water and polymer dilution water when the screens are clear of any thickened sludge.
- Stop the flushing water and open the drain on the flocculation tanks.
- You may need to use a hose to flush down the inside of the screen from the effluent end. Be careful to stand clear of the rotating equipment.
- After the screens are clear, shut down the spray water, drum drive, and all other power to the equipment. Secure all valves to ensure that no sludge or polymers are continuing to drain the WWTP.

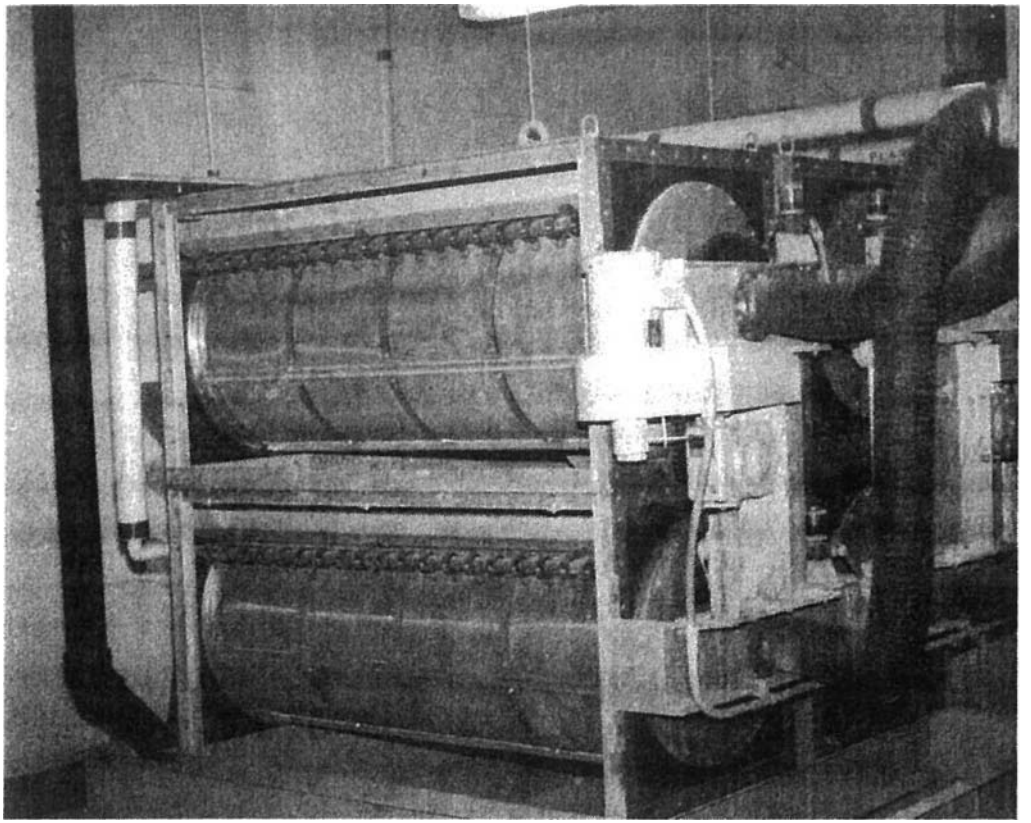


FIGURE 29.21 Rotary drum thickener (side panel removed).

PROCESS CONTROL. The operator may use four variables—sludge feed rate, polymer feed rate, pond depth, and drum speed—to optimize the thickening operation. Each of these variables is discussed here.

Sludge Feed Rate. Sludge feed rate, the wasting rate for the waste stream, varies from day to day. The operator determines the wasting rate each day and sets the feed system to achieve the desired results.

Polymer Feed Rate. This rate depends on the sludge feed rate and on the concentration, volatility, and settleability of the influent. Expressed as pounds of polymer per pound of dry solids, the required polymer feed rate increases as the volatile solids and the SVI increase.

Pond Depth. The incline angle of the drum controls the pond depth. The angle can be adjusted from horizontal to approximately 6 degrees above the horizontal. Increasing the angle results in a drier solids product, but also reduces the drum capacity. Decreasing the angle increases the system throughput capacity, but results in a wetter solids product. The appropriate incline angle for specific applications depends on determinations on-site. A typical starting angle for new installations ranges between 2 and 3 degrees above the horizontal.

The operator can vary drum speed in response to increasing or decreasing feed concentrations to maintain the required product thickness. The subsequent troubleshooting guide indicates how drum speed should change in response to various operational problems.

SAMPLING. At a minimum, a rotary drum thickener should be sampled and analyzed as follows:

- Sample influent for total solids and flow.
- Sample filtrate for TSS and flow.
- Sample thickened sludge for total solids and flow.
- If applicable, determine the total solids of the polymer or whatever quality assurance tests you deem necessary. Measure flow and quantity used (liquid or solid).
- Sample MLSS for SVI. Although this test is not directly with the rotary drum thickener, the SVI of the MLSS ("settling health") has a direct effect on centrifuge performance. The higher or poorer the SVI, the poorer the performance.

TROUBLESHOOTING. Table 29.13 presents a troubleshooting guide that identifies problems and presents possible solutions.

PERFORMANCE. Typical expected performance ranges are presented in Table 29.14. Table 29.15 shows typical hydraulic flow ranges for rotary drum thickeners. Performance data for rotary drum thickeners operating in the United States are contained in Table 29.16.

In each of the WWTPs, the operators advised that someone attend to the drum thickener whenever it was operating. This allows continual adjustment of the unit to handle fluctuating influent characteristics, thereby maintaining best performance. Such attention could require the addition of up to five full-time employees if the thickener operates on a 24-hour-per-day basis. Because all of the installations in Table 29.16 are fairly new, future operations may involve less time for thickener adjustment

TABLE 29.13 Troubleshooting guide for rotary drum thickeners.

Problem	Probable cause	Solutions
No floc formation in mixing tank	Not enough polymer	Increase polymer dosage or decrease sludge throughput
	Old nonactive polymer	Make up a new batch
	Wrong polymer	Complete a bench polymer selection test
	Reaction time of polymer and sludge too short	Inject polymer farther upstream before sludge pump
	Too much polymer	Increase sludge throughput and decrease polymer
Good floc formation in mixing tank but slurry exits sloppily	Drum clogged	Open wash water valve
		Turn on booster pump
		Clean wash water and brush cleaning system
	Sludge throughput too high	Decrease sludge throughput
		Increase rpm of drum
Filtrate dirty	Floc unstable	Increase or decrease polymer
		Move polymer injection point closer or into the mixing tank
	Floc too small	Same as above
		Decrease mixer speed
	Too much turbulence in drum	Sludge throughput too high
		Decrease drum speed
Sludge spills out inlet of drum	Drum rotation too slow	Increase drum rotation
	Sludge throughput too high	Decrease sludge throughput
	Dewater screens are blinded	Clean wash water system
		Adjust frequency of washing cycle

after more experience is gained in judging thickener reaction to changing influent characteristics.

PREVENTIVE MAINTENANCE. Maintenance items or considerations are as follows:

- Daily:
  - Check the drive units for overheating, unusual noise, or excessive vibration; and
  - Check for unusual conditions, such as loose screens or side covers;

TABLE 29.14 Typical rotary drum thickener performance ranges.

Type of sludge	Feed, % TS[a]	Water removed, %	Thickened sludge, %	Solids recovery, %
Primary	3.0–6.0	40–75	7–9	93–98
WAS[b]	0.5–1.0	70–90	4–9	93–99
Primary and WAS	2.0–4.0	50	5–9	93–98
Aerobically digested	0.8–2.0	70–80	4–6	90–98
Anaerobically digested	2.5–5.0	50	5–9	90–98
Paper fibers	4.0–8.0	50–60	9–15	87–99

[a]Total solids.
[b]Waste activated sludge.

TABLE 29.15 Typical flow ranges for rotary drum thickeners.

Drum diameter, m	Hydraulic loading range,[a] gpm[b]
0.6	35–90
1.5	180–240

[a]Assumes a 1% feed concentration of municipal sludge. It is important to note that variations in feed concentrations, polymer dosage, differential speed, and pond depth will act to increase or decrease the hydraulic loading rates for any given machine.
[b]gpm $\times$ (6.308×10^{-5}) = m^3/s.

TABLE 29.16 Rotary drum thickener performance data.

Drum size, m	Influent flowrate, gpm[a]	Influent solids concentration, %	Effluent solids concentration, %	Polymer costs, $/dry ton[b]
0.6[c]	Average = 42 Range = NA	Average = 1 Range = 1–2	Average = 6 Range = 5.5–6	Range = 11–12
1.5[d]	Average = 240 Range = 130–300	Average = 0.9 Range = 0.001–1.5	Average = 5.5 Range = 4–9	Range = 17–18

[a]gpm $\times$ (6.308×10^{-5}) = m^3/s.
[b]ton $\times$ 1.016 = Mg.
[c]Information based on one unit of this size that has since been taken out-of-service due to a change in plant operation.
[d]Informattion based on four units currenttly in operation.

- Weekly:
  - Flush drum screen,
  - Lubricate,
  - Check flush nozzles (clear as required), and
  - Check oil levels;
- Monthly:
  - Check brush,
  - Check reduction motor's oil level,
  - Check level in lubrication unit's grease tank,
  - Check screen casing, and
  - Check drive system; and
- Semiannually:
  - Check all connections and
  - Check brush bearings.

SAFETY. As with any process for handling sludge, hydrogen sulfide may be present with attendant odors and toxic effects. Safety precautions must be followed for proper ventilation, monitoring, and other procedures, as discussed in Chapter 5. The following general safety procedures may apply to the operation and maintenance of rotating thickeners:

- All lubrication and maintenance must be done while equipment is not in operation to prevent accidental start-up. Lockout is a method of keeping equipment from being set in motion and endangering workers. The *Code of Federal Regulations* (1991) 29 *CFR* Part 1910.147 covers the servicing and maintenance of machines and equipment in which the unexpected power-up or start-up of the equipment, or release of stored energy, could cause injury to employees. Tagout occurs when the energy isolation device is placed in a safe condition and a written warning is attached to it. Typically, the employee signs and dates the tag. Removal of the tag and lockout device is done by the same individual when the equipment is safe for restart.
- Sludge and polymers are extremely slippery when spilled; therefore, all spills must be cleaned immediately. Installation of a grated, elevated walkway can alleviate slippery conditions around polymer tanks.
- Adequate ventilation and gas testing should be provided when processing sludge.
- Consideration can be given to the addition of potassium permanganate or peroxide to the feed sludge if hydrogen sulfide (odor) levels are high.

- Never insert fingers, arms, or feet into the unit until lockout/tagout is complete and the unit is secured for maintenance.
- Be especially careful of pinch-points such as sprockets and chains on roller casters. Severe injury may occur if a finger or hand is caught in rotating equipment.
- Do not wear jewelry or loose or bulky clothing near the machine.
- Do not insert items such as tools, samplers, or probes into the drum unless lockout/tagout is complete and the unit is secure for maintenance.

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Chapter 30

Anaerobic Digestion

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PROCESS OVERVIEW

GENERAL THEORY. Anaerobic digestion is a multistage biochemical process that can stabilize many different types of organic material. Digestion occurs in three basic stages (Zehnder, 1978). In the first stage, extracellular enzymes (enzymes operating outside the cells) break down solid complex organic compounds, cellulose, proteins, lignins, and lipids into soluble (liquid) organic fatty acids, alcohols, carbon dioxide, and ammonia. Complex organic materials in the digester feed include primary solids, microbes grown in the aerobic stages of the liquid treatment process, and colloidal material. In the second stage, microorganisms (often referred to as *acetogenic bacteria* or *acid formers*) convert the products of the first stage into acetic acid, propionic acid, hydrogen, carbon dioxide, and other low-molecular-weight organic acids. In the third stage, two groups of methane-forming bacteria work—one group to convert hydrogen and carbon dioxide to methane and the other group to convert acetate to methane and bicarbonate (carbon dioxide in solution). Because both groups of bacteria are anaerobic, the digesters are sealed to exclude oxygen from the process. The three stages are summarized schematically in Figure 30.1.

In most cases, methane-forming bacteria control the process. Methane formers are very sensitive to environmental factors (high ammonia concentrations, low phosphorus concentrations, low pH, temperature, and the presence of toxic substances), and reproduce very slowly. Consequently, methane formers are difficult to grow and are easily inhibited. Therefore, process design and the operation of conventional anaerobic digestion are tailored to satisfy the needs of the methane-forming bacteria.

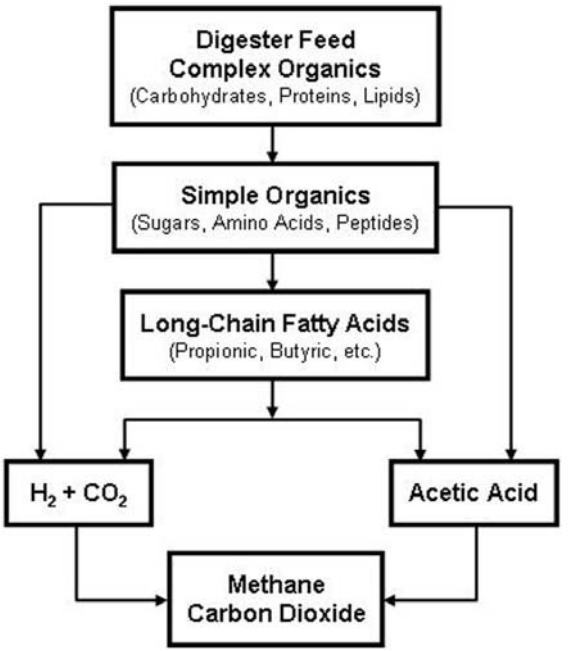


FIGURE 30.1 Biochemical processes in anaerobic digestion.

CONVENTIONAL MESOPHILIC DIGESTION. The majority of anaerobic digestion systems currently in use are configured as conventional mesophilic digesters. In these systems, all stages of the biochemical process occur in the same vessel and are operated at mesophilic temperatures [32 to 38 °C (90 to 100 °F)]. Conventional systems can be categorized as low-rate (no mixing) or high-rate processes, which include mixing and heating. The heating and mixing used in the high-rate processes produce uniform conditions throughout the tank, which results in shorter detention time and more stable conditions than low-rate processes. Consequently, most municipal digestion systems use the high-rate process.

Anaerobic digestion stabilizes solids by reducing the mass of volatile solids (VS), typically by 40 to 60%. Volatile solids reduction (VSR) can be calculated based on the mass of volatile solids in the feed and digester discharge using Equation 30.1.

$$\text{VSR, percent} = \left(\frac{\text{VS}_{\text{feed}} - \text{VS}_{\text{digested sludge}}}{\text{VS}_{\text{feed}}} \right) \times 100 \qquad (30.1)$$

Several methods of calculating VSR are presented and discussed in the U.S. Environmental Protection Agency (U.S. EPA) publication, *Control of Pathogens and Vector Attraction in Sewage Sludge* (U.S. EPA, 1999). These include the Approximate Mass Balance (AMB) method and the Van Kleeck equation. The AMB method assumes that the daily flows to the digester are steady and uniform in composition. It can be calculated using Equation 30.2:

$$\text{VSR, percent} = \left[\frac{(Q_{feed} \times VS_{feed}) - (Q_{digested\ sludge} \times VS_{digested\ sludge})}{Q_{feed} \times VS_{feed}}\right] \times 100 \qquad (30.2)$$

where

Q_{feed} = Volumetric flowrate of the feed sludge,
$Q_{digested\ sludge}$ = Volumetric flowrate of the digested sludge,
VS_{feed} = Volatile solids concentration of the feed sludge, and
$VS_{digested\ sludge}$ = Volatile solids concentration of the digested sludge.

The Van Kleeck method can be used when the digesters have no significant grit accumulation. It can be calculated using Equation 30.3. With the exception of the calculated VSR, all values in Equation 30.3 represent fractional volatile solids.

$$\text{VSR, percent} = \left[\frac{VS_{feed} - VS_{digested\ sludge}}{VS_{feed} - (VS_{feed} \times VS_{digested\ sludge})}\right] \times 100 \qquad (30.3)$$

Digesters are sized to provide sufficient detention time to allow stabilization. High-rate digesters are typically sized for an average solids retention time (SRT) of 15 to 20 days. Slightly shorter detention times (on the order of 12 days) are often used in European designs. Solids retention time is calculated based on the mass of solids in the digester and the mass of digested sludge removed daily. Hydraulic retention time (HRT) is calculated based on the volume of the digester and the volume of digested sludge removed daily. For systems that do not practice decanting, digester SRT and HRT are the same.

ADVANCED DIGESTION PROCESSES. Advanced digestion processes involve modifications to the conventional digestion configuration to achieve more complete digestion, promote pathogen reduction, and improve digester operation. Nearly all advanced digestion processes have reported better VSR than that achieved by conventional mesophilic digestion (Schafer et al., 2002), which increases the content of soluble nutrients (ammonia and phosphorus) in dewatering recycle streams and, thus, can increase the nutrient loads to the wastewater treatment system.

Acid/Gas Digestion. Acid/gas digestion, or two-phase digestion, is carried out in a two-reactor system to provide separate environments for the acid-forming and methane-forming bacteria so each can be optimized for the specific process. In the first phase, the feed substrates are hydrolyzed to produce volatile fatty acids (VFAs), which are converted to methane and carbon dioxide in the second phase. The acid phase is typically limited to an SRT of 1.5 to 2 days; the gas phase requires a minimum SRT of 10 to 15 days. Acid/gas systems have been used to process "difficult-to-digest" solids—including all waste activated sludge (WAS) or mostly WAS feed solids—without significant foaming.

Thermophilic Digestion. Thermophilic digestion processes include one or more stages that are operated at thermophilic temperatures [55 °C (131 °F) or higher]. The main goal of thermophilic treatment is to achieve greater pathogen destruction; however, it can also increase volatile solids destruction and decrease required detention times. Thermophilic digestion can affect the odor characteristics of the digested sludge, thereby increasing the odor potential during dewatering and cake loading. Thermophilic digestion may also affect the dewaterability of the digested sludge; however, the reported results vary. Some installations report using higher polymer dosages with thermophilic digestion, while others have reduced polymer use and increased cake solids (Haug et al., 2002). Because heating to thermophilic temperatures requires significantly more energy than needed for mesophilic digestion, heat recovery is an important step in thermophilic digestion. With the aid of heat exchangers, heat discharged from the thermophilic digester can be used to preheat the digester feed.

MULTISTAGE DIGESTION. Multistage digestion includes various combinations of mesophilic and thermophilic treatment. Temperature-phased anaerobic digestion (TPAD) consists of at least one thermophilic stage followed by a mesophilic "polishing" stage. The objective of TPAD is to take advantage of thermophilic treatment (increased pathogen destruction and increased VSR), while including a mesophilic stage to alleviate the odor and dewaterability concerns associated with high-temperature digestion. Some multistage digestion processes also include acid/gas treatment, using the thermophilic stage with either the acid or gas phase. Several of these processes are offered as proprietary systems, including 2PAD™ by Infilco Degremont, Inc. (Richmond, Virginia) and Enzymic Hydrolysis by Monsal (United Kingdom).

PRETREATMENT PROCESSES FOR DIGESTION. Pretreatment is an "add on" to conventional anaerobic digestion, with the objective of improving digester performance, VSR, and pathogen destruction and reducing foaming potential. Treatment

typically includes application of energy in the form of ultrasound, heat, pressure, or a combination of these. A number of the pretreatment processes are proprietary.

Ultrasound Treatment. Ultrasound treatment (sonication) is used to condition WAS prior to digestion, with the goal of improving digestion and VSR and decreasing digester foaming. Ultrasound is applied to WAS by a series of probes installed in a flow-through vessel. The resulting ultrasonic waves cause cavitation, generating microbubbles that collapse and release energy. The released energy can destroy the cell structure of the microbes in the WAS. Sonication can be used to treat the entire WAS flow or only a portion of it.

Thermal Hydrolysis. Thermal hydrolysis is used to increase pathogen kill and to condition the solids for better digestion by heating raw solids under pressure for a short period. Thermal pretreatment improves the dewaterability of the digested solids by releasing the water bound in the bacterial cells. Thermal hydrolysis processes are mechanically complex and produce offgases that are a significant source of odors. Thermal hydrolysis processes are designed for temperatures of 150 to 220 °C (302 to 428 °F) and pressures of approximately 1380 kPa (200 psi). Reaction times vary from 20 to 30 minutes. A number of thermal hydrolysis processes are available that, depending on the system, can be used on thickened or dewatered sludge.

Thermal hydrolysis processes typically include preheating sludge through a heat exchanger before it enters the reaction tank. Steam is added to the reaction tank to maintain temperature and increase pressure. On completion of the batch reaction, the solids are depressurized and pumped through heat exchangers to lower their temperature prior to mesophilic digestion. A schematic of one type of thermal hydrolysis process, the Cambi® (Norway) system, is presented in Figure 30.2.

Wet air oxidation is a type of thermal hydrolysis in which oxygen (in the form of air or pure oxygen) is added to solids prior to heating and reacting. Wet air oxidation is available via several proprietary processes, including Zimpro® by Siemens (Warrendale, Pennsylvania).

Pasteurization. Pasteurization involves heating solids to a temperature of 70 °C (158 °F) or higher (typically for at least 30 minutes in either a batch or continuous plug-flow operating mode) to kill pathogens. It does not necessarily affect the digestibility of the sludge. Multiple heat exchangers are typically used to preheat incoming sludge and capture heat from the treated sludge. The solids concentration of the feed sludge can affect the heat exchanger's ability to reach target temperatures. A number of proprietary pasteurization systems are available, including Alpha-Biotherm, BioPasteur, Roediger™, and Eco-Therm™.

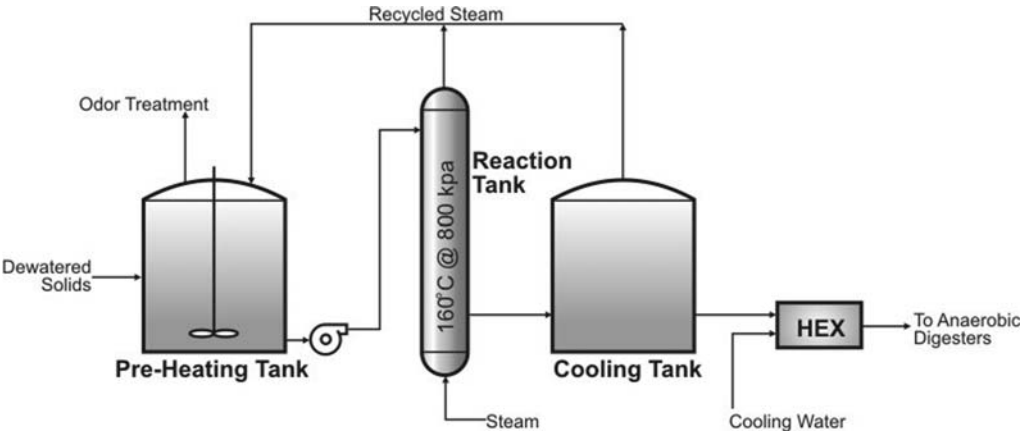


FIGURE 30.2 Thermal hydrolysis process.

Homogenization. Homogenization is used to condition WAS prior to digestion. It is a multistep process that lyses the bacterial cell walls to promote VSR during anaerobic digestion. One such process, offered by MicroSludge™, involves the use of a caustic solution to weaken the cell walls and lower the viscosity of thickened WAS. The treated WAS passes through a screen to remove large debris and enters a high-pressure homogenizer, where it is subjected to a sudden drop in pressure that lyses the cells.

HIGH SOLIDS-CONCENTRATION DIGESTION. Anaerobic digestion is typically used for feed sludge with a total solids concentrations of 3 to 5%. However, it has also been used on feed concentrations of 7 to 8% total solids at a number of facilities, mostly in Europe. The digesters in these facilities are typically equipped with either roof-mounted mechanical mixers or pumped mixing systems with internal nozzles. Digestion of high-solids feed can produce foam; therefore, antifoaming systems are usually included. The Torpey and recuperative thickening processes are types of high- solids digestion in which a portion of the digested sludge is recirculated to a sidestream or upstream thickener.

High solids-concentration digestion can reduce the needed digester volume or effectively increase the capacity of an existing digester. Thickening the feed to 6 or 7% total solids can significantly increase its viscosity, as well as change its mixing characteristics. Pumping and mixing systems designed to support digestion with feed concentrations of 3 to 5% total solids may not support digestion at significantly higher feed concentrations. Consequently, all components of the digestion system should be de-

signed to support a high solids-concentration process. The process also effectively increases the volatile solids loading on the digester and, because high-solids digestion concentrates feed constituents, toxicity effects can be exacerbated.

Regulatory Issues. Land application of biosolids is governed by U.S. EPA's 40 *CFR* Part 503 (U.S. Code of Federal Regulations, 1993). While many of the requirements of this regulation, such as site management and application rates, are outside the scope of the anaerobic digestion process, the requirements pertaining to pathogen and vector attraction reduction can be achieved via digestion.

CLASS A AND CLASS B PATHOGEN REDUCTION. U.S. EPA's 40 *CFR* Part 503 establishes two levels of pathogen reduction requirements: Class A and Class B. The objective of Class A, which is the more stringent requirement, is to reduce the density of *Salmonella* sp. bacteria, enteric viruses, and viable helminth ova to below detectable levels. Biosolids that meet Class A criteria are subject to few restrictions; in most localities, they can be given or sold to the public or directly land-applied by the utility. The regulations identify six alternatives to meet Class A Criteria, each of which requires that the treated biosolids meet either the following fecal-coliform or *Salmonella* sp. density at the time they are used, sold, or given away:

- Fecal coliform—fewer than 1000 most probable number (MPN) per gram of total dry solids and
- *Salmonella* sp.—fewer than 3 MPN per 4 g of total dry solids.

Of the six treatment alternatives, five may be applicable to digestion processes and are described herein; more detailed information is available in *A Plain English Guide to the EPA Part 503 Biosolids Rule* (U.S. EPA, 1994). It should be noted that to meet Class A requirements, pathogen reduction must be achieved before or concurrently with vector attraction reduction.

- *Alternative 1—Thermally Treated Biosolids.* This alternative applies to treatment systems that use heat to reduce pathogens. Several equations are used to determine the required heating time, depending on the treatment temperature and solids concentration.
- *Alternative 2—Biosolids Treated in a High-pH/High-Temperature Process.* This alternative does not apply to anaerobic digestion.
- *Alternative 3—Biosolids Treated in Other Known Processes.* This alternative is used to demonstrate that a new treatment process meets Class A pathogen reduction criteria. It requires monitoring of viruses and helminth ova until it is shown that

the treatment process consistently reduces pathogens to Class A levels. Once the process has been demonstrated to meet Class A requirements, the process parameters must be monitored to show consistent operation.

- *Alternative 4—Biosolids Treated by Unknown Processes.* This alternative differs from Alternative 3 by requiring pathogen testing (enteric viruses and helminth ova) for each batch of biosolids, rather than monitoring the process parameters. This alternative is used in situations where the actual treatment process is unknown or does not fulfill other Class A process requirements.
- *Alternative 5—Biosolids Treated by Processes to Further Reduce Pathogens (PFRP).* This alternative identifies seven PFRP that meet Class A requirements. None specifically apply to anaerobic digestion; however, pasteurization (one of the listed technologies) can be used as predigestion treatment to meet Class A criteria.
- *Alternative 6—Biosolids Treated in a PFRP Equivalent.* This alternative allows permitting authorities determine whether other treatment processes are equivalent to PFRP technologies, either for a specific installation or on a nationwide basis.

Class B requirements establish pathogen limits that are less stringent than Class A limits. Because Class B biosolids are expected to contain significantly higher concentrations of pathogens than Class A biosolids, they cannot be sold or given away and application-site restrictions apply. The following three treatment alternatives meet Class B pathogen criteria:

- *Alternative 1—Monitoring of Indicator Organisms.* The fecal coliform density must be less than 2 million MPN or 2 million colony forming units (CFU) per gram of total solids, based on the geometric mean of seven samples.
- *Alternative 2—Biosolids Treated by Processes to Significantly Reduce Pathogens (PSRP).* This alternative includes five PSRP, of which only one applies to anaerobic digestion. This process requires a minimum mean cell residence time of 15 days in the anaerobic digester at a temperature of 35 to 55 °C (95 to 131 °F).
- *Alternative 3—Biosolids Treated in a PSRP Equivalent.* This alternative allows permitting authorities to determine whether other treatment processes are equivalent to PSRP technologies, either for a specific installation or on a nationwide basis.

VECTOR ATTRACTION REDUCTION REQUIREMENTS. Both Class A and Class B biosolids must meet vector attraction reduction (VAR) requirements. These requirements are intended to reduce the putrescibility of the solids. Highly pu-

trescible solids will tend to attract vectors, such as flies and rodents. There are 11 VAR options for biosolids. The following two options apply to anaerobic digestion:

- *Option 1—Achieve 38% Reduction in Volatile Solids Content.* The VSR can be met through digestion and any additional reduction that occurs before the biosolids leave the treatment plant.
- *Option 2—Additional Digestion of Anaerobically Digested Biosolids.* In cases where the organic material in the feed solids has undergone some stabilization preceding anaerobic digestion, it may be difficult to show an additional 38% VSR. Under this option, a bench-scale anaerobic digester can be used to show compliance with VAR. The biosolids meet the VAR requirement if the VSR is less than 17% during a 40-day bench-scale test at a temperature between 30 and 37 °C (86 and 99 °F).

DIGESTER FACILITIES AND EQUIPMENT

Anaerobic digestion facilities can be constructed using a variety of tank configurations and equipment types.

TANK CONFIGURATION. The most common type of digester currently in use in North America is the cylindrical tank, also known as a "pancake" digester. Cylindrical tanks typically have cone-shaped floors, with slopes of 1:4 to 1:6 to facilitate collection and removal of heavy sludge and grit. Cylindrical digesters, which are typically constructed of concrete, can be equipped with gas-holder covers to provide storage for digester gas. Cylindrical digesters in Europe are often constructed with 1:1 aspect ratios.

Egg-shaped digesters (ESDs) have bottoms with steeper slopes than the cylindrical tanks (typically, slopes that are at least 1:1). They may be constructed of concrete or steel and are available in several variations [Figure 30.3(a) and (b)]. Common features of ESDs include a conical bottom and a domed top. The advantages of ESDs include a reduced potential for grit accumulation because of their steep bottom slopes, a geometry that allows for more efficient mixing and thus reduces energy use, and less potential for scum accumulation owing to the small liquid surface area at the top of the egg-shaped vessel. The disadvantages of ESDs include lack of capacity for gas storage within the tank and a shape that is more difficult to insulate. In addition, their relatively high profile can cause aesthetic concerns in some locations. Egg-shaped digesters are in widespread use in Europe and are gaining popularity in the United



FIGURE 30.3A Egg-shaped digester.



FIGURE 30.3B Egg-shaped digester.

States. While construction costs of ESDs can be significantly higher than those of cylindrical tanks, these costs can be offset by lower operating costs, which are attributable to more efficient mixing and the reduced need for cleaning.

Imhoff tanks are two-chamber digestion vessels consisting of an upper chamber for solids sedimentation and collection and a lower chamber where the settled solids are anaerobically digested. Imhoff tanks are an older technology that is now rarely seen in municipal wastewater treatment applications.

Lagoon digestion systems consist of earthen lagoons fitted with floating membrane covers that are used to contain and collect the digester gas. The lagoons are not heated and are typically not mixed. Because they are not heated, the digestion rate is variable. Consequently, lagoons are designed to provide a long sludge detention time. Lagoons are frequently used in industrial waste applications; their use in municipal wastewater treatment is less common.

SECONDARY DIGESTERS. Most medium-to-large digestion facilities include both primary and secondary digesters. Most of the stabilization and gas production occurs in the primary digester. The digestion system design loading rates and SRT are based on primary tank volume; however, if secondary digesters are heated and mixed, their active volumes can be included when calculating operating loading rates and SRT.

While primary digesters are mixed and heated to optimize digestion and meet pathogen-reduction requirements, secondary digesters may or may not be mixed and heated. Digester-heating systems are often configured to use primary digester heat-exchanger equipment to provide heat to a secondary digester when a primary digester is out of service.

An unheated secondary digester may serve the following purposes: as a storage vessel for digested solids, as a standby primary tank, and as a source of seed sludge. In addition, at installations where the digester is decanted to increase the solids concentration, the secondary digester can be used as a quiescent basin for supernatant withdrawal.

Because an important purpose of secondary digesters is their use as storage vessels, they typically have floating or membrane covers to allow drawdown. The variable storage capacity in the secondary digester is limited by the cover travel. In floating or gas-holder covers, solids withdrawal should cease before the cover rests on the corbels. Further removal will cause a vacuum to develop beneath the cover, which can cause air to be drawn into the digester and create a potentially explosive condition. Membrane covers can allow significantly greater drawdown, depending on the configuration of the installed mixing equipment.

DIGESTER COVERS. Digester covers keep oxygen out of the anaerobic environment in the digester. Covers also prevent digester gas and odors from escaping to the atmosphere, reduce the explosion hazard associated with the methane in the digester gas, and insulate the top of the digester. There are four basic types of digester covers: fixed, floating, gas-holder, and membrane (Figure 30.4). The features of the different types of covers are described in Table 30.1.

Fixed Covers. Fixed covers are available in several types of construction. Reinforced concrete covers may be flat-slab shaped or dome-shaped and may be self-spanning or column-supported with material of varying thicknesses, depending on the design.

Some fixed covers are constructed of steel plates welded to the upper chord of a truss or to an arch-rib supporting framework. The supporting framework is connected to the top of the wall by a sliding arrangement that allows the cover to expand or contract in response to changes in temperature.

Fixed-cover digesters require operator attention during solids addition and withdrawal. If the digester is full, the incoming flow must equal the outgoing flow. Adding solids without withdrawing an equal volume will cause overpressure, which can lift the cover from its wall mountings. Withdrawal of solids without a corresponding

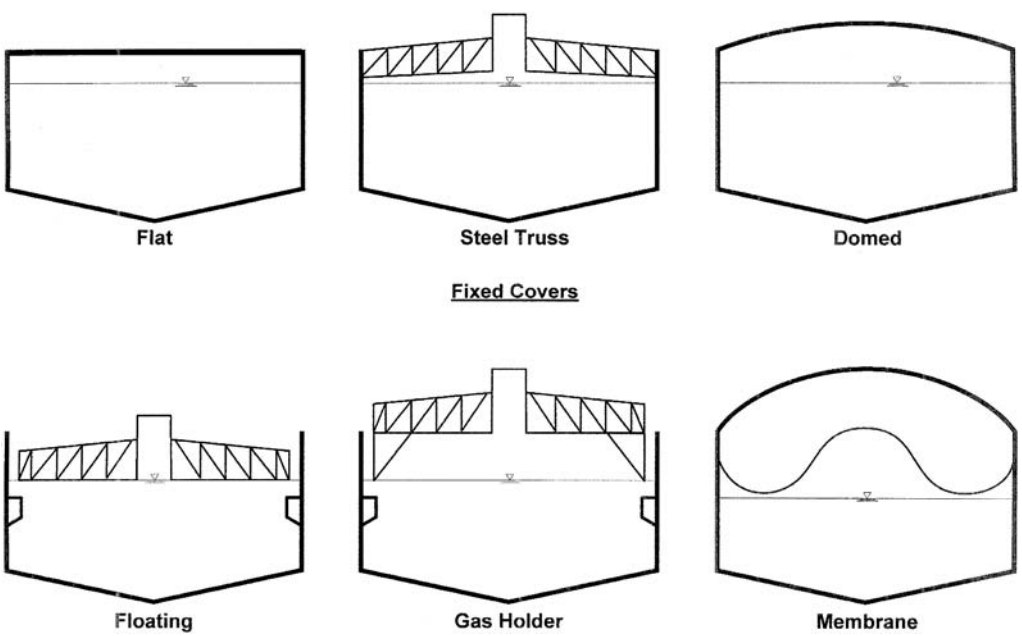


FIGURE 30.4 Digester covers.

TABLE 30.1 Digester cover features.

	Fixed cover	Floating cover	Gas holder cover	Membrane cover
Drawdown capability	Not recommended	Yes	Yes	Yes
Gas storage	No	No	Yes (limited)	Yes
Odor potential	Low	Moderate	Low to moderate	Low
Recommended use	Primary digesters	Primary or secondary digesters	Primary or secondary digesters	Primary or secondary digesters

addition will create a vacuum that can damage the covers or cause them to collapse. Both overpressurization and vacuum conditions can be alleviated by installing safety relief valves; however, even with the relief valves, fixed-cover systems often develop gas leaks at the interface of the cover and the digester wall.

Floating Covers. Floating covers float directly on the liquid surface, supported by a system of roller bearings and guide rails along the digester wall that controls both vertical and lateral movement of the cover and prevents excessive tilting. The guide rail systems are available in vertical or spiral configurations; while vertical systems are less complex, the spiral systems provide more efficient control of the cover's vertical movement. The range of vertical motion of floating covers is typically 1.5 to 3 m (5 to 10 ft), with a corresponding capacity for solids drawdown.

Floating covers offer several advantages over fixed covers, the most important of which is the ability to vary the liquid level in the digester without the danger of over- or underpressurization. Because it rises and descends with the liquid level, a floating cover compensates for the suction created when removing solids, as well as minimizes the possibility of overpressurization during solids addition.

Gas-Holder Covers. Gas holder covers are similar to floating covers; however, they are designed to accommodate gas storage as well as digester drawdown. The gas-holder cover, which floats on digester gas rather than on the liquid surface, is equipped with a skirt that extends below the liquid surface to contain gas. A concrete ballast ring below the skirt stabilizes the cover and helps control gas pressure.

The operator should check the floating cover periodically to ensure that it is level and moves freely. A tilted cover may reflect uneven loading resulting from water accumulation in the attic space, snow buildup, or binding between the wall and the cover skirt. Excessive foaming may also be obvious during the cover inspection.

Membrane Covers. Membrane gas-holder covers provide gas storage and separate the anaerobic digester contents from the atmosphere. A photo of an installed membrane cover is shown in Figure 30.5. The cover consists of an inner membrane and an outer membrane. Both membranes are attached to the tank wall, preventing escape of gas to the atmosphere. The fixed outer membrane is inflated by a blower system. The inner membrane is inflated and deflated in response to the volume of gas in the digester headspace. The inner membrane can typically travel up and down the entire depth of the digester tank, enabling it to be almost completely emptied.

CORROSION PROTECTION. Exposed surfaces of anaerobic digesters are vulnerable to corrosion caused by high concentrations of hydrogen sulfide in digester gas. If the digester is operating at a low pH, carbon dioxide can form carbonic acid, which is also corrosive. Areas affected by corrosion include any surfaces that are not submerged, such as the undersides of the covers, the tank walls above the liquid surface, and the exterior surface of the covers, which are exposed to the atmosphere. If there are any leaks in the cover that allow gas to collect in the attic space, structural elements of

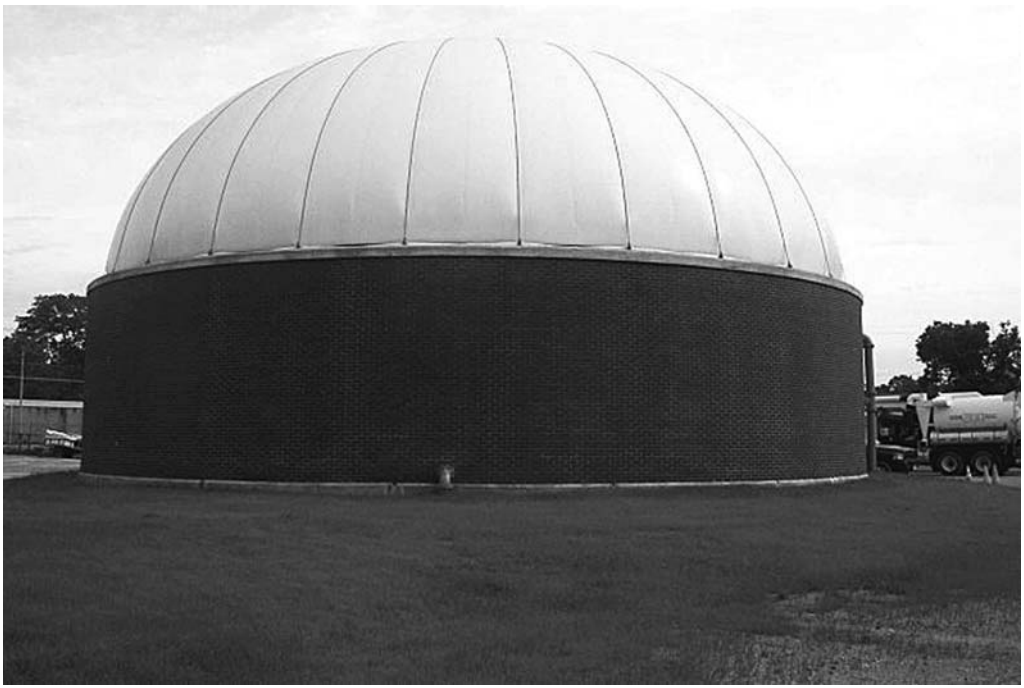


FIGURE 30.5 Membrane cover (courtesy of Siemens Water Technologies).

the cover may also corrode. Corrosion can be minimized by using corrosion-resistant construction materials, protective coatings, and cathodic protection.

The exterior surfaces of covers should be inspected quarterly. Metal covers should be recoated, if necessary, using the type of coating recommended by the cover manufacturer or that described by the engineering specifications. Typically, the cover needs to be recoated every 5 to 10 years, depending on the location and weather conditions. The underside of the cover should be inspected whenever the tank is taken out of service and emptied. Repairs may include power washing, sandblasting, and recoating. Covers that show significant corrosion should be evaluated for structural integrity. Because the attic area of a digester cover can be vulnerable to digester-gas accumulation and corrosion, it should not be entered by plant staff unless proper precautions and safety codes are followed.

ODOR ISSUES. Fixed digester covers are attached directly to the digester tank wall, forming a seal that prevents the escape of digester gas and odors. Floating covers and gas-holder covers are separated from the tank wall by a small gap of approximately 8 cm (3 in.) to accommodate cover movement. The liquid in the digester forms a water seal in this area, minimizing the escape of gas. However, in the event of foaming, foam can interfere with the water seal and digester gas will escape. The most common source of digester gas odors from fixed, floating, or gas-holder covers is the pressure-relief valve. Gas can also escape from deteriorated seals and cause odors at the digester facility. Inspection and proper maintenance of the pressure-relief valves will minimize the escape of digester gas.

Membrane covers are attached directly to the digester wall, which minimizes the escape of gas; however, the gas may seep into the space between the inner and outer membranes. During pressure regulation, air can be discharged from the membrane cover. Moreover, if there are any pinhole leaks or seepage that allow digester gas into this space, the air can contain hydrogen sulfide, volatile organic compounds, and associated odors. Carbon filters can be installed on the air discharge line to remove hydrogen sulfide and minimize odors.

DIGESTER MIXING. ***General Theory.*** Mixing of high-rate digestion systems, along with heating, uniform feed rates, and thickening of feed sludge, is used to provide optimum environmental conditions for the microorganisms that accomplish anaerobic digestion. Effective mixing provides the following benefits:

- Distribution of influent solids throughout the digester;
- Dispersal of influent solids for maximum contact with microorganisms;

- Prevention of thermal stratification;
- Reduction of scum buildup;
- Reduction of the buildup of settled material on the digester floor;
- Dilution of digestion inhibitors, such as toxic material or unfavorable pH or temperature of feed materials; and
- Improved separation of digester gas from digester liquid.

These benefits can be grouped as process stability, scum and foam control, and prevention of solids deposition. To satisfy process requirements, the digester contents must not be subjected to large fluctuations in raw sludge substrate, solids concentration, temperature, and bacterial metabolic end products. Most anaerobic digesters contain scum, which accumulates on the liquid surface starting in locations of low turbulence. While scum accumulation is typically controlled by mixing scum into the digester contents, large-diameter tanks allow it to spread over a larger area, making it more difficult to incorporate. Appropriate configuration of digester mixing equipment can reduce or eliminate scum accumulation. Deposits of grit on the bottom of the anaerobic digester result in the loss of active volume and lead to costly and onerous cleanup procedures requiring extended downtime. Grit accumulation is most often encountered with nearly flat-bottomed conventional digesters. In digesters with sloped bottoms, grit and settleable solids slide down the sides to a single location where they can be either removed, as in the case of grit and heavy solids, or resuspended, as in the case of lighter material. If the grit and solids are allowed to remain in the digester for an extended period, they will concentrate into a solid mass that is difficult, if not impossible, to resuspend or remove through pumping.

UNMIXED DIGESTION. Unmixed digestion, which was the earliest type of anaerobic digestion, takes place in low-rate or standard-rate digesters. Because they provide no auxiliary mixing, the contents of these digesters are stratified, with a scum layer on top of the liquid surface and stabilized biosolids and grit on the digester floor. Because of the relatively small volume available for the digestion process, these digesters are sized for a typical detention time of 30 to 60 days, which is adequate to achieve stabilization under low-rate conditions. Use of low-rate digestion is typically limited to small facilities treating less than 3.8 m^3/h (1.0 mgd) and is uncommon even for such installations.

MIXED DIGESTION. Mixed digestion takes place in high-rate digesters with controlled mixing and heating, uniform feed rates, and thickening of digester feed to provide optimum conditions for the microorganisms. The stable and uniform environ-

ment created by mixing promotes high-rate digestion and allows the use of higher loading rates than low- or standard-rate digestion. Types of mixing systems available for digesters include mechanical and gas mixing systems.

Mechanical Mixing. Mechanical mixing systems include pumped systems and impeller-type mixers.

Pumped Mixing Systems. Pumped mixing systems consist of pumps, piping, and nozzles (Figure 30.6). The pumps are typically "chopper" pumps or pumps incorporating in-line grinders that prevent fibrous materials from accumulating and causing plugging problems. The pumps are installed outside the tanks to facilitate maintenance. The high-velocity nozzles are mounted inside the tank and are oriented to discharge in a flow pattern that completely mixes the tank contents. Flow patterns vary by manufacturer; however, typical patterns include a toroidal configuration (helical pattern rotating around the center) and "dual-zone" mixing, combining a uniform and a vertical flow pattern to provide a nearly uniform velocity throughout the tank.

The systems are designed so the equipment inside the digester does not need regular maintenance. Pumps require the maintenance that is typical for pumps of this type. A significant increase in pressure at the discharge end of a mixing pump could indicate a problem with the associated mixing equipment, such as clogged piping or nozzles.

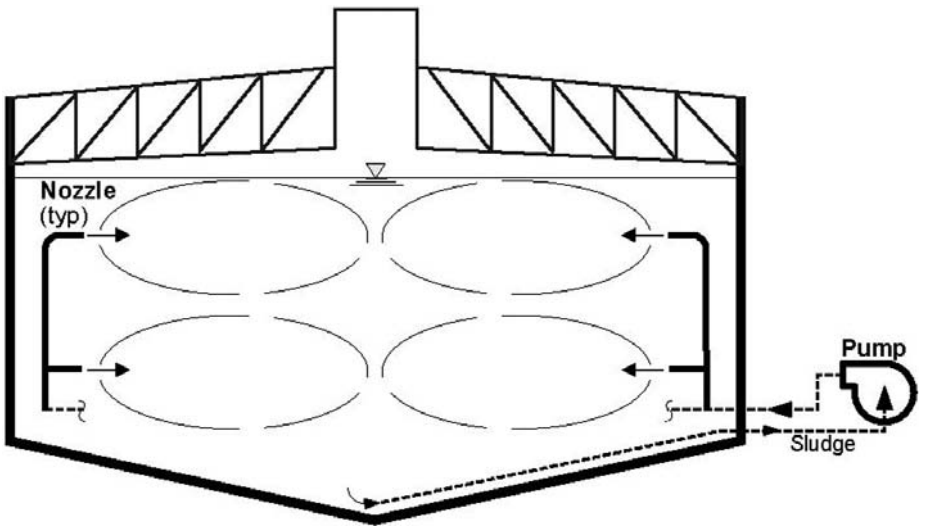


FIGURE 30.6A Pumped mixing schematic.



FIGURE 30.6B Pumped mixing system.



FIGURE 30.6C Pumped mixing system nozzle (courtesy of Vaughan Co., Inc.).

Impeller Mixing. Impeller mixing systems consist of an impeller, a drive shaft, and a drive (Figure 30.7). Impellers can be mounted in a draft tube to direct flow within the vessel. The draft tube may include a discharge nozzle that is aimed tangentially to the wall to create a swirling action in the tank. Impeller drives are typically reversible to allow discharge at either the top or bottom of the draft tube or to reverse the impeller to clear blockages. To avoid deposits in low-velocity zones, some utilities routinely reverse impeller direction for 2 hours every 24 hours.

Various configurations are used for impeller mixing. The mixer and draft tube assembly can be mounted at the center, at the mid-radius point, or outside the tank. Impeller mixers without draft tubes are typically mounted at the center of the digester cover.

A common problem with impeller mixers is rags, hair, and other stringy materials wrapped around and entangled in the mixer blade and shaft, which interferes with their operation. Manufacturers offer "weedless" impellers to help reduce this problem. Rag buildup can be monitored by measuring the motor's current draw. A fouled mixer can sometimes be cleared by reversing its direction. To clear large accumulations, mixers can be removed via a crane or the tanks can be dewatered and the accumulated rags cut away. In addition to monitoring buildup of debris, the drive unit and bearings should be serviced in accordance with the manufacturer's recommendations. External

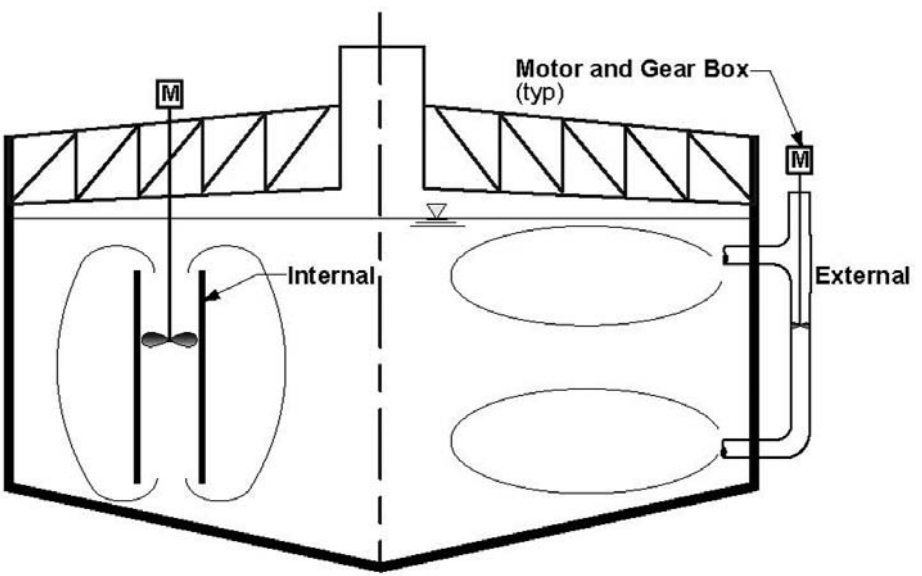


FIGURE 30.7 Mechanical draft tube mixing schematic.

draft tube mixing systems may also be subject to vibration, which can require corrective maintenance.

Gas Mixing. The four major types of gas mixing systems are bottom diffusers, lances, bubble guns, and gas lifters.

The compressor is the heart of all gas mixing systems. Compressors used include the rotary lobe, rotary vane, and liquid ring types, all of which are described in more detail in the section entitled "Gas Handling." Provisions for removing moisture and sediment from digester gas should be provided upstream from the compressors. Sediment traps should be cleaned at regular intervals. Bottom diffuser, bubble gun, and gas lifter systems include a flow-balancing manifold to distribute the flow evenly among the units inside the digesters. Condensate from the flow-balancing manifolds should be removed on a regular basis. Flow-balancing manifolds located outdoors in a cold climate should be protected from freezing.

Each gas mixing system includes means of controlling the gas pressure, such as high-pressure relief valves that allow the gas to be bypassed to the compressor suction or sent to storage when the compressor discharge pressure exceeds desired limits. If set properly, the relief valve opens only when the discharge line becomes plugged.

A low-pressure regulator bypasses gas whenever the pressure in the digester drops below a predetermined level. This prevents the development of a vacuum in the digester that could draw in air and create an explosive mixture. The low-pressure relief system should sense the gas pressure via a pipe connected directly to the digester. If the sensor is connected to the same pipe as the compressor suction, a false reading will be obtained. The sensing line must be kept clear at all times.

Pressure switches can be used to control high- and low-pressure conditions, but their use requires that the system be restarted by an operator whenever the pressure fluctuates. This is particularly troublesome during initial startup, when gas pressure varies.

Bottom Diffusers. Bottom diffuser mixing systems include diffusers or boxes on the digester floor near the center of the tank. All boxes receive and discharge equal amounts of compressed gas, creating a rising gas column.

To ensure even distribution of gas among the boxes, the gas flow must be checked periodically, because the boxes are prone to plugging. Plugging can be cleared by redirecting the entire gas flow through the affected box or by flushing it with high-pressure water. Bottom diffusers can also become covered with solids, which will affect the mixing pattern in the digester.

Lances. Lance mixing systems direct compressed gas to several discharge points in the tank (Figure 30.8). Sequencing the gas flow to various points causes the mixing action

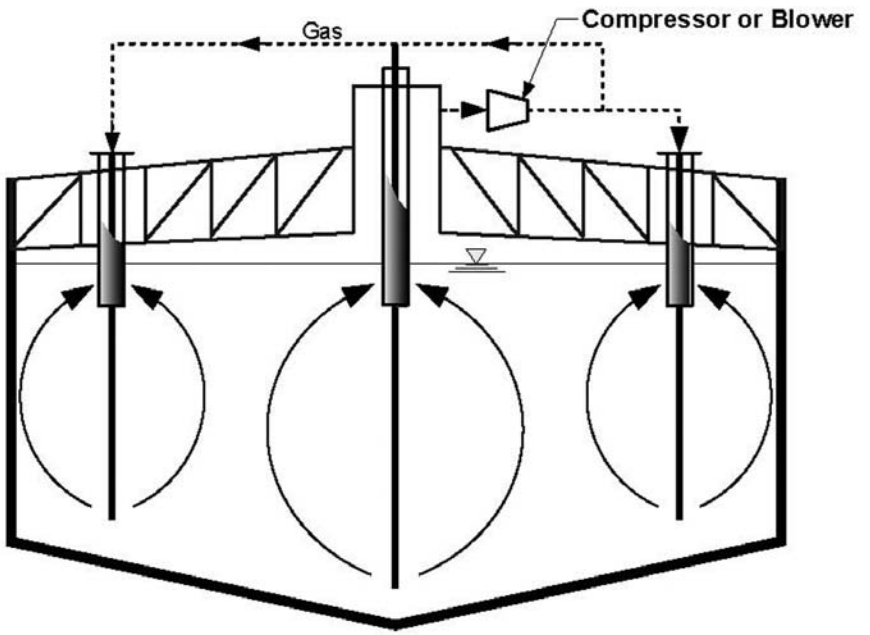


FIGURE 30.8 Lance mixing schematic.

to be distributed throughout the tank. The maximum depth of tank mixing is controlled by the depth at which the gas is discharged. Typically, the mixing will take place within 1.8 to 2.4 m (6 to 8 ft) below the point of gas discharge. Below this depth, materials settle and can accumulate.

Lances are typically spaced equally in a circle, at two-thirds the tank radius, with an additional lance in the center. The lances, which are typically 5-cm-diameter (2-in.-diameter) pipes mounted to the cover, discharge near the bottom of the tank. With many lance configurations, the gas cycles intermittently through the lances, which can cause them to become plugged with solids and rags. Straight pipe is used to minimize plugging. If plugging does occur, lance caps can be removed and the lances cleaned.

The sequential flow of gas to the lances is controlled by a series of motorized valves or by a single rotary valve. The motorized valves in the early systems allowed moisture to collect in the valves when they were closed. These valves should be inspected regularly for moisture-related deterioration. Rotary valves allow continuous gas flow, which reduces moisture problems. However, corrosion caused by contact with digester gas can still be a significant problem. Therefore, the sleeves in the valves should be greased annually.

Bubble Gun Systems. Bubble gun systems consist of bubble generators and vertical barrels. Compressed gas accumulates in a bubble generator at the base of the vertical barrel and forms a single large bubble, which rises through the pipe barrel, acting as an expandable piston. The bubble gun mixing system and bubble gun equipment are shown in Figure 30.9(a) and (b). The gas bubble forces the solids upward through the barrel and out the top, drawing solids into the barrel behind it. After leaving the barrel, the gas continues to rise to the liquid surface. Gas bubbles leave the barrel at the same rate as new bubbles are released from the generator, which results in continuous solids flow and establishes the circulation pattern. The numbers and configurations of the bubble guns depend on tank size. Because the barrels in a bubble gun system must be submerged, digesters equipped with bubble gun mixing systems have limited drawdown capability.

Even distribution of gas among the bubble guns is essential to the operation of the system. Flow-balancing controls should be checked periodically for plugged lines or clogged bubble generators. The generator siphon, with its many bends, is particularly susceptible to plugging. To clear a plug, a cleanout line is typically provided. Increasing the gas flow may also help clear a clogged generator. If these methods fail, the tank must be dewatered to gain access to the generator.

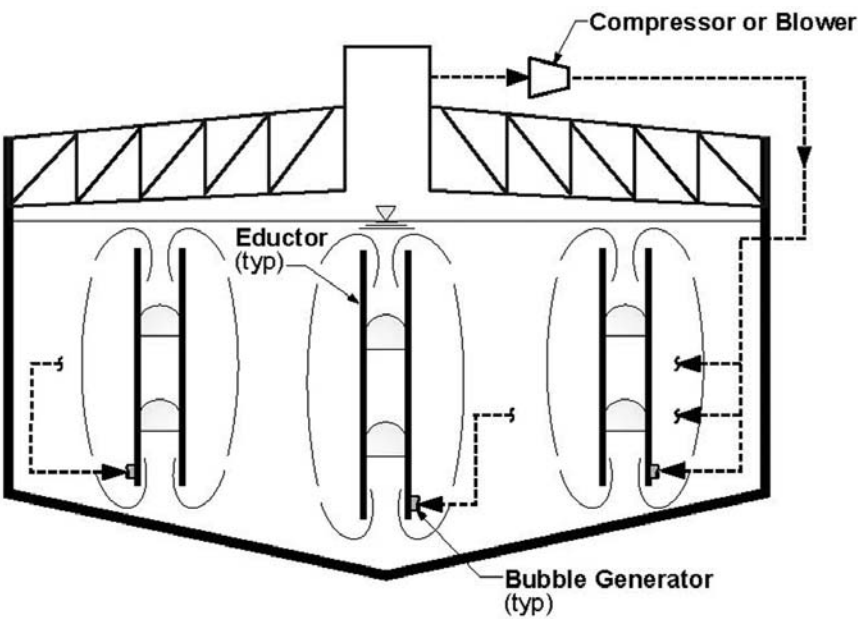


FIGURE 30.9A Bubble gun mixing schematic.



FIGURE 30.9B Bubble gun mixing system.

Draft Tube System. The draft tube system works much like an air lift pump (Figure 30.10). Gas is injected into the draft tube via lances installed in a vertical tube, which typically discharges the gas below the midpoint of the draft tube. As the gas is released, it carries solids upward through the draft tube, drawing in more solids at the base of the tube. The solids that leave the top of the tube flow away radially. Large tanks are equipped with multiple draft tubes; smaller vessels typically contain a single tube located in the center. Small ESDs can use a jet/draft tube system for mixing. Lances can be vulnerable to plugging, as described in the preceding "Lances" section.

Evaluation of Mixing System Performance. Because anaerobic processes are completely enclosed, it is difficult to directly observe the effectiveness of their mixing systems. Several testing procedures have been developed to measure the effectiveness of mixing, including solids profiles, temperature profiles, and tracer studies.

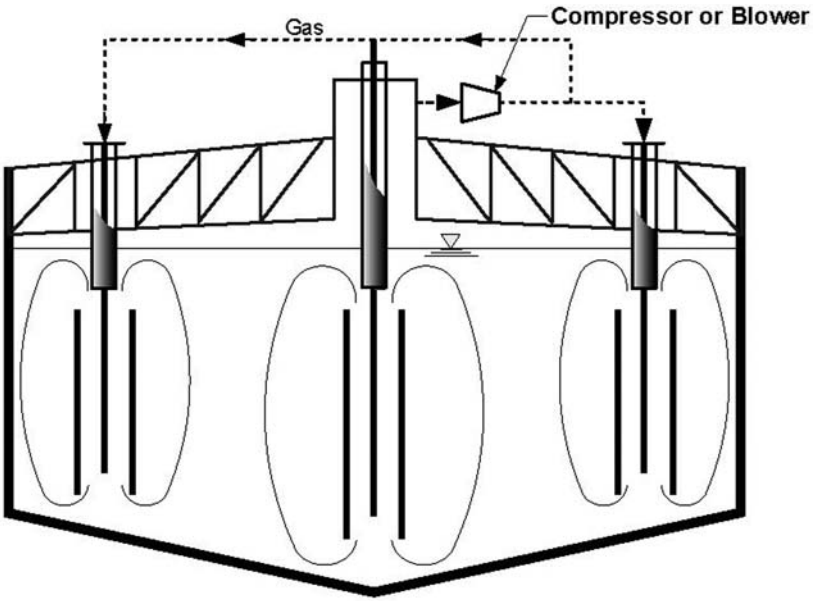


FIGURE 30.10 Draft tube mixing schematic.

The purpose of digester mixing is to produce a uniform condition in the tank. One method to evaluate solids uniformity is to perform a solids profile analysis. This test involves collection of solids samples at 0.6-m (2-ft) depth intervals, progressing from the top of the digester to the bottom. The samples can be withdrawn via sample wells (thief holes) in the cover using a spring-loaded sampling device. The samples are then analyzed for total solids. A concentration variation of more than 5000 mg/L from the average indicates poor mixing at the sample location. If the tested solids do not have a propensity to stratify, the results of the solids profile may be inconclusive. Solids profile testing should be performed every 6 months.

Another method to measure mixing efficiency is the temperature profile. The testing procedure is similar to that used for the solids profile testing, with temperature readings taken at fixed depth intervals. If any reading varies from the average by more than a specified value [typically 0.5 to 1.0 °C (1.0 to 2.0 °F)] the variation indicates poor mixing. The results of temperature profile tests may be inconclusive if the heat dispersion in the tank, even without mixing, is sufficient to produce a uniform temperature profile.

Tracer studies are yet another method to evaluate digester mixing. This method involves adding a quantity of tracer material, such as lithium, to the digester and col-

lecting samples from the digester discharge at fixed intervals. The samples are analyzed for tracer concentrations, which are then compared to theoretical concentrations that would result from complete mixing. Although the tracer study produces the most accurate results of the mixing evaluation methods discussed, it is also the most complicated, lengthy, and costly.

If a digester fails to pass a mixing effectiveness test, the mixing system should be checked for mechanical problems.

CALCULATION OF TURNOVER RATES. The turnover rate of digester contents, which is calculated by dividing the digester volume by the pumping rate, can be used as a measure of the amount of mixing provided. Turnover rate analysis can only be performed for mixing systems in which the pumping rate can be measured, which limits its use to pumped mixing. Turnover rates can be calculated using the following equation:

$$TR = DV/PR \tag{30.4}$$

where

TR = turnover rate (min);
DV = digester volume, based on sidewater depth, digester diameter, and bottom cone volume [L (gal)]; and
PR = pumping rate [L/min (gpm)].

Typical turnover rates range from 2 to 4 hours. If available, computational fluid dynamics can be used to determine the turnover rate.

Mixing energy evaluations can also be used to measure the amount of mixing in a system. Typical mixing energy rates range from 7 to 13 kW/L (0.25 to 0.50 bhp/1000 ft^3).

DIGESTER HEATING. ***Heating Theory.*** Each group of methane-forming microorganisms has an optimum growth temperature. If the temperature fluctuations are too wide, methane formers cannot develop the large, stable population needed for the digestion process. Digestion virtually ceases at temperatures below 10 °C (50 °F). Most digesters operate in the mesophilic temperature range [32 to 38 °C (90 to 100 °F)], while some operate in the thermophilic range [55 to 60 °C (131 to 140 °F)]. Regardless of the operating temperature selected, the temperature of the digester contents should not

deviate from it by more than 0.6 °C (1 °F) per day. It is good practice to log the digester temperature once per shift and watch for temperature swings.

Because methane-forming microorganisms are temperature-sensitive, maintaining a constant digester temperature is one of the most important operator-controlled functions and requires a heating system that is reliable, well-maintained, and well-understood. The digestion process cannot survive more than a few days without heat.

The total heat required for digestion is based on the following:

- *Sludge heating*—the heat required to raise the temperature of the incoming raw sludge to the digester operating temperature, and
- *Transmission losses*—the heat required to make up the heat losses from the digester to its surroundings.

Solids Heating. The temperature of the incoming sludge is typically lower than the temperature of the contents of the operating digester; therefore, heat must be added. The heat needed to raise the incoming solids temperature typically represents more than 60% of the total heat demand. The heat needed to raise the temperature of the influent sludge to the digester operating temperature can be expressed by the following equation:

$$Q = (S)(C_s)(T_o - T_i) \tag{30.5}$$

where

Q = solids heating requirement [kJ/d (Btu/hr)];
S = solids mass flowrate [kg/d (lb/hr)];
C_s = specific heat of solids [4.2 kJ/kg·°C (1.0 Btu/lb·°F)];
T_o = digester operating temperature [°C (°F)]; and
T_i = solids influent temperature [°C (°F)].

Reducing the amount of carrier water in the digester feed via thickening directly reduces the amount of heat required to raise the temperature of the digester feed to the digester operating temperature.

The digester feeding frequency affects the capacity requirements of the solids heating system. For example, a system designed to support a 24-hour-per-day feeding schedule will be overloaded if the daily volume of solids is fed in 3 hours. Such an overload may result in a temperature drop in the digester; moreover, re-establishing the proper operating temperature may take the rest of the day. Fluctuations in temperature are detrimental to the anaerobic bacteria.

Transmission Losses. The heat required to make up for heat losses from the digesters is expressed by the following equation:

$$Q = (U)(A)(T_o - T_i) \quad (30.6)$$

where

Q = digester transmission loss [kJ/d (Btu/hr)];
U = heat transfer coefficient [kJ/d·m^2·°C (Btu/hr·sq ft·°F)];
A = area of transmission loss [m^2 (sq ft)];
T_o = digester operating temperature [°C (°F)]; and
T_s = temperature of surroundings [°C (°F)].

Because different zones of the digester have unique heat transfer conditions, such as heat transfer coefficient or temperature of surrounding area, heat losses are calculated separately for each zone and then added together to determine the total losses for the digester. Resources for estimating heat transfer coefficients include Tables 22.12 and 22.13 of Water Environment Federation's *Design of Municipal Wastewater Treatment Plants* (WEF, 1998); *Cooling and Heating Load Calculation Manual* (McQuiston and Spitler, 1992); and information from manufacturers' catalogs. If transfer loss from one location, such as the digester covers, is particularly high, application of insulating material should be considered.

INTERNAL HEATING SYSTEMS. An internal heating arrangement transfers heat to solids in the digester vessel. Early internal heating arrangements consisted of pipes mounted to the interior face of the digester walls, and mixing tubes equipped with hot water jackets (Figure 30.11). These systems have lost popularity because much of the heating equipment and piping is inaccessible for inspection or service, unless the tank is dewatered. Also, rags and other debris collect on the pipes, reducing the heat-transfer efficiency and accelerating cleaning frequency.

EXTERNAL HEATING SYSTEMS. In external heating systems, solids are recirculated through an external heat exchanger (Figure 30.12). The recirculation pump maintains a flow velocity of 1.2 m/s (4 ft/sec), which creates turbulence across the heated surface and minimizes fouling.

The feed sludge pump is typically interlocked with the recirculation pump, causing it to operate whenever feed sludge enters the heat exchanger. The feed and the active digester sludge are blended and preheated before they enter the digester, which

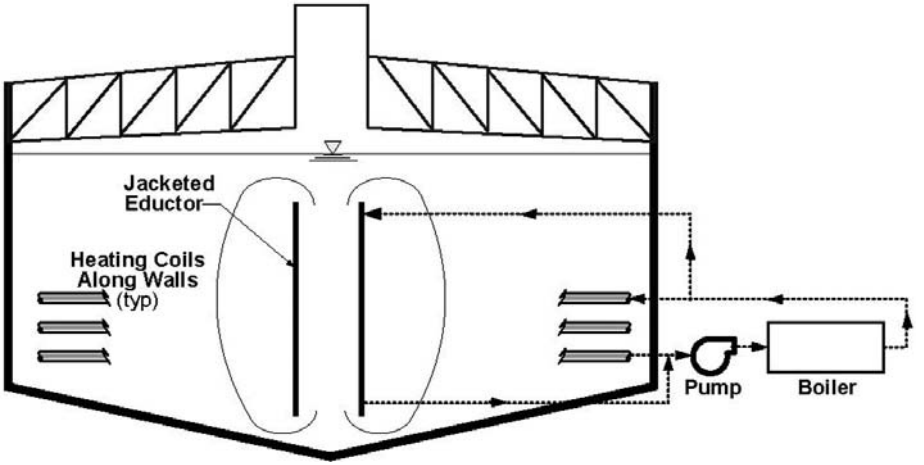


FIGURE 30.11 Internal heating schematic.

prevents the formation of cold, inactive zones of solids in the digester. The feed sludge can also be preheated by blending it with the heated sludge from the discharge of the heat exchanger.

The inlet and outlet temperatures of the heat-exchanger sludge should be monitored. A significant drop in the difference between the two indicates reduced heat transfer that may be caused by a malfunction of the solids pumps, hot water pumps,

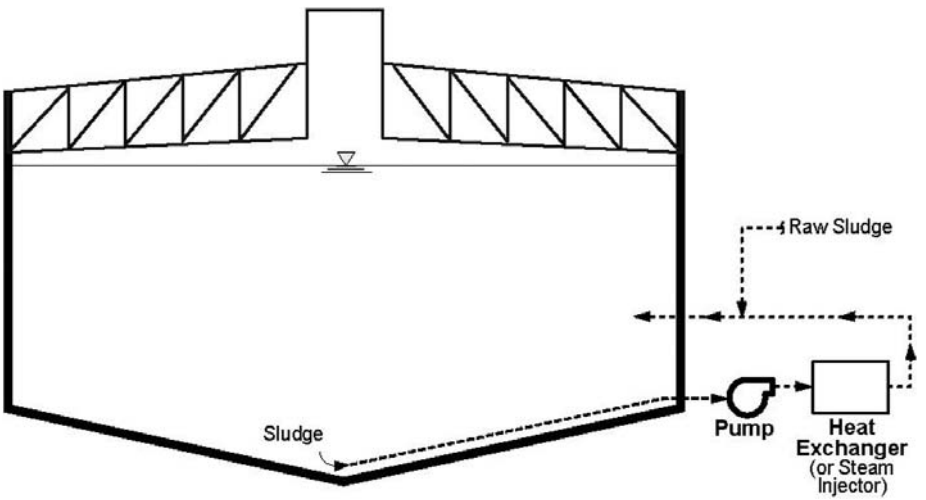


FIGURE 30.12 External heating schematic.

or the hot water supply. If these are operating properly, the heat exchanger needs to be checked for plugging, lime buildup, or fouling of the heat exchanger surfaces.

Three types of typical external heat exchangers—tube-in-tube, tube-in-bath, and spiral-plate—and their operation are described in the following sections.

Tube-in-Tube Heat Exchanger. A tube-in-tube heat exchanger consists of a serpentine arrangement of solids tubes surrounded by larger-diameter water tubes (Figure 30.13). The solids travel back and forth through the tubes via the solids-return bends, making thermal contact with the heating water on the outside of the tube. The heating water circulates through the annular space between the solids tube and the water tube countercurrent to the solids flow, which maximizes heat transfer. The temperature of heating water is typically limited to 66 °C (150 °F) to minimize solids accumulation on the inside surface of the tubes. The pressure through the heat exchanger should be monitored periodically. An increase in the drop in pressure is an indication of solids accumulation or fouling and requires cleaning of the solids tubes. The interior of the tubes can be accessed by removing the curved tubing at the end of each serpentine. If the tubes are large enough to accommodate a "pig", it is a cleaning option. If plugging



FIGURE 30.13 Tube-in-tube heat exchanger.

is excessive, grinders can be installed upstream of the heat exchangers to break up masses of fibers and rags that may have accumulated in the digester. Screening can also be used to remove fibers and rags from the solids.

Shell-and-Tube and Tube-in-Bath Heat Exchangers. Shell-and-tube and tube-in-bath heat exchangers consist of a serpentine arrangement of tubes in a hot water bath (Figure 30.14). In the shell-and-tube heat exchangers, the hot water flow is directed through baffling, which results in more efficient heat transfer. A hot water pump is used to create turbulence in the bath, thereby increasing the heat transfer. As with tube-in-tube heat exchangers, the pressure through the solids tubes should be monitored to detect caking or fouling.

Spiral-Plate Heat Exchanger. Spiral-plate heat exchangers consist of an assembly of two long strips of metal plate wrapped to form a pair of concentric spiral passages (Figure 30.15). Alternate edges of the passages are closed, forming separate channels



FIGURE 30.14A Tube-in-shell heat exchanger.

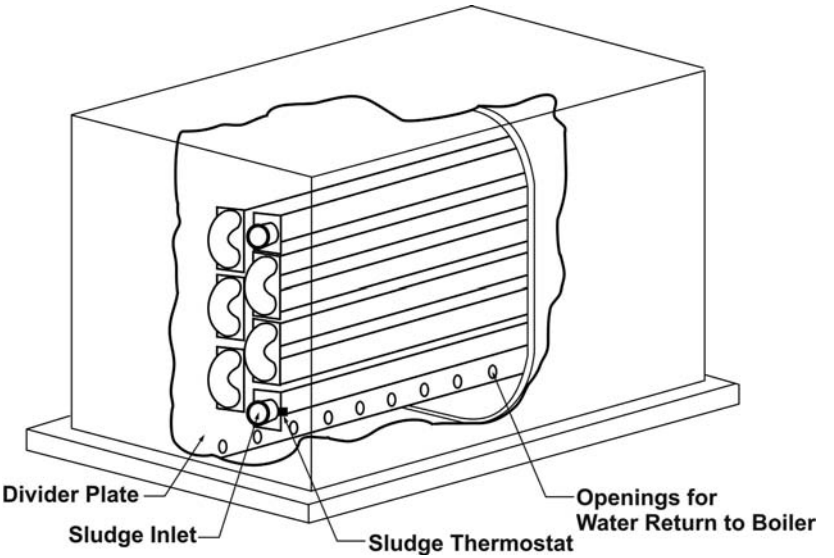


FIGURE 30.14B Tube-in-bath heat exchanger.

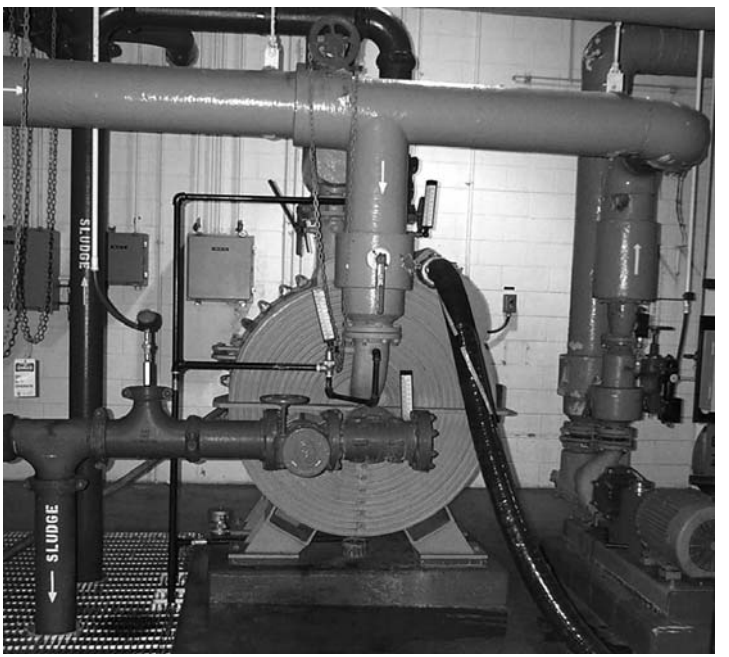


FIGURE 30.15 Spiral plate heat exchanger.

for solids and heating water. The units are typically constructed with hinged doors to provide access to the solids passages.

The solids passages of the spiral heat exchanger should be inspected regularly for plugging. Any plugging must removed from the bars separating the concentric plates. Pressure gauge readings should be taken daily to monitor the degree of plugging between cleanings. A significant increase in pressure drop indicates a plugged passage. Grinders are typically installed upstream from spiral heat exchangers to help prevent plugging.

SOLIDS-TO-SOLIDS HEAT TRANSFER SYSTEMS. Although most digestion systems do not include provisions for heat recovery from digested sludge, some new facilities are considering this option to reduce fuel use. Solids-to-solids heat transfer systems include recovery of heat from the discharge of mesophilic or thermophilic digesters to preheat feed sludge.

Solids-to-solids heat transfer systems use solids-to-solids heat exchangers, which include cube-type (Figure 30.16), tube-in-tube, and spiral-type heat exchangers. In each

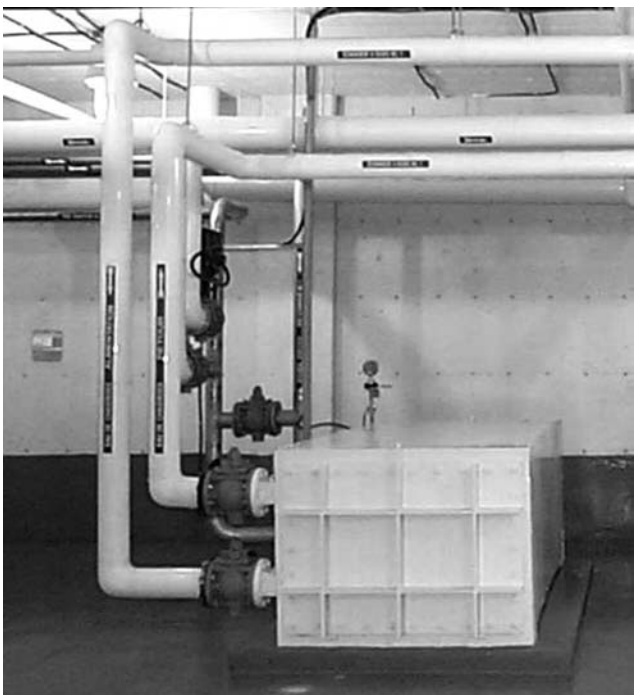


FIGURE 30.16 Cube heat exchanger (courtesy of DDI).

type, hot and cold sludge are introduced to opposite sides of a heat transfer wall, through which heat is transferred from the hot sludge to the cold sludge. The cube- and spiral-type heat exchangers include provisions for access and cleaning of both sides of the heat exchanger surface.

Heat can also be transferred through a system of two solids-to-water heat exchangers and an interconnecting heating water loop, which works by first transferring heat from the hot sludge to the heating water loop in a tube-in-tube or shell-and-tube-type heat exchanger. The heated water is then pumped to another heat exchanger, which transfers heat to the cold sludge. Operation and maintenance issues associated with this system are similar to those of other tube-in-tube, shell, and tube-type heat exchangers.

STEAM INJECTION HEATING. Steam injection heating systems inject hot steam directly into solids. The systems consist of internally modulated injection heaters and solids recirculation pumps, piping, and valves. The steam is injected into the solids stream via variable area steam nozzles that are modulated to control the temperature of the solids–steam mixture. Systems can be configured with either one or two heaters. In two-heater systems, one heater heats the feed sludge and the other replaces radiant heat losses from the digester in a recirculation line. In single-heater systems, one heater is sized to meet all heat requirements.

The following conditions must be met for the steam injection system to work properly:

- Heater steam pressure [typically 103 kPa (15 psi)] must be higher than the solids pressure;
- Solids discharge piping must be kept clean to maintain a low operating pressure;
- Particles in the solids feed must be small enough to pass through the nozzle to avoid plugging; and
- The makeup water must be softened to avoid scale buildup in the boiler and steam system.

HEATING SOURCES. Digesters can be heated with either hot water or steam. Heat sources include boilers and waste heat recovery.

Hot Water Systems. Hot water systems consist of a heat source, recirculation pumps, and temperature controls. Such systems typically include two separate loops. One loop is used for the solids heat exchangers, with a recommended temperature of 66 °C

(150 °F) to minimize fouling of the heat exchanger surfaces. The second loop supports the boilers, which should be maintained at a temperature of at least 82 °C (180 °F) to avoid the formation of sulfuric acid, which leads to corrosion. A temperature control valve between the loops controls the blend of hot water from the boiler loop with recirculated water from the heat exchanger loop to maintain the temperature upstream from the heat exchangers at 66 °C (150 °F).

The water in the heating loop should be conditioned with water treatment chemicals to inhibit corrosion and scaling; the water should be tested annually, with more chemicals added as necessary. During startup, sufficient time should be allowed for the system to reach operating temperature before making any adjustments.

Steam Systems. Steam systems consist of a conditioning makeup water system, a steam boiler, a steam-to-water heat exchanger, and a heating water loop or direct steam injection heater. The conditioning system softens the feed water to prevent buildup of scale in the system. The steam-to-water heat exchanger transfers heat from the steam produced by the boiler to the heating water loop, which operates at lower temperatures than the steam side to minimizing fouling.

The feed must be monitored regularly to ensure that it is adequately conditioned. Maintenance of the steam system consists of regular monitoring and repairing steam traps as needed.

Boilers. Fire tube, water tube, and sectional cast iron-type boilers supply heating water or steam to digester heating systems. Common fuels for heating the boilers include digester gas, natural gas, and fuel oil. Digester gas should be treated to prevent corrosion of the fuel valve train and the combustion zone. Treatment methods are discussed in the "Gas Handling" section. The boilers should be inspected as recommended by the boiler manufacturer, with particular attention to the combustion area, which is susceptible to corrosion. Codes and regulations should be followed, including those pertaining to annual boiler inspections and boiler operator certification. The facility's insurance carrier may also have special maintenance or inspection requirements that need to be identified and followed.

Heat Recovery. Digester gas is often used as fuel for engines and turbines that are used to drive equipment, such as pumps or blowers, or produce electricity. Waste heat recovered from cooling water systems or turbine exhaust gases can be used to heat digesters and buildings. Heat can also be collected as hot water from the exhaust of engines or combustion turbines and pumped to a water-to-water heat exchanger to be transferred to the heating water loop of digester sludge heat exchangers. Typically,

sufficient heat can be recovered from the engines or turbines to eliminate the need for supplemental digester heat. However, a backup boiler should be available for use during combustion equipment maintenance or other outages.

GAS HANDLING. ***Gas Production Theory.*** Digester gas, also known as *biogas*, is formed during the last stage of digestion, when microorganisms convert organic acids and carbon dioxide (CO_2) to methane (CH_4) and water. Gas production is directly related to the quantity of volatile solids destroyed by digestion. Typical values range from 0.75 to 1.1 m^3/kg (12 to 18 cu ft/lb) of volatile solids destroyed. The total amount of volatile solids destroyed can be calculated by deducting the amount of volatile solids in the digested sludge from the total quantity fed to the digester.

Because the quantity of digester gas produced depends on destruction of volatile solids, it is used as a measure of overall digester performance. Gas quantities should be routinely measured to determine the average production for a corresponding volatile solids destruction. Gas production should then be monitored in relation to the measured volatile solids destruction to provide an indication of the condition and performance of the digestion process.

Digester Gas Characteristics. The biogas generated in the anaerobic digestion process is composed primarily of methane (60 to 65%) and carbon dioxide (35 to 40%). The physical and chemical characteristics of methane, which imparts the fuel value to biogas, are summarized in Table 30.2.

TABLE 30.2 Physical and chemical properties of methane.

Physical characteristics	**Colorless, odorless**
Specific gravity	0.55 at 21 °C (70 °F)
Density	0.042 kg/m^3 at 21 °C (70 °F)
Hazard	Extremely combustible
Flammability limits in air	Forms an explosive mixture with air (5 to 15% volume). Avoid naked flames or spark-producing tools when there is unburnt gas in the air.
Toxicity	Asphyxiant at high concentrations (causes insufficient intake of oxygen)
Typical heating value	37 750 kJ/m^3 (1016 Btu/cf) (natural gas)
	Biogas has a lower heating value of 22 400 kJ/m^3 (600 Btu/cf) because it typically contains only 60 to 65% methane.

Digester gas typically contains impurities, such as foam, sediment, hydrogen sulfide (H_2S), and siloxanes; it is also saturated with moisture at digester operating temperatures. The various contaminants in digester gas include the following:

- *Carbon dioxide*—Carbon dioxide in digester gas dilutes its energy content and lowers its energy value. However, removal of carbon dioxide from the gas mixture to enrich the fuel value of digester gas is not a common practice.
- *Moisture*—Moisture in digester gas will form condensate in the system piping and can combine with hydrogen sulfide to form sulfuric acid, which will accelerate deterioration of the check valves, relief valves, gas meters, and regulators. If the condensate is not drained, it can also block gas flow at low points in the piping. If moisture is not removed from the digester gas prior to combustion, it will reduce the energy available for the heating system. Gas produced by thermophilic digestion, at associated high temperatures, will contain more moisture than gas generated by mesophilic digestion.
- *Hydrogen sulfide*—Hydrogen sulfide is an extremely reactive compound that, when combined with water, forms an acidic solution that is highly corrosive to pipelines, gas storage tanks, and gas utilization equipment. If present in a digester, it will shorten the usable life of many digester gas system components. Hydrogen sulfide is also a dangerous compound that can be lethal at concentrations above 700 parts per million (ppm).
- *Siloxanes*—Siloxanes are volatile organic chemicals containing silicon that are used in many commercial, personal care, industrial, medical, and even food products. Personal care products, such as shampoos, hair conditioners, cosmetics, deodorants, detergents, and antiperspirants, are thought to be the main sources of the siloxanes found in wastewater, which are released as gas during the anaerobic digestion process. When oxidized in gas utilization equipment, they form an abrasive fine silicon dioxide sand that accumulates on moving parts or heat exchange surfaces, causing accelerated wear and loss of heat transfer efficiency.

Gas Treatment. Digester gas is a valuable resource that can be used to meet a treatment plant's energy requirements. However, the gas must be treated to remove contaminants that would otherwise damage equipment fueled by the gas and shorten its useful life. Consequently, before digester gas is used as an energy source, it may need to be treated to remove siloxanes, moisture, and sediment, as well as to lower its hydrogen sulfide concentrations.

FOAM AND SEDIMENT REMOVAL. Many systems are equipped with sediment traps and foam separators for cleaning digester gas. These devices provide a

"wide spot" in the gas piping system for slowing velocities, collecting foam and particulates entrained in the gas, and removing collected condensate. The foam separator (Figure 30.17) is a large vessel with an internal plate fitted with water nozzles that provide a continuous spray. The foam- and sediment-laden gas enters the vessel near the top and travels down through the spray wash under the baffle wall and up through a second spray wash, exiting the vessel through an elevated discharge nozzle. The spray wash and the internal plate reduce foam in the gas to prevent carryover to gas utilization equipment.

HYDROGEN SULFIDE REMOVAL. Several methods are available to remove hydrogen sulfide from digester gas. The iron sponge process treats digester gas by passing it through a permeable bed of iron sponge (hydrated ferric oxide in the form of iron-dipped wood chips soaked in water). As the gas passes through the iron media, it undergoes an exothermic (heat-producing) reaction that converts the hydrogen sulfide to ferric sulfide and water.

The iron sponge can be regenerated and reused repeatedly before replacement. The need for regeneration or replacement can be determined by measuring the hydro-

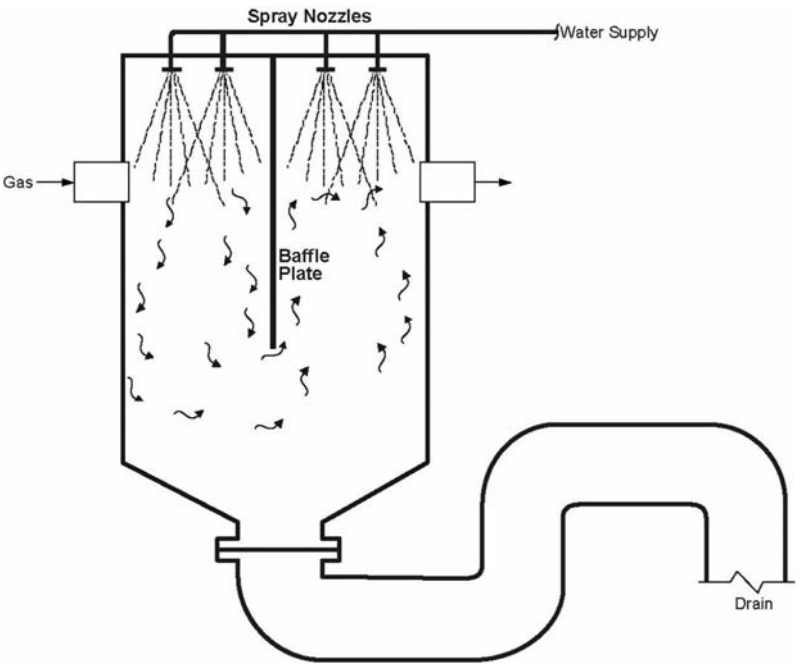


FIGURE 30.17 Foam separator.

gen sulfide concentration in the treated gas. An "exhausted" sponge typically consists of a combination of ferric sulfide and wood chips, a nonhazardous waste that can be disposed at any landfill.

Regeneration of an iron sponge is a highly exothermic reaction using water and air to release sulfur from the iron and reform the hydrated ferric hydroxide. If the iron chips are not submerged in a flowing water bath and controlled properly, they can overheat and combust spontaneously.

Several proprietary processes are available that involve passing digester gas through a bed containing media that react selectively with hydrogen sulfide (Figure 30.18). The medium used in these systems is a proprietary, free-flowing granular product that will not ignite and cannot be regenerated.

Ferric chloride injected into the digester can reduce the amount of hydrogen sulfide in digester gas by reacting with sulfur to generate a solid iron sulfide. Iron salts can be added at the following locations in the treatment process:

- The primary clarifier (helps settling and improves overall facility odor control),
- The primary clarifier and/or WAS feed to the digester,

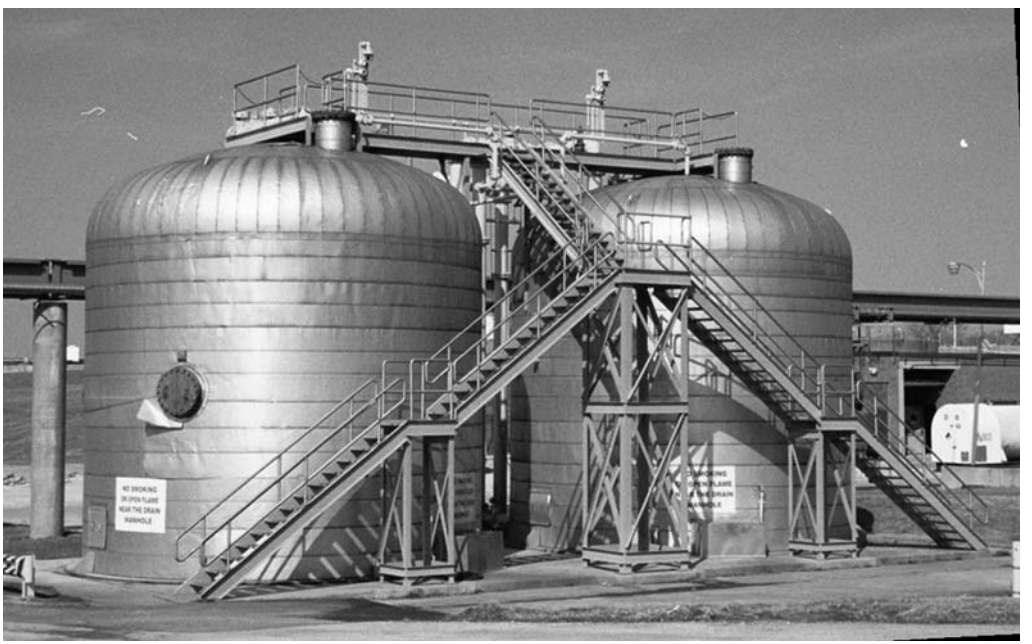


FIGURE 30.18 Hydrogen sulfide treatment.

- The suction side of the digester sludge-recirculation pump, and
- The suction side of a mechanical mixer.

Iron salts should not be added directly upstream from the heat exchangers because this can result in deposits of vivianite on heat exchanger surfaces.

MOISTURE REDUCTION. Moisture is condensed from digester gas as it cools. Gas piping should have a slope of at least 1% toward the condensate collection point. To effectively remove the moisture, the gas flow should not exceed 3.7 m/s (12 ft/sec) countercurrent to condensate flow.

The condensate is collected in traps that should be located at the low points in long pipe runs and wherever gas is cooled. Drip taps, which can be controlled manually or automatically, provide a convenient and safe means for the removal of accumulated condensate. Manually operated drip taps are recommended for indoor applications. Float-controlled, automatic drip taps are also available, but these require frequent maintenance to keep the valves operating. Should the float stick, gas can escape to the surrounding atmosphere, which limits their use to outdoor installations (where permitted by local codes and safety considerations).

Moisture can also be removed from the gas by cooling it to approximately 4 °C (40 °F) in a refrigerant-type dryer (Figure 30.19). The dryer is typically made of stainless steel or other materials resistant to hydrogen sulfide corrosion. Corrosion can be minimized by removing hydrogen sulfide from the gas before drying. Refrigerant drying may also remove up to 20 to 40% of siloxanes from the digester gas.

CARBON DIOXIDE REMOVAL. Carbon dioxide can be removed from the digester gas via water or chemical scrubbing, carbon sieves, or membrane permeation; however, all of these technologies are expensive and their use may be cost-effective only if the gas is to be upgraded to natural gas quality and sold.

SILOXANE REMOVAL. Heating the digesters [to 35 °C (95 °F)] causes the siloxanes in the sludge to volatize into their gaseous form, which, when burned, becomes a sand-like material (silicon dioxide) that is too fine to be captured in ordinary scrubbers and collects on combustion equipment or in combustion chambers. To protect the equipment, siloxanes should be removed from the digester gas before combustion via gas dryers or activated carbon scrubbers.

Gas Drying. Siloxanes are relatively heavy volatile compounds that tend to adhere to water vapor in the digester gas stream. A significant fraction of siloxanes can be

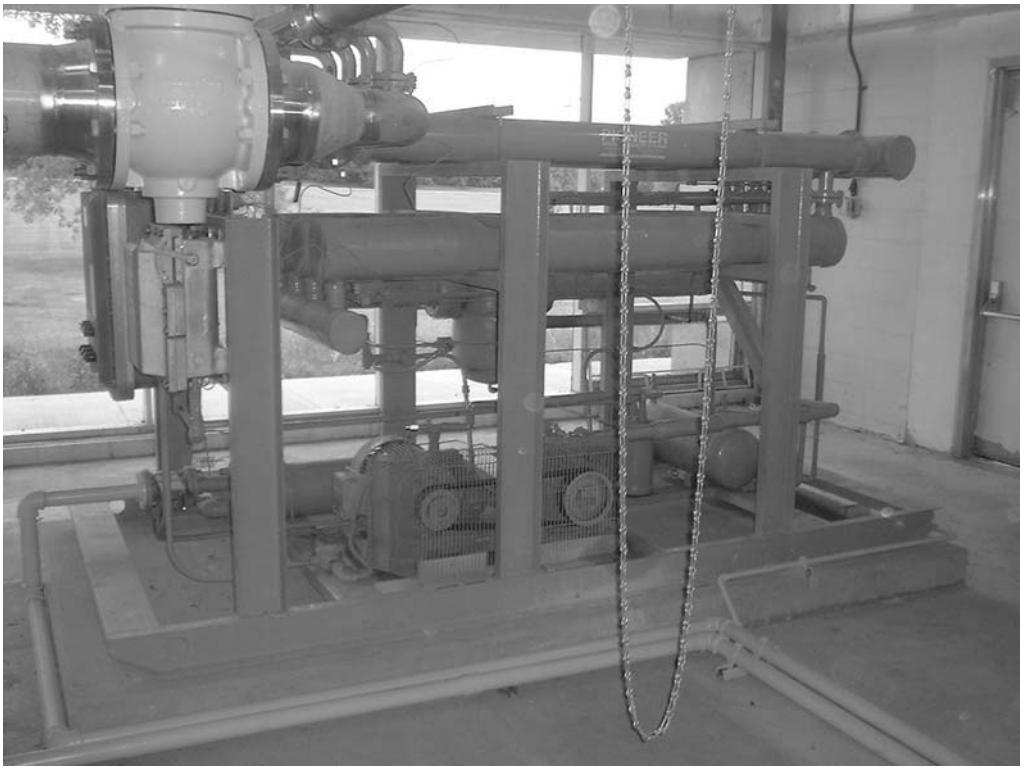


FIGURE 30.19 Refrigerant dryer.

removed along with moisture when the gas is dried. To remove more than 90% of the siloxanes, the gas must be dried to a dew point temperature of −29 to −23 °C (−20 to −10 °F) or lower, as determined by temperature sensors in the drying process. The drying equipment consists of a refrigerant-type dryer that cools the digester gas as it passes through the dryer. The dryers are typically equipped with heat recovery systems that use the heat removed from the gas to raise its exit temperature above the dew point.

While gas-drying systems are relatively simple in concept, those that operate at the temperatures required for siloxane removal are vulnerable to significant amounts of ice formation, which must be removed to protect the pipes from bursting and damaging the refrigeration system.

Activated Carbon Scrubbers. Activated carbon scrubbers used to remove siloxanes from digester gas operate according to the same principles as the carbon scrubbers

used for odor control in wastewater treatment plants (WWTPs). The digester gas is passed through a vessel filled with activated carbon (Figure 30.20), which captures the organics, including siloxanes, hydrogen sulfide, and several other compounds in digester gas. With proper maintenance and replacement of the carbon, the siloxanes in the digester gas should be removed to below detection limits. However, activated carbon is not selective for siloxanes and will remove other compounds as well. Consequently, if the digester gas contains other organics, the carbon will require frequent replacement. Removal of hydrogen sulfide before it passes through the carbon scrubbers will provide better siloxane removal and extend the life of the carbon bed.

GAS COMPRESSION. Gas from the digesters is supplied at a relatively low pressure [typically, a 150- to 300-mm (6- to 12-in.) water column, or up to 450 mm (18 in.)



FIGURE 30.20 Activated carbon treatment for siloxanes.

for digesters designed for higher pressures], which makes it difficult to use the gas in some types of combustion equipment. Furthermore, in digesters with gas mixing equipment, the pressure supplied to this equipment must overcome piping losses and the static head of the liquid in the digester. In both instances, gas compression or pressure boosting is needed. Table 30.3 lists typically used gas-compression equipment and their applications.

TABLE 30.3 Gas-compression equipment.

Type	Applications	Operation and maintenance
Liquid ring compressors (centrifugal with sealing of impeller provided by water ring)	Commonly used for gas mixing at 103 kPa (15 psig) or more, or where higher pressures for gas supply are required for high-pressure storage or for engines or turbines. Gas recycle used for startup and flow control.	Able to handle dirty gas. Require rebuilding approximately every 2 years. May use plant water, or, if this causes deposits, potable water for sealing water. Lower efficiency than other compressors. Less chance of overheating when used with gas recycle for flow control. Special attention should be given to water level control in separators to prevent gas escaping. A compressor with a water seal increases system complexity, a significant sidestream flow, and additional pollutants compared to a compressor system with a seal.
Rotary positive-displacement blowers	Gas mixing [limited to about 103 kPa (15 psig)]. Flow controlled by changing speed.	Require nearly annual rebuilding if handling dirty gas. May require noise enclosure. Need thermal shutoff for recycle gas applications.
Reciprocating compressors	Generally used for lower flow and higher pressure applications. Used for higher pressure to furnish gas to engines and turbines. Usually require water-cooling system for compressor and intercoolers and after coolers. Some applications of air cooling.	Not tolerant of dirty gas. May require particulate scrubbing to clean gas. High efficiency. Higher maintenance because of close-fitting moving parts.
Hermetically sealed blowers	Low pressure [less than 14 kPa (2 psig)]. Typically used as boosters for boilers where higher flow and low pressure are required. Blower requires gas flow for cooling of sealed blower within the gas pipe. Limited flow control by gas recirculation, potential overheating.	Not tolerant of dirty gas. Can be used following gas dryer. Sealed to reduce potential gas leakage.
Multiple-stage centrifugal blowers	Used to supply gas for utilization equipment at higher flows than reciprocating compressors and at similar higher pressures. Must be designed with seals and materials that are corrosion-resistant and safe for gas use. Flow control by inlet damper.	Not tolerant of dirty gas. Require particulate scrubber to clean gas. May require lubrication oil system and oil cooling if gearbox is used.

STORAGE. Equipment fueled with digester gas typically needs a steady flow of the gas. Therefore, facilities that use digester gas for plant operation or cogeneration, rather than flaring it, should include storage provisions to dampen fluctuations in gas production.

Several types of gas storage are available. The most common means of low-pressure gas storage is the floating gas-holder cover. The storage capacity under the cover depends on the available vertical travel distance of the cover and the tank diameter. Gas storage is typically limited to 1 to 2 hours at gas production. Membrane storage, which also operates at low pressures, can provide up to twice the amount of storage provided by floating gas-holder covers. Membrane storage can be installed either on the digester, to serve both as cover and storage space, or on the ground as a standalone structure (Figure 30.21).



FIGURE 30.21 Membrane gas storage (courtesy of JDV Equipment Corporation).

Gas-storage spheres, which hold gas at pressures of 550 to 700 kN/m^2 (80 to 100 psi), are standalone structures available in a variety of sizes (Figure 30.22). They can accommodate larger quantities of gas than other storage systems, but the gas must be compressed before it is stored. The energy use associated with gas-storage spheres can be significant.

GAS SYSTEM EQUIPMENT. ***Flow Measurement.*** Gas production is a measure of digester performance. Reliable monitoring equipment alerts plant operators to process malfunctions and gas leaks. The flow meters used for gas monitoring can be broadly classified as positive-displacement, thermal-dispersion, and differential-pressure (Table 30.4).

Separate flow meters are recommended for each digester because digester gas-production rates vary. Separate flow meters are also recommended to monitor gas use by the utilization equipment. The gas may contain moisture and impurities, which may cause maintenance problems for the metering devices.

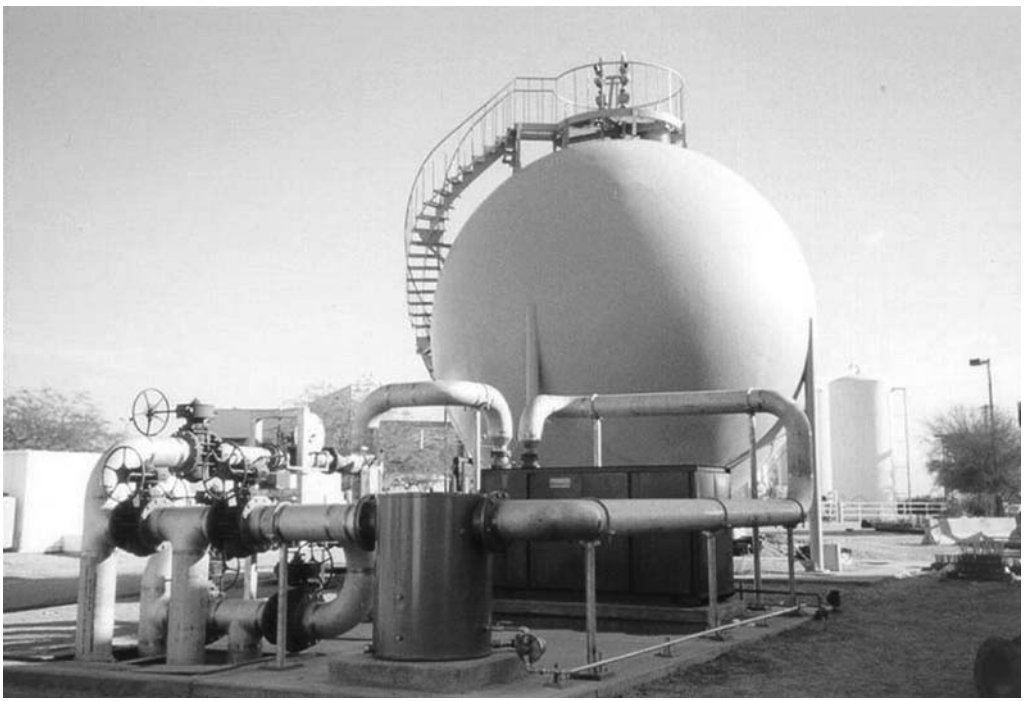


FIGURE 30.22 Steel gas storage sphere.

TABLE 30.4 Gas-flow indication and metering.

Type	Applications	Operation and maintenance
Positive displacement	Used in many plants. Large devices that require bypasses when servicing. Accurate gas measurement unless dirty. Do not require upstream and downstream straight-pipe sections for accuracy.	Somewhat tolerant of dirty gas. Require periodic cleaning and rebuilding.
Thermal dispersion insert	Increasingly used technology because of tolerance of dirty gas and simple installation. Accurate for low flows. Some accuracy problems with zero flow, such as for flares. Require some upstream and downstream straight-pipe distances for accuracy. Can be inserted and removed through ball valve.	Smaller than most metering devices. Require periodic cleaning of probe. Must not have liquid impinging on probe. No bypass needed, reducing need for piping and isolation valves to service.
Pressure differential orifices and Venturis	Commonly used in older plants. Upstream and downstream straight-piping sections needed.	Require frequent cleaning when used for dirty gas. Accuracy dependent on instrument cleanliness. Can significantly constrict gas flow when fouled.

Gas System Safety and Control Devices. Gas systems include safety and control equipment to limit flashbacks, measure and control system gas pressure, and burn unused gas. Gas system safety and control devices are listed in Table 30.5, along with descriptions of their use and maintenance requirements.

GAS UTILIZATION. Digester gas is a valuable fuel that has traditionally been used to heat boilers to produce steam or hot water for process and building heating, to operate combustion turbines or engine generators to produce electric power (and hot water from heat recovery for heating), or to operate dryer facilities to remove moisture from the solids (with heat recovery to heat digesters). Digester gas collection and utilization technologies have been steadily improving over the years, and energy recovery from digester gas is now regarded as one of the more mature and successful waste-to-energy technologies.

Thermal Energy. Digesters typically produce more gas than needed for digester heating. The excess gas can be used to heat buildings or treatment processes. If digester gas is used to generate steam rather than to heat water, energy would also be available for cooling buildings via absorption chillers. Because building heating and cooling loads are seasonal, the energy requirements vary depending on ambient temperature.

TABLE 30.5 Gas system safety and control devices.

Type	Applications	Operation and maintenance
Flame traps (large pipe) and flame check valves (small piping)	Used to stop flame propagation in a pipe. Flame traps installed with thermal shutoff valves as noted below. Installed on gas supplies to engines, compressors, boilers, flares, or other sources of ignition. Also used on digester covers with pressure- and vacuum-relief valves.	Require periodic cleaning, typically monthly. May require insulation and heating in cold climates to prevent ice formation. Foam will blind the devices, rendering other devices, particularly relief valves, ineffective.
Thermal shutoff valves	Spring-loaded or pressure-operated isolation valves that trip-shut at flame temperatures. Must be installed between flame trap and source of ignition.	Replace element periodically or when tripped. Usually includes an indicator to show that the valve has tripped. May require insulation and heating in cold climates to prevent ice formation.
Pressure- and vacuum-relief valves	Provided for all digester covers to prevent overpressurization or vacuum conditions in the digester. Typically adjustable, weighted valves, built as common unit. Should be set below design limits of cover. Typically two sets provided for each cover to allow servicing of one set while keeping digester in service. Typically discharge to area around valves. Available with pipe to allow discharge away from valves.	Check seals periodically; replace if leaks develop. May require insulation and heating in cold climates to prevent ice formation. Relief valves are last safety measure for digester covers to prevent overpressure or vacuum. These valves do not provide liquid relief.
Back pressure valves	Typically provided with waste gas flares. Maintain pressure upstream by relieving overpressure to flare. Usually uses weights to set relief pressure; however, some use springs. Upstream sensing line should ideally be in gas-collection piping header, away from the valve and large enough to reduce the potential for clogging.	Frequent maintenance required to prevent sticking (open or closed). These valves regulate pressure in the gas-collection piping system and are the first level of protection for overpressurization of the digester cover.
Low-pressure check valves	Used to prevent backflow of gas. Typically constructed with leather or flexible flap to ensure operation at low pressure. Not commonly used.	Check flap and replace if not functioning.
Waste gas flare or burners	Provided to dispose of surplus gas. Usually provided with standing pilot or electronic ignition.	Provided for all plants to serve as a means of suitable disposal of gas. Untreated gas should not be freely released.
Open pipe or "candle flare"	Used for smaller plants and where stringent air-emissions control is not needed. Generally visible flame, gas-disposal device.	Good pilot-gas supply is needed (may require natural gas or propane supply). Heat and corrosion make periodic replacement necessary. Pilot system requires frequent servicing.

TABLE 30.5 Gas system safety and control devices (*continued*).

Type	Applications	Operation and maintenance
Controlled combustion flare, ground flare, or emissions controlled flare	Used at plants where stringent air emissions are required and visible flame is not desired. Control air supply to maintain sufficient temperature to completely burn gas. These flares must be operated at a specific temperature to achieve emission limits. If oversized, auxiliary fuel may be required, which increases operating costs.	Require periodic system maintenance for controls and air blowers.
Pressure indication	Manometers used for low pressure [760 mm wc (30 in. wc) or lower]. Gauges used for higher pressures, particularly for gas utilization lines.	Periodically clean manometers, replace fluid, and calibrate gauges. Pressure gauges should be provided with an isolating diaphragm to prevent gas contaminants from fouling the mechanism.

Boilers do not have to be fueled with high quality gas; however, the hydrogen sulfide concentrations in the gas should be reduced to less than 1000 ppm for use in a boiler and the water vapor should be condensed to avoid problems with the gas nozzles.

Digester gas can also be used to generate heat for such processes as thermal drying of dewatered cake. Digesters can typically produce enough gas to supply 50 to 80% of the drying energy requirement for drying, with the remainder supplied by natural gas. Heat recovered from the dryer condenser/scrubber return stream can be used to heat the digesters.

Power Generation. Digester gas can be collected and used to generate electricity with onsite power generation equipment. The heat recovered from the power-generation units in the form of hot water or steam (from combustion turbines only) can be used to heat digesters or heat or cool buildings. If all the recovered heat is used, the overall efficiency of gas use can approach 80%.

The amount of power production varies depending on digester gas production; however, most medium-to-large wastewater treatment facilities generate less than 5 MW of power. Onsite power-generation systems include traditional engine generators, combustion turbine generators (for larger facilities), microturbines, and fuel cells. Internal combustion engines are by far the most commonly used generating equipment.

Approximately 80% of the power-generation facilities at WWTPs are reciprocating engines. Depending on the scale of operation, a combustion turbine and/or a steam turbine can also be used.

The gas quality requirements for cogeneration equipment are more stringent than those for boilers. The gas should be cooled to remove moisture, and typically requires scrubbing to remove hydrogen sulfide and siloxanes.

Distribution via Natural Gas Network. Another option for digester gas utilization is to treat it to the quality of natural gas by removing all the contaminants, including carbon dioxide, and distribute the upgraded gas through a natural gas supply network. This is practical only where large quantities of digester gas are available.

SAFETY. Digester gas can be hazardous because it is composed primarily of methane and carbon dioxide, both of which are colorless and odorless and can displace air, thus causing asphyxiation. Consequently, digestion facilities should be equipped with gas detectors and analyzers, as well as a self-contained breathing apparatus for use in the event of a gas leak.

Methane is highly combustible when mixed with air at concentrations of 5 to 20% methane. To keep out air, gas-handling systems are designed to operate under positive pressure. Because air can be introduced into a digester if solids withdrawals exceed the liquid operating range provided by floating or gas-holder covers, precautions should be taken to prevent draining operating digesters below the recommended level.

Any air in the digester will mix with gas and eventually enter the gas piping system. If the air-and-gas mixture should reach a flame source (waste gas burner, boiler, or engine), it would cause the flame to flash back in the pipe. The piping is equipped with flame traps to eliminate the flashback; however, the gases can expand in the pipe and cause pressure increases sufficient to rupture the gas line before the flame trap has an opportunity to snuff the flame. To reduce the possibility of pipe rupture during a flashback, the flame trap should be located as close as possible to the potential ignition source, with a maximum distance of 9 m (30 ft).

Digester gas leaks are another explosion hazard. Digester facilities are typically equipped with monitoring instruments that measure the lower explosivity limit, as well as the concentration of hydrogen sulfide in the gas. Because of the fire and explosion hazards, areas of digester facilities can be subject to National Fire Protection Association (NFPA) standards governing electrical classifications, construction materials, and fire-protection measures. Specific information on anaerobic digestion facilities is presented in Chapter 6 of *Standards for Fire Protection in Wastewater Treatment and Collection Facilities* (National Fire Protection Association, 2003a). According to NFPA stan-

dards, most areas in anaerobic digestion facilities are considered to be susceptible to explosion hazards; consequently, safety measures include use of nonsparking tools, prohibition of smoking or open flames, provision of adequate ventilation, and explosion-proof electrical equipment.

An additional safety consideration is the toxicity of digester gas. The effects of hydrogen sulfide at different concentrations are listed in Table 30.6. Although hydrogen sulfide has a strong rotten-egg odor, after short exposure the nose becomes numb to the odor, which may lead to the false conclusion that the hazard has diminished or disappeared. Consequently, hydrogen sulfide detectors should be used and calibrated on a regular basis. Hydrogen sulfide is heavier than air; therefore, detection equipment should be installed to adequately monitor all elevations of the digester facility.

Safety equipment associated with the digester gas system, such as flame arresters, pressure-relief valves, gas burners and controls, gas compressors, condensate traps, and detection instrumentation, should be inspected regularly.

Areas in the digester facility that should be considered confined spaces include digesters that have been taken out of service and emptied, as well as the attic space under digester covers. These areas should be entered in accordance with Occupational Safety and Health Administration (OSHA) Part 1910.146, *Permit Required Confined Spaces*, or, where applicable, similar safety codes.

TABLE 30.6 Effects of hydrogen sulfide at various concentrations.

Concentration (ppm[1])	Effects/Standards
5	Easily detectable odor
10	Permissible exposure limit (PEL[2]), slight eye irritation
15	Short-term exposure limit
50	Ceiling limit, maximum concentration of exposure at any time during a work shift
100	Coughing, eye irritation, loss of sense of smell after 2 to 15 minutes
300–500	Dizziness, nausea, bronchitis, pulmonary edema; also immediately dangerous to life and health
600–700	Rapid unconsciousness, cessation of respiration, followed by death
1000–2000	Unconsciousness at once, death in a few minutes
40 000	Explosive range [approximately 4 to 44% (40 000 to 440 000 ppm)]

[1]ppm = parts per million, that is, parts of gas per million parts of air by volume. A 1% gas–air concentration is equal to 10 000 ppm.
[2]PEL = 8-hour weighted average concentration at which workers can be repeatedly exposed each work shift without adverse effects (California Occupational Safety and Hazard Agency standard).

DIGESTER OPERATIONS

STARTUP AND SHUTDOWN. ***Startup.*** The objective of anaerobic digester startup is to achieve steady-state operation and the required volatile solids reduction in the shortest possible time. Successful biological commissioning requires an effective equipment startup of the various systems and subsystems, including the gas-handling system, heat exchangers, solids pumps, mixing equipment, and auxiliary systems before introducing volatile solids to the digester. The three parameters that are critical to ensuring a smooth startup process are

- Maintenance of a specific operating temperature;
- Constant mixing; and
- A specific volatile solids loading rate, with a daily variation not to exceed ± 10%.

To minimize failures of the equipment or biological processes, the operator should inspect and test the digester equipment, as follows:

1. Remove all debris from the digester tank.
2. Inspect all valves for proper and smooth operation.
3. Inspect all gas control, conditioning, and safety devices, including, but not limited to, sedimentation traps, foam separators, manometers, waste gas flare, flame traps, and pressure-relief valves.
4. Inspect and lubricate the solids pumps and verify that they are free of debris and have correct drive alignments.
5. Clean heat exchangers and tighten all piping connections.
6. Adjust and lubricate the digester mixing system, whether mechanical or gas.
7. Verify that the digester boiler system is operational for approximately 24 hours before filling the digester.

Digester startup can be divided into two phases: preparation and operation. During the preparation phase—typically the first 4 days—the digester is filled to its minimum operating level, allowed to reach operating temperature, and mixing is started. Initially, the digester can be filled with any of the following liquids:

- Unthickened WAS (before polymer addition),
- Secondary clarifier effluent (unchlorinated),
- Primary clarifier effluent, and
- A combination of raw sludge and WAS.

Anaerobic seed sludge is not needed for effective biological commissioning. Digester commissioning typically requires 45 days; however, use of seed sludge can reduce this time by 7 to 10 days. The ratio of primary solids to WAS in the seed material should resemble the digester feed as closely as possible. The digester contents should be mixed and heated to the operating temperature during the initial 3-day commissioning period. The digester gas system should be returned to the main gas line when digester filling begins.

At the end of the preparation period, the digester should be operating at the desired temperature and ready to receive sludge. At this point, the digester may be loaded with the following:

- Primary clarifier effluent (preferred source),
- Secondary clarifier effluent (unchlorinated),
- Unthickened WAS (before polymer addition), and
- A combination of raw sludge and WAS.

The organic loading rate should initially be approximately 0.16 kg volatile solids/m^3·d (0.01 lb volatile solids/d/cu ft) and should be increased every 3 days, provided that the digester process-control parameters are within the desired limits. The key to the startup process is control of the volatile solids loading rate. Feed sludge composition or ratios are not important. The digester feeding should be done during a 24-hour period, if possible, to reduce the instantaneous loading rates on the digester and minimize foaming potential.

The operating parameters listed in Table 30.7 should be monitored daily during startup and analyzed using trend charts to identify both positive and negative trends and predict possible digester upsets. Within the target range, the rate of change of an individual parameter is more significant than its absolute value.

Once the operating parameters indicate that the digester is operating at steady state, organic loading should be increased every 3 days at increments of 0.16 kg of volatile solids/m^3·d (0.01 lb of volatile solids/d/cu ft) until it has reached the design volatile solids loading rate.

Shutdown. Digester shutdown should be carefully planned. Prior to shutdown, the pressure- and vacuum-relief valves should be inspected for proper operation to avoid damage to the digester cover. At least 5 weeks before shutdown, a gradual reduction in volatile solids loading should be started for the target digester, while the volatile solids loading rate to the digesters remaining on-line is incrementally increased and their liquid levels kept as high as possible to maintain the maximum HRT. Maintaining the

TABLE 30.7 Digester monitoring table.

					Sample location	
Parameter	**Units**	**Test method**	**Target**	**Frequency**	**Feed sludge**	**Recirculated sludge[3] or digested solids**
Temperature[1]	°C (°F)	Meter	32–38 °C (90–100 °F)	Daily		X
Volatile acids	mg/L	5560C[4]	50–330	Daily		X
Alkalinity (Alk)	mg/L	2320[4]	1500–5000	Daily	X	X
VA : Alk ratio	(none)	Calculated	0.1 to 0.2	Daily	N/A	N/A
pH	pH units	Meter	6.8–7.2	Daily	X	X
Total solids[2]	%	2540B[4]	(record)	Daily	X	X
Volatile solids[2]	%	2540E[4]	(record)	Daily	X	X
Flow[2]	Liters (gallons)	Meter	(record)	Daily	X	X
Gas production	cfd	Meter	12 to 16 ft^3/lb volatile solids destroyed	Daily	Gas system	
Gas composition (CO_2)	%	Gas analyzer	Less than 35% CO_2	Daily	Gas system	

[1]Temperatures for mesophilic digesters. Thermophilic digester target temperatures may vary based on design.
[2]Measure total and volatile solids content and flow separately for all feed sludges.
[3]Sampled upstream of raw sludge introduction point.
[4]*Standard Methods* (APHA et al., 2005).

maximum HRT should minimize the biological upsets caused by the higher volatile solids loading. The on-line digester's volatile acid-to-alkalinity (VA : ALK) ratio should be monitored daily and the results posted in a trend chart format to assess the effects of increasing volatile solids loading. If the ratio changes by more than 30%, the excess volatile solids loading should be bypassed to a solids holding tank to avoid a process upset.

At least 1 week before the draining cycle is started, the target digester should be completely removed from the normal fill and draw cycle as follows:

- The digester fill valve closed.
- The digested solids withdrawal valve remains closed.
- The solids heating water pumps are secured.
- The solids-recirculation pumps remain in operation, but the heat exchanger is bypassed.
- The solids mixers remain in operation.
- All target digester-gas header valves are closed, isolating the target digester from the common gas header.

Discontinuing the feeding and heating of the digester should significantly reduce gas production.

Draining the digester tank, if necessary, includes the following additional steps:

- Discontinue mixing.
- Add nitrogen gas to the digester gas headspace to displace the digester gas through the pressure-relief valve. The digester is a confined space, and clearance for maintenance or construction activities should be accomplished in accordance with the contractor's or utility's confined-space-safety plan. The application of an inert gas for purging is effective if rapid entrance to the digester is required. Inert gas application should displace explosive gases, but will not create a safe atmosphere for entry, so forced air ventilation is mandatory.
- Monitor the gas flow using a remote monitoring sensor.

FEEDING AND WITHDRAWAL SCHEDULE. ***Digester Feeding.*** Uniformity and consistency are keys to digester operation. Sudden changes in feed solids volume or concentration, temperature, composition, or withdrawal rates will inhibit digester performance and may lead to foaming. The ideal feeding procedure is a continuous, 24-hour-per-day addition of a blend of different types of feed solids (primary and

WAS). Where continuous feeding is impossible, a 5- to 10-min/h feed cycle is used. Smaller WWTPs that operate a single 8-hour shift use a schedule of at least three feedings: at the beginning, middle, and end of the shift.

Two criteria may determine the digester's capacity to process solids properly: (1) the SRT and (2) the volatile solids loading rate. These criteria determine the amount of food the microorganisms must stabilize and the time available to consume that food. At feed solids concentrations below 3%, the processing capacity is typically limited by SRT. At concentrations higher than 3%, the processing capacity may be affected by the volatile solids loading rate.

For a well-mixed high-rate digester, SRT typically ranges from 15 to 20 days. With total detention times significantly shorter than 15 days, the methane-forming organisms cannot reproduce quickly enough to replace those that are withdrawn. Shorter detention times also reduce the system's buffering capacity (its ability to neutralize volatile acids). Conditions that can shorten detention time include pumping dilute sludge and excessive accumulations of grit and scum in the digester. Sending sludge with the highest possible solids concentration to the digester (within design conditions) will increase the available detention time and reduce heating requirements.

Organic loading rates for a well-mixed and heated digester typically range from 1.6 to 3.2 kg of volatile solids/m^3·d (0.1 to 0.2 lb of volatile solids/d/cu ft). The organic loading rate typically controls the anaerobic digestion process. An *organic overload* is a volatile solids loading that exceeds the daily limits by more than 10%. Typical causes of organic overloads include the following:

- Starting the digester too rapidly,
- Excessive volatile solids loadings as a result of erratic feeding or a change in feed solids composition,
- Volatile solids loadings exceeding the daily limits by more than 10%,
- Loss of active digester volume because of grit accumulation, and
- Inadequate mixing.

Solids Withdrawal. Solids should be withdrawn from the primary digester immediately prior to feeding raw sludge to prevent short-circuiting. In digesters with surface overflow, the timing and rate of solids withdrawal and feed are coordinated to occur concurrently. Solids should be withdrawn at least daily to avoid a sudden drop in the active microorganism population, as well as disruption of the digester's VA:ALK ratio, which would affect its buffering capacity. The primary digester may be regulated to

simply overflow to the secondary digester or to the digested sludge storage tank as raw sludge is added. Solids may be withdrawn from the following locations:

- The bottom of the digester,
- The overflow structure, and
- Any point within a well-mixed digester.

A benefit of removing solids from the bottom of the digester is that it may also remove the grit that accumulates on the bottom of the digester. If possible, solids removal should be performed periodically.

It is important to recognize that, because digestion destroys volatile solids, the concentration of the biosolids removed from the digester will be lower than the feed concentration, unless the digester is decanted.

Decanting. Decanting is used to increase the concentration of digested solids. Because decanting requires a variable liquid level, it can only be used if the digester tank is equipped for pumped withdrawal rather than gravity flow using a static liquid level. Decanting also requires that the digester contents be settled to separate the heavier solids from the supernatant. Because settling involves discontinuing digester mixing, this method is not recommended for primary digesters. The secondary digester is typically mixed or heated until several hours or days before decanting begins.

Decanting should be controlled within a narrow range of liquid levels. The key to its success is slow withdrawal and slow filling. If the secondary digester does not include gas storage, the tank is equipped with decant valves and piping with at least four valves that are located at 12- to 18-in. intervals below the high water level.

Decanting an anaerobic digester involves the following steps:

1. Determine the secondary digester liquid level and verify that an adequate volume is available for decanting. The volume decanted should always be the same to ensure uniform detention time.
2. Collect a sample for laboratory analysis of the settleability of the digested solids using settlometer equipment. Record the results every 30, 60, or 90 minutes, depending on the solids-settling characteristics.
3. Based on the settlometer test results, determine if the secondary digester can be decanted successfully. Settlometer values will vary by installation and must be determined based on decant volume and quality.
4. Allow secondary digester contents to settle for 6 to 8 hours after mixing and solids-heating systems are turned off.

5. Slowly open the lowest decant valve and collect a sample of the decant liquid after 10 minutes of continuous flow. Close the lowest decant valve. Perform a 15-minute centrifuge analysis or microwave test of the sample to determine the approximate total solids concentration.
6. Slowly open the second-lowest decant valve and collect a sample of the decant liquid after 10 minutes of continuous flow. Close the decant valve. Perform a 15-minute centrifuge analysis or microwave test of the sample to determine the approximate total solids concentration.
7. Continue to open, collect samples, and close the various decant valves until you have identified the valve that discharges the decant liquid with the lowest total solids concentration.
8. Continue to sample the decant liquid every 20 minutes to determine its quality and minimize recycling the digester solids to the liquid stream treatment.
9. At the proper liquid level, close all decant valves and restart the heating and mixing systems.

SCUM CONTROL. Scum accumulation in digesters is common. Scum is a combination of undigested grease and oil and often contains buoyant materials, such as plastics, that are not removed at the plant's headworks. Scum floats on the digester liquid surface and can accumulate, forming a dense mat. Properly designed and operated digester mixing systems can typically blend the scum into the tank contents.

If the digester operates without mixing for longer than 8 hours, scum may rise and float on the liquid surface. After mixing is restarted, the scum is resuspended within the liquid. The primary method of scum control is to keep the digester mixing system well-maintained during operation.

DIGESTER CLEANING. The frequency of digester cleaning depends on such factors as influent screening, grit-removal efficiency, and digester mixing and configuration. Normal cleaning frequency for cylindrical digesters is every 2 to 5 years. Because of the complexity of the cleaning procedure, many utilities prefer to operate anaerobic digester systems in a "run-to-failure" mode, which means that the digesters are only cleaned after several years of steadily declining performance.

Cleaning procedures must protect against the known physical hazards of toxic gases, confined-space entry, and materials handling, but also from site-specific unknowns, including the following:

- Failure of internal or external valves and piping,
- Failure of digester roofs or cover coatings,

- Deterioration of concrete,
- Downtime and expense associated with mechanical or structural repairs, and
- Potential for overloading operational digesters.

Failure analysis of mechanical, electrical, and instrumentation systems and implementation of repairs should be considered before digester cleaning. The cleaning process should also include chemical or mechanical cleaning of digester piping systems.

Cleaning must be done using the correct lockout and tagout procedures listed in OSHA Part 1910.333, *Electrical*; confined-space-entry procedures listed in OSHA Part 1910.146, *Permit Required Confined Spaces*; or other applicable safety codes. Precautions should be taken against the following hazards:

- *Asphyxiation or suffocation*—The atmosphere should be tested for oxygen and hydrogen sulfide, and monitoring should be continued for the duration of cleaning.
- *Explosions*—Before anyone enters the digester, it should be purged with a noncombustible gas, such as carbon dioxide (CO_2) or nitrogen (N_2), to eliminate the potential for explosion.
- *Leaks*—Before cleaning is started, all of the digester's cross-connection valves to be cleaned should be secured by being closed, tagged, and locked out. The digester gas valve should also be checked to verify that it does not leak. Circuit breakers that control moving equipment in the tank should be opened and tagged.

As digested sludge is removed from the tank, air can be drawn into the tank through defective sampling ports, open hatches, or vacuum-relief valves, creating an explosion hazard. The most explosive condition is created by a methane–air mixture containing 5 to 20% methane. Monitoring for explosive conditions should be done continuously during cleaning.

After completion of cleaning and before the digester is returned to service, the digester should be refilled with any combination of the following:

- Primary clarifier effluent (preferred),
- Secondary clarifier effluent (unchlorinated),
- Unthickened WAS (before polymer addition), and
- A combination of raw sludge and WAS.

Transferring contents from a "dirty" digester to restart a clean digester is not recommended because the inert matter in the transferred material can form deposits in the newly cleaned digester.

After the liquid in the cleaned digester reaches the minimum mixing level, the heating water pumps, solids-recirculation pumps, and solids-mixing systems should be started. As the digester contents reach the proper operating temperature, the remaining liquid level should be raised using a controlled volatile solids loading program. The anaerobic digestion process should be completely stabilized and operating at the design volatile solids loading rate within 45 days from attaining the proper operating temperature. The total time for efficient and effective digester cleaning is approximately 90 days.

If a digester is to be cleaned by a contractor, the cleaning contract should define the boundaries of the work and provide the following specific information from the owner:

- Digester liquid volume;
- Analytical results of well-mixed digester contents defining the solids composition in terms of metals, nutrients, total solids, and volatile solids concentrations;
- Available disposal site (landfill, onsite lagoon, etc.) and stabilization requirements for the digester contents;
- Quality and quantity of cleaning-process sidestreams returned to the treatment plant;
- Responsibility for opening the digester and venting digester gases—this is best accomplished jointly by plant and contractor staff;
- Cleanliness criteria for tankage and piping;
- Available facilities, including work area dimensions, water supply (flowrate and pressure), and electric power supply (voltage and amperage);
- Quantities, types, and concentrations of solids from the facility that the contractor must process during the digester shutdown; and
- Coordination of lockout and tagout of power and valve isolation.

The contractor's qualifications should include the following:

- Required insurance,
- At least 5 years of actual experience,
- Company-wide and site-specific safety programs,
- Documentation verifying company-wide and site-specific employee training, and
- Appropriate references.

PRECIPITATE FORMATION AND CONTROL. The digestion process can produce crystalline precipitates that affect both the digestion system and downstream solids-handling processes. The precipitates can accumulate on pipes and dewatering equipment, causing damage and blockages and requiring costly and time-consuming maintenance (Figure 30.23). Common precipitates include struvite, vivianite, and calcium carbonate. The constituents that form these precipitates are present in undigested solids and are released during the digestion process and converted to soluble forms that can react and crystallize. Their formation varies from site to site, depending on the chemistry of the digested solids and the treatment processes. Because precipitates preferentially form on rough or irregular surfaces, glass-lined sludge piping and long-radius elbows help minimize their accumulation.

The formation of struvite {magnesium ammonium phosphate [$MgNH_4PO_4 \cdot 6(H_2O)$]} depends on the relative concentrations of these constituents, as well as the pH of the digested sludge. The turbulence caused by pumping and dewatering strips carbon dioxide from the liquid, raising its pH and creating conditions favorable for struvite formation. Struvite formation can be controlled by adding iron salts (ferric chloride or ferric sulfate) or polymeric dispersing agents. Iron salts, which can be added at such locations as the headworks, the final clarifiers, or digesters, react with the phosphate in the solids matrix to form vivianite [$Fe_3(PO_4)_2$]. While some of the available phosphate forms vivianite, the ratio of the remaining phosphate to magnesium and ammonium changes, affecting the struvite reaction. Iron requirements are site-specific, but struvite



FIGURE 30.23 Struvite deposition in pipe.

accumulation can typically be prevented via iron dosages of 7 to 14 kg (15 to 30 lb) of iron (as Fe) per dry ton of solids. Because iron preferentially reacts with hydrogen sulfide, high sulfide concentrations in the solids will increase the iron requirement.

Dispersing agents prevent struvite accumulation by interfering with crystal formation. A number of proprietary dispersing agents are available from polymer manufacturers. Required dosages vary widely.

In such locations as centrifuge centrate lines or belt filter press filtrate lines, plant effluent can be used to dilute the concentration of the limiting constituent below the precipitation threshold.

Vivianite is the desired product when iron is added to control struvite. While vivianite is a crystalline solid like struvite, it remains in the solids matrix rather than accumulating on pipes and equipment, unless iron is added directly upstream from heat exchangers; in the latter case, it can accumulate on heat exchangers, causing plugging and interfering with heat transfer.

Less common precipitates include various calcium complexes, such as calcium carbonate. Causes of calcium scaling are not as clearly understood as struvite or vivianite scaling.

Precipitates that form in pipelines or on equipment can be removed by a combination of acid-washing, pigging, and scraping.

MONITORING AND TESTING. Proper sampling is critical for effective anaerobic digester process-control monitoring. Trend charts are an effective means of tracking changes in digester feed characteristics or operation, as well as predicting possible process upsets. They can be used for monitoring volatile suspended solids, total daily solids feed, VA:ALK ratio, VSR, and gas production. According to trend charts, the rate of change of an individual constituent is more significant than its absolute value.

Anaerobic digestion control is based on samples collected from three points in the digestion process: (1) digester feed, (2) recirculated sludge, and (3) digested solids. Solids sampling points are typically located in the digester building. Each digester has one sampling point for influent and one for discharge.

Samples for performance evaluations should be collected from each active digester. Recommended sampling locations, frequencies, and analyses are listed in Table 30.7. The following guidelines for collecting and analyzing samples are essential to obtaining accurate results:

- The sample must be representative;
- pH analysis must be performed immediately to avoid a deviation in pH due to loss of carbon dioxide;

- All digesters must be sampled in rapid succession;
- All sample containers must be cleaned thoroughly before and after use; and
- If the sample is not analyzed immediately, it must be refrigerated.

After the samples are analyzed, the results should be compared with data from previous analyses to verify that the present data points are within reasonable ranges. If not, additional samples should be collected and analyzed to confirm the results. If data appear to be reasonable, the new data points should be added to the existing trend analyses to gauge overall anaerobic digester performance. If the trend charts indicate movement toward the limits, corrective actions should be taken. Early action may prevent the process parameter from moving outside the desired range. However, a single high or low data point does not constitute a trend. Corrective action should be based on multiple data points that indicate a continued change in digester performance.

Temperature. Microorganisms in the anaerobic digestion process require specific temperature ranges to live and thrive. Digestion nearly ceases at approximately 10 °C (50 °F); however, the microorganisms of concern are most effective in the mesophilic range [30 to 38 °C (85 to 100 °F)]. High-temperature digesters operate in the thermophilic range [55 to 60 °C (131 to 140 °F)]. Regardless of the selected operating temperature, the tank temperature must deviate from that value by more than 0.6 °C (1 °F) per day. Each group of methane-forming microorganisms has an optimum temperature for growth; if the temperature is permitted to fluctuate, the methane formers cannot develop a large, stable population. It is a good practice to log the digester temperature daily to eliminate temperature swings.

pH. Digesters can operate at pH ranges from 6.0 to 8.0, with the desired operating range being 6.8 to 7.2. If the pH falls below 6.0, un-ionized volatile acids become toxic to methane-forming microorganisms. At pH values above 8.0, un-ionized aqueous ammonia (dissolved ammonia) becomes toxic to methane-forming microorganisms. These key pH values reflect the ionization constants for ammonia and acetic acid. The pH of the digester contents is controlled by the amount of volatile acids and alkalinity.

Alkalinity. The digester's buffering capacity, or its ability to resist changes in pH, is indicated by its alkalinity. Calcium, magnesium, and ammonium bicarbonates are examples of buffering substances typically found in a digester. The digestion process produces ammonium bicarbonate; the other buffering substances are contained in raw sludge. The concentration of total alkalinity in a well-established heated digester typically ranges from 1500 to 5000 mg/L. As a rule, the higher the alkalinity, the more

stable the digester. Alkalinity enables the digester to better handle a sudden increase in organic load without upset.

Volatile Acids. Volatile acids are intermediate digestion byproducts. Although typical volatile acid concentrations in an anaerobic digester range from 50 to 300 mg/L, higher concentrations are acceptable if sufficient alkalinity is available to buffer the acid.

Volatile Acid to Alkalinity Ratio. The VA:ALK ratio is an indicator of the progress of digestion and the balance between the acid fermentation and methane fermentation microorganisms. The VA:ALK ratio is shown in Equation 30.7:

$$\text{VA:ALK} = \frac{\text{Volatile acids (mg/L)}}{\text{Alkalinity (mg/L)}} \tag{30.7}$$

Because of the need for balance between volatile acids and alkalinity, the VA:ALK ratio is an excellent indicator of digester health. Careful monitoring of the rate of change in this ratio can indicate a problem before a pH change occurs. The VA:ALK ratio should be approximately 0.1 to 0.2. Digester pH depression and inhibition of methane production occur if the ratio exceeds 0.8; however, ratios higher than 0.3 to 0.4 indicate upset conditions and the need for corrective action (see the "Troubleshooting Guide" section of this chapter).

DIGESTER UPSETS AND CONTROL STRATEGIES. The four basic causes of digester upsets are hydraulic overload, organic overload, temperature stress, and toxic overload. Hydraulic and organic overloads occur when the design hydraulic or organic loading rates are exceeded by more than 10% per day. The overload conditions can be controlled via management of digester feeding, as well as ensuring that the effective digester volume is not diminished by grit accumulation or poor mixing. Digester feeding is controlled via proper operation of upstream headworks, clarifiers, and thickeners to ensure the feed solids concentrations.

In the event of a digester upset, an effective control strategy includes the following steps:

1. Stop or reduce solids feed,
2. Determine the cause of the imbalance,
3. Correct the cause of the imbalance, and
4. Provide pH control until treatment returns to normal.

If only one digester tank is affected, the loading on the remaining units can be carefully increased to allow the upset unit to recover. If overloading is affecting several units,

reducing the feed will require a method of dealing with the excess solids by hauling them to another facility, providing temporary storage onsite, or chemically stabilizing and disposing of them.

Temperature. Temperature-related stress is caused by a change in digester temperature of more than 1 or 2 °C (2 or 3 °F) in fewer than 10 days, which would reduce the biological activity of the methane-forming microorganisms. If the methane formers are not quickly revived, the acid formers, which are unaffected by the temperature change, continue to produce volatile acids, which will eventually consume the available alkalinity and cause the pH to decline.

The most typical causes of temperature stress are overloading solids and exceeding the instantaneous capacity of the heating system. Most heating systems can eventually heat the digester contents to the operating temperature, but not without a harmful temperature variation.

Another cause of temperature stress is operating the digester outside its optimum temperature range. For example, a mesophilic digester has an optimum temperature range of 32 to 38 °C (90 to 100 °F). At temperatures lower than 32 °C (90 °F), the biological process slows. At temperatures above 38 °C (100 °F), the digester efficiency is not improved and the system is wasting energy.

Toxicity Control. The anaerobic process is sensitive to certain compounds, such as sulfides, volatile acids, heavy metals, calcium, sodium, potassium, dissolved oxygen, ammonia, and chlorinated organic compounds. The inhibitory concentration of a substance depends on many variables, including pH, organic loading, temperature, hydraulic loading, the presence of other materials, and the ratio of the toxic substance concentration to the biomass concentration. The inhibitory levels of several compounds are listed in Tables 30.8, 30.9, and 30.10.

Sodium sulfide or ferric or ferrous sulfate can be added to alleviate heavy metal toxicity. Because toxic heavy metal sulfides have low solubility and are less soluble than ferric sulfide, the toxic metals precipitate as sulfides. Ferric chloride can be used to

TABLE 30.8 Effect of ammonia nitrogen on anaerobic digestion (U.S. EPA, 1979).

Ammonia concentration, as N[a] (mg/L)	Effect
50–200	Beneficial
200–1000	No adverse effects
1500–3000	Inhibitory at pH 7.4 to 7.6
>3000	Toxic

[a]Nitrogen

TABLE 30.9 Total concentration of individual metals required to severely inhibit anaerobic digestion (U.S. EPA, 1979).

	Concentration in digester contents		
Metal	**Dry solids (%)**	**Moles metal/kg dry solids**	**Soluble metal (mg/L)**
Copper	0.93	150	0.5
Cadmium	1.08	100	—
Zinc	0.97	150	1.0
Iron	9.56	1710	—
Chromium			
6+	2.20	420	3.0
3+	2.60	500	—
Nickel	—	—	2.0

control sulfide concentration by precipitation as ferric sulfide. Excessive use of these chemicals can result in pH depression.

pH Control. The key to controlling the digester pH is to add bicarbonate alkalinity to react with acids and buffer the system pH to about 7.0. Bicarbonate can be added directly or indirectly as a base that reacts with dissolved carbon dioxide to produce bicarbonate. Chemicals used for pH adjustment include lime, sodium bicarbonate, sodium carbonate, sodium hydroxide, ammonium hydroxide, and gaseous ammonia. Lime addition can be messy and will produce $CaCO_3$. Although ammonia compounds can be used for pH adjustment, they may cause ammonia toxicity and increase the ammonia load on the liquid treatment processes through return streams. Consequently, their use is not recommended.

TABLE 30.10 Stimulating and inhibitory concentrations of light metal cations (U.S. EPA, 1979).

	Concenration (mg/L)		
Cation	**Stimulatory**	**Moderately inhibitory**	**Strongly inhibitory**
Calcium	100–200	2500–4500	8000
Magnesium	75–150	1000–1500	3000
Potassium	200–400	2500–4500	12 000
Sodium	100–200	3500–5500	8000

During a digester upset, volatile acid concentrations may begin to rise before bicarbonate alkalinity is consumed. Because pH depression does not occur until alkalinity is depleted, it may be observed only after the digester is well on its way to failure. The relationships between alkalinity, volatile acids, methane production, carbon dioxide production, and pH during an upset are indicated in Figure 30.24.

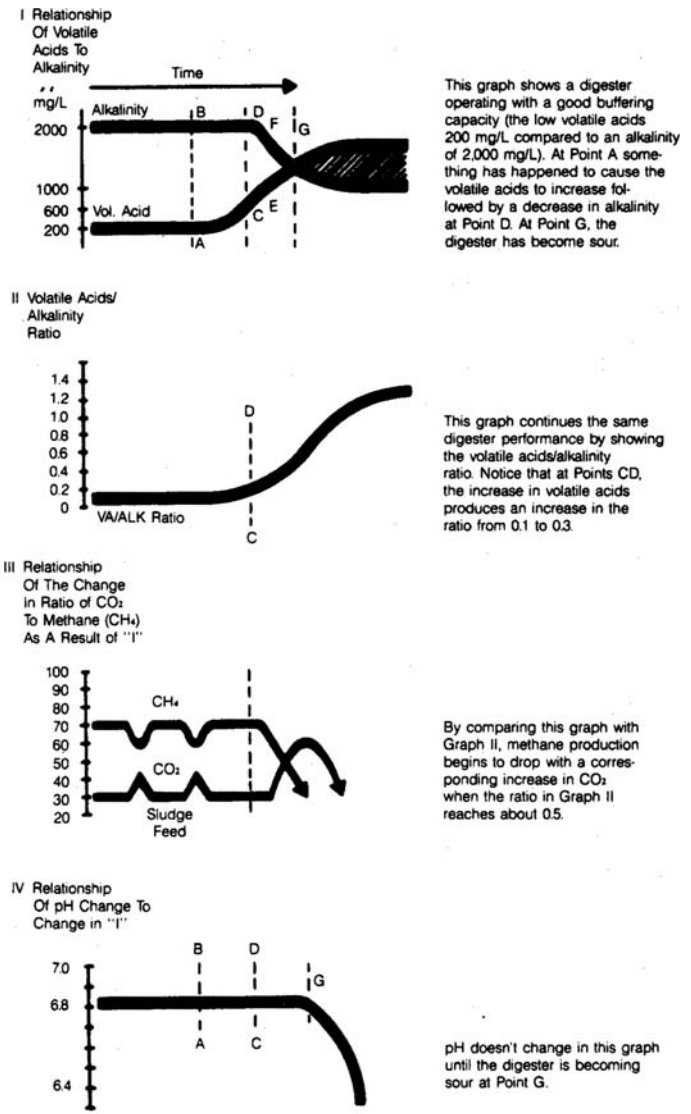


FIGURE 30.24 Change sequence in digester.

The correct chemical dosage for pH control can be calculated based on the measured concentrations of volatile acids and alkalinity. The VA:ALK ratio should be approximately 0.1 to 0.2. When the ratio exceeds 0.3 to 0.4, corrective action should be taken by decreasing the digester volatile solids loading rate from 1.6 kg/m^3·d to 1.2 kg/m^3·d (0.10 to 0.075 lb volatile solids/ft^3·d), which will decrease solids feed and withdrawal rates by approximately 25%, and by maintaining the internal digester sludge temperature at 35 °C (95 °F), ±1 degree.

An increase in the VA:ALK ratio to 0.5 or above indicates a process upset and the need to add alkalinity. The proper alkalinity dosage can be calculated using the volatile acids concentration. The volatile solids loading rate should be decreased from 1.6 kg/m^3·d to 0.8 kg/m^3·d (0.10 to 0.05 lb volatile solids/ft^3·d), which will reduce the solids feed and withdrawal rates by approximately 50%.

Increases in the VA:ALK ratio to 0.8 or above indicate a process upset with pH depression and inhibition of the methane formers. This requires the addition of alkalinity and reduction of volatile solids loading to 0.16 kg/m^3·d (0.01 lb volatile solids/ft^3·d) until the VA:ALK ratio drops to 0.5 or lower.

Alkalinity addition can be calculated using the following procedures:

1. Determine volatile acid and alkalinity concentrations (as $CaCO_3$).
2. Using a target VA:ALK ratio of 0.1 and the measured volatile acids concentration, calculate total desired alkalinity using the following equation:

$$\text{Alkalinity (mg/L)} = \frac{\text{Volatile acids (mg/L)}}{0.1} \tag{30.8}$$

1. Subtract the measured alkalinity value from the alkalinity requirement calculated in Step 2 to determine the alkalinity addition requirement.
2. Calculate the required chemical dosage for the alkalinity addition calculated in Step 3 based on the equivalent weight ratios presented in Table 30.11.
3. Adjust chemical dosages based on the purity of delivered chemical.
4. Determine total chemical addition for the digester based on digester volume and chemical dosage calculated in Step 6 using the following equations:

$$\text{Chemical addition (kg)} = \frac{\text{Alkali addition (mg/L)} \times \text{Digester volume (L)}}{106} \tag{30.9}$$

$$\text{Chemical addition (lb)} = \frac{\text{Alkali addition (mg/L)} \times \text{Digester volume (gal)} \times 8.34\text{(lb/gal)}}{106} \tag{30.10}$$

TABLE 30.11 Alkalinity equivalent weight ratios.

Chemical name	Formula	Ratio
Anhydrous ammonia	NH_3	0.32
Aqua ammonia	NH_4OH	0.70
Anhydrous soda ash	Na_2CO_3	1.06
Caustic soda	NaOH	0.80
Hydrated lime	$Ca(OH)_2$	0.74

Dose the calculated amount of chemical over an extended period to avoid scaling on the heat exchanger or pipelines. Typically, alkalinity is added over a 3- or 4-day period. Mix well, and frequently monitor volatile acids, pH, and alkalinity. Avoid toxicity from the cations associated with the alkalis. Confirm that the vacuum-relief device is operable.

Digester Foaming. Digester foam consists of fine gas bubbles trapped in a semi-liquid matrix with a specific gravity of 0.7 to 0.95. The gas bubbles are generated below the solids layer and are trapped as they form.

While some foaming always occurs, it is considered excessive if it plugs piping or escapes from the digester. Excessive foaming can cause the loss of active digester volume, structural damage, spillage, and damage to the gas-handling system, as well as being malodorous and unsightly. The most common cause of digester foaming is organic overload, which results in the production of more VFAs than can be converted to methane. The acid formers (which release carbon dioxide) work much more quickly than the methane-forming microorganisms. The resulting increase in carbon dioxide typically increases foam formation. Factors that can contribute to organic overload include:

- Intermittent digester feeding;
- Separate feeding or inadequate blending of primary sludge and WAS;
- Insufficient or intermittent digester mixing; and
- Excessive amounts of grease or scum in digester feed (especially problematic if the digester is fed in batches).

Organic overload can be minimized by feeding the digesters continuously (or as often as possible), blending different feed sludges well before feeding, ensuring that the digester-mixing system is operable, and limiting the quantities of grease or scum in the digester feed.

TABLE 30.12 Troubleshooting guide.

Indicators	Probable cause	Check or monitor	Solutions
DIGESTER COVERS—FIXED			
1. Gas pressure higher than normal during freezing weather.	1. Pressure-relief valve stuck or closed.	1. Weights on pressure-relief valve.	1. If freezing is a problem, apply a light grease layer impregnated with rock salt to lever action and springs.
2. Gas pressure lower than normal.	2. a. Pressure-relief valve or other pressure-control devices stuck open. b. Gas line or hose leaking.	2. a. Pressure-relief valve and devices. b. Gas line and/or hose.	2. a. Manually operate pressure and vacuum relief and remove corrosion if present and interfering with operation. b. Repair broken lines as needed.
3. Leaks around metal covers.	3. Anchor bolts pulled loose and/or sealing material moved or cracking.	3. Bolts and sealing materials.	3. Repair concrete with fast-sealing concrete repair material. Apply new sealant material to leaking area using material with durable plasticity.
4. Gas leak through digester cover.	4. Fastener failure.	4. Apply soap solutions to suspected area and check for bubbles.	4. Replace defective fasteners.
DIGESTER COVERS—FLOATING			
1. Cover tilting; little or no scum around the edges.	1. a. Weight distributed unevenly. b. Water from condensation or rainwater collecting inside dome. c. Ice accumulation on surface	1. a. Location of weights. b. Check around the edges of the metal cover. (Some covers with insulating wooden roofs have inspection holes for this purpose.) c. Check for ice on cover	1. a. If moveable ballast or weights are provided, adjust location until the cover is level. If no weights are provided, use sand bags to level cover. (Note: pressure-relief valves may need to be reset if a significant amount of weights is added.) b. Use siphon or other means to remove the water. May also require significant cover repair to eliminate leaks. c. Manually remove ice accumulation
2. Cover tilting; heavy thick scum accumulating around edges.	2. a. Scum accumulation, causing excess drag on cover. b. Guides or rollers out of adjustment. c. Broken rollers.	2. a. Probe with a stick to determine scum accumulation. b. Distance between guides or rollers and the wall. c. Determine the normal position if the suspected broken part is covered by sludge. Verify correct location using manufacturer's information and/or prints if necessary.	2. a. Use chemicals or degreasing agents, such as Digest-aide or Sanfax, to soften the scum. Hose down with water. Continue on regular basis every 2 to 3 months, or more frequently if needed. b. Soften up the scum (as in "2a") and readjust rollers to prevent binding. c. Drain tank if necessary, taking care to prevent binding or uneven cover descent. Use of a crane or jacks may be required to prevent structural damage.

TABLE 30.12 Troubleshooting guide (*continued*).

Indicators	Probable cause	Check or monitor	Solutions
3. Freezing problems in PRV.	3. See fixed digester cover troubleshooting guide, Item 1.	3. See fixed digester cover troubleshooting guide, Item 1.	3. See fixed digester cover troubleshooting guide, Item 1.
DIGESTER COVERS—GAS HOLDER TYPE			
1. Cover guides and/or rollers causing cover to bind.	1. Scum accumulation restricting travel.	1. Check scum accumulation and verify amounts.	1. See floating cover troubleshooting guide, Item 1.
2. Cover binds although rollers and guides are free.	2. Damaged or binding internal guide or guy wires.	2. Lower cover to corbels. Open hatch; vent digester. Using breathing apparatus and explosion proof light, inspect internal equipment from outside digester. If cover movement is restricted, it may be necessary to secure using a crane or by other method to prevent skirt damage to sidewalls.	2. Drain and repair, holding the cover in a fixed position if necessary.
3. Cover tilting, heavy thick scum accumulating around edges.	3. a. Scum accumulation in one area causing excess drag. b. Guides or rollers out of adjustment.	3. a. Probe with a stick to determine scum accumulation. b. Distance between guides or rollers on the wall.	3. a. Use chemicals or degreasing agents, such as Digest-aide or Sanfax, to soften the scum; hose down with water. Continue on regular basis every 2 to 3 months, or more frequently if needed. b. Soften up the scum [as in 3(a)]. Readjust rollers to eliminate skirt binding.
4. Gas pressure higher than normal during freezing weather.	4. a. Water accumulation in gas line. b. Pressure-relief valve stuck or frozen in place.	4. a. Find and eliminate water accumulation point; empty all traps. b. Weights on pressure-relief valve.	4. a. Protect line from weather by covering and insulating overflow box. b. If freezing is a problem, apply light grease layer impregnated with rock salt.
5. Gas pressure lower than normal.	5. a. Pressure-relief valve or other pressure-control devices stuck open. b. Gas line or hose leaking.	5. a. Pressure-relief valve and devices. b. Gas line and/or hose.	5. a. Manually operate pressure and vacuum relief; remove corrosion if present and interfering with operation. b. Repair as needed.

TABLE 30.12 Troubleshooting guide (*continued*).

Indicators	Probable cause	Check or monitor	Solutions
SOLIDS MIXING—MECHANICAL MIXERS			
1. Corrosion of exposed parts by weather and/or corrosive wastewater gas.	1. Lack of paint or other protection.	1. Note presence of rust, corrosion, or bare exposed metal.	1. a. Construction of protective structure. b. Preparation and painting of surfaces.
2. Gear reducer wear.	2. a. Lack of proper lubrication. b. Poor alignment of equipment.	2. Excessive motor amperage; excessive noise; vibration and evidence of shaft wear.	2. a. Verify correct type and amount of lubrication from manufacturer's literature. b. Correct imbalances caused by accumulation of material on the internal moving parts.
3. Shaft seal leaking.	3. Packing dried out or worn.	3. Evidence of gas leakage when checked by soap solution or evident gas odor.	3. a. Follow manufacturer's instructions for repacking. b. Replace packing any time the tank is empty if it is not possible when unit is operating.
4. Wear on internal parts.	4. Grit or misalignment.	4. Visual observation when tank is empty. Compare with manufacturer's drawings for original size. Motor amperage will also decrease as moving parts are worn away.	4. Replace or rebuild. Experience determines the frequency of this operation.
5. Imbalance of internal parts due to accumulation of debris on the moving parts (large-diameter impellers or turbines are most affected).	5. Poor grinding and/or screening.	5. Vibration, heating of motor, excessive amperage, noise.	5. a. Reverse direction of mixer if possible. b. Stop and start alternately. c. Draw down tank and clean moving parts.
6. Power source interruption.	6. High ambient temperature.	6. Excessive amperage, corroded power connections, overheating causing circuits to kick out.	6. Protect motor by covering with ventilator housing.
SOLIDS MIXING—GAS MIXERS			
1. Compressor running hot and/or noisy.	1. a. Low lubricant level. b. High ambient temperature. c. High discharge pressure. d. Clogged suction.	1. a. Check lubricant level. b. Check for excessive ambient temperature. c. Check compressor for excessive wear. d. Check valve discharge position e. Check suction valve position	1. a. Add lubricant b. Provide ventilation if necessary c. Adjust valve position d. Backflush lines

TABLE 30.12 Troubleshooting guide (*continued*).

Indicators	Probable cause	Check or monitor	Solutions
2. Gas feed lines plugging.	2. a. Lack of flow through gas line. b. Debris in gas line.	2. Identify low temperature of gas feed pipes or low pressure in the manometer or pressure gauges.	2. a. Flush out gas lines with water. b. Clean feed lines and valves.
DIGESTER GAS SYSTEM			
1. Gas is leaking through pressure-relief valve (PRV) on roof.	1. Valve not sealing properly or is stuck open.	1. Check the manometer for normal digester gas pressure.	1. Remove PRV cover and move weight holder until it seats properly. Clean and install new ring if needed.
2. Manometer shows digester gas pressure is above normal.	2. a. Obstruction or water in main burner gas line. b. Digester PRV is stuck shut. c. Waste gas burner line pressure-control valve is closed.	2. a. If all points are operating and normal, check for a waste gas line restriction or a plugged or stuck safety device. b. Gas is not escaping properly. c. Gas meters indicate excess gas is being produced, but not going to waste gas burner.	2. a. Purge with nitrogen; drain condensate traps and check for low spots. **Caution:** Do not force air into the digester. b. Remove PRV cover and manually open valve; clean valve seat. c. Open valve
3. Manometer shows digester gas pressure below normal.	3. a. Too-fast withdrawal, causing a vacuum inside digester. b. Too much alkalinity addition.	3. a. Check vacuum breaker to verify it is operating properly. b. Sudden increase in CO_2 in digester gas.	3. a. Stop digester discharge and close off all gas outlets from digester until pressure returns to normal. b. Stop addition of alkalinity.
4. Frozen PRV valve.	4. Winter conditions.	4. Remove valve cover and inspect PRV.	4. Possible remedies: a. Place vented barrel over valve with an explosion-proof light bulb inside.
5. Pressure-regulating valve not opening as pressure increases.	5. a. Inflexible diaphragm. b. Ruptured diaphragm.	5. Isolate valve and open valve cover.	5. a. If no leaks are found (using soap solution), diaphragm may be lubricated and softened using neatsfoot oil. b. Ruptured diaphragm requires replacement.
6. Yellow flame from waste-gas burner.	6. Poor quality gas with high CO_2 content.	6. Check CO_2; content will be higher than normal.	6. Check concentration of solids feed; it may be too dilute. If so, increase solids concentration.
7. Gas flame lower than usual.	7. a. High gas usage. b. Gas leak from digester piping or safety devices. c. Low gas production due to process problems.	7. a. Check gas-production rate against gas usage. b. Check gas-collection and -distribution system, starting at digester main collection point.	7. a. This may be normal. b. Check for leaking gas; when found, isolate and repair.

TABLE 30.12 Troubleshooting guide (*continued*).

Indicators	Probable cause	Check or monitor	Solutions
8. Waste gas burner not lit.	8. a. Pilot flame not burning. b. Obstruction or water in main waste-gas line or pilot natural gas line. c. Pressure-control valve closed due to malfunction.	8. a. Pilot line pressure at waste-gas burner. b. Condensate traps. c. Waste-gas pressure-control valve.	8. a. Re-light natural gas pilot line. b. Drain condensate traps. c. Open valve and verify that setting will allow valve to open when pressure is about 0.06 kPa (¼-in. water column) above all other use point pressures.
9. Gas meter failure.	9. a. Debris in line. b. Electrical failure.	9. a. Condition of gas line. b. Fouled or worn parts.	9. a. Isolate digester; flush gas line with water, moving from digester to point of use. b. Replace worn parts.
SOLIDS TEMPERATURE CONTROL—EXTERNAL HEAT EXCHANGERS			
1. Low rate of solids fed through the exchanger.	1. High temperature override shuts pump down to prevent solids caking on the exchanger.	1. a. Pressure and water temperatures. b. Check high-temperature circuit for hot water heater to verify that the temperature setting is correct.	1. a. Open closed valve on pump. b. Check for and remove obstruction in the solids pump. c. Check for and remove obstruction in heat exchanger. d. Check temperature control valve for proper operation.
2. Recirculation pump not running; power circuits OK.	2. Temperature override in circuit to prevent pumping too-hot water through tubes.	2. Visual check; no pressure on solids line.	2. a. Allow system to cool off. b. Check temperature-control circuits.
3. Solids temperature drops and cannot be maintained at normal level.	3. a. Solids plugging heat exchanger. b. Solids recirculation line is partially or completely plugged.	3. a. Check inlet and outlet pressure and exchanger. b. Check pump inlet and outlet pressure.	3. a. Open heat exchanger and clean. b. Clean recirculation line.
4. Solids temperature rises.	4. Temperature controller is not working properly.	4. Check water temperature and controller setting.	4. If over 49 °C (120 °F), reduce temperature. Repair or replace controller.
5. Temperature readings not accurate.	5. Probes have electrical short or separation internally.	5. Compare with thermometer known to be accurate.	5. Leave probe connected to readout device; immerse in bucket of water at approximate digester temperature with thermometer in it. Compare readings.
6. Unable to maintain temperature.	6. Hydraulic overloading.	6. Feed sludge concentration.	6. Increase influent sludge concentration.

TABLE 30.12 Troubleshooting guide (*continued*).

Indicators	Probable cause	Check or monitor	Solutions
SOLIDS TEMPERATURE CONTROL—INTERNAL HEATING			
1. Low water feed rate to heat exchanger.	1. a. Air lock in line. b. Valve partially closed.	1. Inlet and outlet meter readings lower than normal but equal.	1. a. Bleed air-relief valve. b. Upstream valve may be partially closed.
2. Low heat loss between inlet and outlet water.	2. Coating on tubes.	2. Temperature gauges on inlet and outlet lines read about the same.	2. Remove coating on the water tubes.
3. Solids caked on the outside of the heat exchanger tubing.	3. Temperature too high.	3. Temperature records.	3. a. Remove solids coating. b. Control water temperature to 54 °C (130 °F) maximum.
4. Coating on inside of heat exchanger piping.	4. Temperature too high.	4. Temperature records.	4. May be controlled by adding chemicals to boiler makeup water.
SOLIDS PUMPING AND PIPELINES			
1. Pump suction and discharge pressure erratic. Pump makes unusual sounds.	1. Sand, grease, or debris plugging suction line.	1. Pump suction and discharge pressure.	1. a. Backflush the line with heated digester sludge. b. Use mechanical cleaner. c. Apply water pressure. **Caution:** Do not exceed working line pressure. d. Add approximately 3.6 g/L (3 lb/100 gal) water trisodium phosphate (TSP) or commercial degreaser. (Most convenient method is to fill scum pit to a volume equal to the line, add TSP or other chemical, then admit to the line and let stand for 1 hour.)
DIGESTED SLUDGE			
1. Gray digested sludge.	1. a. Improper digestion. b. Short-circuiting or insufficient mixing.	1. a. Layers of unmixed sludge in tank bottom.	1. a. See solids mixing troubleshooting guide.
2. Sour odor.	2. a. pH of digester is too low. b. Second stage of digestion is not performing properly. c. Overloaded digester.	2. a. Check pH at different levels. b. Check CO_2 content of gas. c. Check volatile solids loading rate.	2. a. Adjust pH using lime or other caustic. b. Let digester rest. c. Reduce volatile solids loading rate.
3. Complete lack of biological activity.	3. Highly toxic waste, such as metals or bacteriocide, in digester feed.	3. a. Gas production (or lack of). b. Analyze sample by spectrophotometer or chemical means.	3. Empty digester and re-start digester.

TABLE 30.12 Troubleshooting guide (*continued*).

Indicators	Probable cause	Check or monitor	Solutions
DECANTING			
1. Foam observed in supernatant from single-stage or primary tank.	1. a. Scum blanket breaking up. b. Excessive gas recirculation.	1. a. Check condition of scum blanket. b. Volatile solids loading.	1. a. Normal condition, but stop withdrawing supernatant if possible. b. This condition may indicate an organic overload in digester, making it necessary to slow down feeding.
2. Lumps and particles of scum in supernatant from single-stage or primary tank.	2. a. Scum layer breaking up due to excessive mixing or gas production. b. Scum layer too thick.	2. a. Observation through window in digester cover. (Unusual increase in gas production is also an indicator.) b. Depth of scum layer, measured through thief hole or through gap between floating cover and digester wall.	2. a. Decrease mixing time, adjust sludge feed b. See scum blanket troubleshooting guide.
3. Supernatant from single-stage or primary tank is gray or brown.	3. a. Inadequate stratification; raw sludge in pockets in the tank. b. Digestion time is too short. Solids concentration is too low, or digester capacity is reduced due to grit and scum accumulation. c. Digester ecological balance is upset. d. Overloading digester.	3. a. Check mixing; under-mixing may be culprit. Take samples at various depths to detect pockets of undigested sludge. Check temperature gradient in the digester. b. Probe digester to determine grit deposits. c. CO_2 content; compare gas production to amount of volatile solids being fed. Gas production should average 0.7 to 1 m^3/kg (12 to 16 cu ft/lb) volatile solids destroyed.	3. a. Increase mixing, feeding frequency, or recirculation. b. Adjust feed concentration. Increase mixing or clean out digester. c. Reduce feed rate or increase detention time by some other means.
4. Supernatant has a sour odor.	4. a. Digester pH is too low. b. Overloaded digester (rotten egg odor). c. Toxic load (rancid butter odor).	4. pH of supernatant should be 6.8.	4. a. Adjust pH using lime or other caustic. b. Reduce volatile solids loading.

TABLE 30.12 Troubleshooting guide (*continued*).

Indicators	Probable cause	Check or monitor	Solutions
5. The supernatant solids are too high, causing plant upset.	5. a. Excessive mixing and not enough settling time. b. Supernatant draw-off point not at same level as supernatant layer. c. Raw sludge feed point too close to supernatant draw-off line. d. Not withdrawing enough digested sludge.	5. a. Observe separation pattern using 10 to 20 L of digester contents in a glass carboy. b. Locate stratum of supernatant by sampling at different depths. c. Determine volatile solids content. Should be close to value found in well-mixed sludge and much lower than raw sludge. d. Compare feed and withdrawal rates; check volatile solids to see if sludge is well digested.	5. a. Allow longer settling periods before withdrawing supernatant. b. Adjust tank operating level or draw-off pipe to get into stratum. c. Modify feed/draw-off piping configuration. d. Increase digested sludge withdrawal rates. **Caution:** Daily withdrawal should not exceed 5% of digester volume.
SCUM BLANKET			
1. Rolling movement is slight or absent.	1. a. Mixer is off. b. Inadequate mixing. c. Scum blanket is too thick.	1. a. Mixer switch or timer. b. Measure blanket thickness.	1. a. May be normal if mixers are set on a timer. If not, and mixers should be operating, check for malfunction. b. Consider increasing the mixing time. c. See Item 4 below.
2. Scum blanket is too high.	2. Supernatant overflow line is plugged.	2. a. Check gas pressure; it may be above normal or relief valve may be venting to atmosphere. b. Check supernatant line for flow.	2. a. Lower contents through bottom draw-off; rod supernatant line to clear plugging. b. Increase mixing time or break up blanket by some other physical means.
3. Scum blanket too thick.	3. Lack of mixing; high grease content.	3. Probe blanket for thickness through thief hole or through gap between floating cover and tank wall.	3. a. Break up blanket using mixers. b. Use solids-recirculation pumps and discharge above the blanket. c. Use Sanfax or Digest-aide to soften blanket. d. Break up blanket physically with pole.
4. Draft tube mixers not moving surface adequately.	4. Scum blanket too high, allowing thin sludge to travel under it.	4. Rolling movement on solids surface.	4. a. Lower solids level to 7 to 10 cm (3 to 4 in.) above top of tube, allowing thick material to be pulled into tube. Continue for 24 to 48 hours. b. Reverse mixing direction (if possible).

While intermittent or insufficient mixing can result in organic overload, it can also allow a scum layer to form on the liquid surface. Feed sludge concentrations higher than the design value can also have an adverse effect on the mixing system.

Blockages in gas piping can also contribute to foaming. If water accumulates in the gas piping, it can cause a blockage, which will increase the pressure in the digester headspace. When the blockage is removed, the sudden drop in pressure can cause the digester contents to foam. Frequent draining of water from the gas system piping will prevent this situation.

Filamentous bacteria, such as *Nocardia*, trap gas in their structure and release surface-active agents that collect on bubble surfaces, causing foaming. Filamentous bacteria can typically be controlled via proper operation of the liquid stream and digester treatment processes.

The type of solids fed to the digesters can also cause foaming problems. Digester feed consisting of 100% WAS or having a high ratio of WAS to primary solids can commonly lead to foaming.

TROUBLESHOOTING GUIDE. Possible indicators and causes of digester problems and recommendations for corrective actions are presented in Table 30.12.

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Chapter 31

Aerobic Digestion

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INTRODUCTION TO AEROBIC DIGESTION

Aerobic digestion is a biological treatment process that uses long-term aeration to stabilize and reduce the total mass of organic waste by biologically destroying volatile solids. This process extends decomposition of solids and regrowth of organisms to a

point where available energy in active cells and storage of waste materials are sufficiently low to permit the waste sludge to be considered stable for land application (see the Rules and Regulations section of this chapter).

Aerobic Digestion may be used to treat (1) waste activated sludge (WAS) only, (2) mixtures of WAS or trickling filter sludge and primary sludge, (3) waste sludge from extended aeration plants, or (4) waste sludge from membrane bioreactors (MBRs). Aerobic digestion treats solids that are mostly a result of growth of the biological mass during the treatment process. The aerobic digestion process renders the digested sludge less likely to generate odors during disposal and reduces bacteriological hazards.

Aerobic digestion was widely used to stabilize waste solids from municipal and industrial wastewater treatment plants (WWTPs) because of their relatively simple operation, low equipment cost, and safety issues. In the past, the disadvantages associated included high energy costs, reduced exothermic-biological energy during cold weather, alkalinity depletion, poor pathogen reduction, poor volatile solids reduction, and poor standard oxygen uptake rates (SOURs). As a result of these performance difficulties, early attempts to use aerobic digestion as a solution to solids disposal and handling regulations led to relatively long solids retention time (SRT) values, which made both the capital and operating cost very unappealing.

Research was initiated by Enviroquip, Inc. (Austin, Texas) in the early 1990s in response to the new performance requirements of the Rules and Regulations for beneficial reuse (U.S. EPA, 1992). Results from their research were presented during a series of aerobic digestion workshops from 1997 to 2001 at the Water Environment Federation (Alexandria, Virginia) conferences. Each year, the work presented during the workshops was compiled in books, resulting in a five-volume series of either hardcopy books or later compact discs, which were all available to the public. Aerobic Digestion Workshops Volumes I through V include comprehensive design guidelines, operational data, and extensive research focused entirely on aerobic digestion and have been used by both the engineering community and operators as reference manuals. Please see the References section at the end of this chapter.

Research resulted in the identification of techniques that improved the process performance of aerobic digestion. These techniques are grouped into the following categories: (1) prethickening, (2) staged operation, (3) aerobic–anoxic operation, and (4) temperature control. These techniques and their benefits are summarized in Table 31.1. These techniques are explored in depth later in this chapter.

The aerobic digestion process was initially used in designs for new plants that normally treated WAS from treatment systems that did not contain a primary settling process, waste activated or trickling filter sludge only, or mixtures of waste activated

TABLE 31.1 Effects of digester improvement techniques on digester performance (Daigger et al., 1997).

Technique	Improvements in aerobic digester performance
1. Prethickening	• Increases SRT in existing facilities • Reduces overall volume requirements • Increases volatile solids destruction • Increases temperature • Accelerates digestion and pathogen destruction rate
2. Staged operation	• Reduces overall volume requirement • Improves solids stabilization • Improves pathogen destruction • Reduces capital cost of aeration equipment and tankage • Reduces oxygen requirement for process and mixing
3. Aerobic-anoxic operation	• Alkalinity recovery and pH balance • Energy savings • Nitrogen removal • Phosphorus removal
4. Temperature control	• Reduces SRT and volume • Reduces capital cost of aeration equipment and tankage • Provides reliable process all year

and trickling filter sludge. Typically, if a primary settling process was incorporated into the design, anaerobic digestion was the process of choice because reliable techniques to thicken and aerobically digest higher than 4% solids were not established at the time. Because of tighter effluent standards on both nitrogen and phosphorus being enforced in the United States in the late 1990s, primary clarifiers were slowly eliminated from the process trains. This was typically done to preserve a good carbon-to-nitrogen ratio (6:1 recommended, 4:1 minimum), which is normally required to achieve successful biological nitrogen removal. As a result of the combination of the new effluent limits and techniques, which provided the capabilities to control aerobic digestion processes and accurately predict the performance of the system, aerobic digestion has become appealing once again. A number of anaerobic digesters have been converted to aerobic digesters because of the relative easy operation and lower equipment cost and because they can produce a better quality supernatant with both lower nitrates and phosphorus, thereby protecting the liquid side upstream. Additional benefits of aerobic digestion are: achieving comparable volatile solids reduction with shorter retention periods; less hazardous cleaning and repairing tasks (California State University, 1991);

and an explosive digester gas is not produced, although the gases produced cannot be used for fuel combustion as in anaerobic digestion. Aerobic digestion has been used primarily in plants of a size less than 19 000 m^3/d (5 mgd), while, above this size, anaerobic digestion was typically the process of choice. However, in recent years, the process has been used in larger WWTPs, with capabilities up to 190 000 m^3/d (50 mgd) (Metcalf and Eddy, 2002; Water Environment Federation, 1998).

DESCRIPTION OF AEROBIC DIGESTION PROCESSES

Aerobic and facultative microorganisms use oxygen and obtain energy from the available biodegradable organic matter in the waste sludge during aerobic digestion. However, when the available food supply in the waste sludge is inadequate, the microorganisms begin to consume their own protoplasm to obtain energy for cell maintenance reactions. Eventually, the cells will undergo lysis, which will release degradable organic matter for use by other microorganisms. The end products of aerobic digestion typically are carbon dioxide, water, and "nondegradable" materials (i.e., polysaccharides, hemicellulose, and cellulose). This phenomenon, called *endogenous respiration*, is approximately described by the following equations (Metcalf and Eddy, 2002; Water Environment Federation, 1995):

$$C_5H_7O_2N + 5O_2 \rightarrow 4CO_2 + H_2O + NH_4HCO_3 \quad (31.1)$$

Destruction of biomass in aerobic digestion

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O \quad (31.2)$$

Nitrification of released ammonia-nitrogen

$$C_5H_7O_2N + 7O_2 \rightarrow 5CO_2 + 3H_2O + HNO_3 \quad (31.3)$$

Complete nitrification

$$2C_5H_7O_2N + 12O_2 \rightarrow 10CO_2 + 5H_2O + NH_4^+ + NO_3^- \quad (31.4)$$

With partial nitrification

$$C_5H_7O_2N + 4NO_3^- + H_2O \rightarrow NH_4^+ + 5HCO_3^- + 2N_2 \quad (31.5)$$

Denitrification using nitrate nitrogen as electron acceptor

$$C_5H_7O_2N + 5.75O_2 \rightarrow 5CO_2 + 0.5N_2 + 3.5H_2O \quad (31.6)$$

With complete nitrification and denitrification

The term $C_5H_7O_2N$ in eq 31.1 is the classic formula for biomass or cellular material in an activated sludge system. The cellular material is oxidized aerobically to carbon dioxide, water, and ammonia. Only approximately 75 to 80% of the cell material can be oxidized; the remaining amount is composed of inert components and organic compounds that are not biodegradable. Ammonia is released as shown in this equation, but then it is combined with some of the carbon dioxide (CO_2) to produce a form of ammonium bicarbonate (NH_4HCO_3). The main observation from this reaction is that aerobic digestion produces both ammonia and alkalinity in the presence of oxygen in the initial phase.

If additional oxygen is provided, then the second reaction will occur as shown in eq 31.2. Ammonia reduction may be required to reduce odors in aerobic digestion; however, the nitrification of the released ammonia also creates nitrate and 2 moles of acidity. The 2 moles of acidity are shown in the form of hydrogen (H^+), which can also be described as a loss of 2 moles of alkalinity.

So, in the first reaction, while the destruction of biomass produces 1 mole of alkalinity as ammonium bicarbonate, the nitrification destroys 2 moles of alkalinity. Depending on the amount of alkalinity in the feed solids, it is very easy to destroy the alkalinity and see dramatic decreases in pH, down to the 5+ range, which begins to adversely affect the digestion process.

If a digester system is capable of recovering the lost alkalinity biologically, without the need of chemical addition through denitrification, not only can nitrogen removal be accomplished, which is important to land application, but also a reduced energy requirement because process air requirements up to 18% could be realized by making use of nitrate instead of using oxygen. If a digester system is capable of complete nitrification and denitrification, then eqs 31.1 to 31.6 apply.

The techniques that enable the operators to successfully control pH, recover lost alkalinity, and optimize aerobic digestion, while saving oxygen, are described in the Design Techniques to Optimize Aerobic Digestion section in this chapter.

A number of variations of the aerobic digestion process exist, including (1) mesophilic conventional, (2) high-purity-oxygen, (3) thermophilic, and (4) cryophilic aerobic digestion. Mesophilic conventional aerobic digestion is the most typically used aerobic digestion process. As a result, the majority of this chapter reviews this process. However, a brief overview of the other aerobic digestion processes follows.

HIGH-PURITY-OXYGEN AEROBIC DIGESTION. High-purity oxygen is used in this aerobic digestion process instead of air. Recycle flows and the resultant sludge are very similar to those obtained through conventional aerobic digestion. Typical influent sludge concentrations may vary from 2 to 4%. High-purity-oxygen aerobic

digestion is particularly applicable in cold weather climates because of its relative insensitivity to changes in ambient air temperatures due to the increased rate of biological activity and the exothermal nature of the process.

High-purity-oxygen aerobic digestion is conducted in either open or closed tanks. Because the digestion process is exothermic in nature, the use of closed tanks will result in a higher operating temperature and a significant increase in the rate of volatile suspended solids reduction. The high-purity-oxygen atmosphere in closed tanks is maintained above the liquid surface, and the oxygen is transferred to the sludge through mechanical aerators. In open tanks, the oxygen is introduced to the sludge by a special diffuser that produces minute oxygen bubbles. The bubbles dissolve before reaching the air–liquid interface (Metcalf and Eddy, 2002). High operating costs are associated with the high-purity-oxygen aerobic digestion process because of the oxygen generation requirement. As a result, high-purity-oxygen aerobic digestion is cost-effective generally only when used in conjunction with a high-purity-oxygen activated sludge system. Neutralization may be required to offset the reduced buffering capacity of the system, (Metcalf and Eddy, 2002).

AUTOTHERMAL THERMOPHILIC AEROBIC DIGESTION. Autothermal thermophilic aerobic digestion (ATAD) represents a variation of both conventional and high-purity-oxygen aerobic digestion. In this process, the feed sludge is prethickened to provide a digester feed solids concentration greater than 4%. The reactors are insulated to conserve the heat produced from the biological degradation of organic solids by thermophilic bacteria. Thermophilic operating temperatures in insulated reactors are in the range 45 to 70 °C, without external supplemental heat provided, other than the aeration and mixing devices located inside the vessels. Because of this phenomenon, the process is termed *autothermal* (Metcalf and Eddy, 2002).

Advantages. The major advantages of ATAD are as follows:

1. Decrease in retention times (smaller volume required to achieve a given suspended solids reduction) to approximately 5 to 6 days to achieve volatile solids reduction of 30 to 50%, similar to conventional aerobic digestion;
2. Greater reduction of bacteria and viruses compared with mesophilic anaerobic digestion (Metcalf and Eddy, 2002); and
3. When the reactors are well-mixed and maintained at 55 °C and above, pathogenic viruses, bacteria, viable helmith ova, and other parasites can be reduced to below detectable levels, thus meeting the pathogen reduction requirements for Class A biosolids.

Disadvantages. The major disadvantages of ATAD are as follows:

1. Poor dewatering characteristics of ATAD biosolids per John Novak (Daigger et al., 1998);
2. Objectionable odors are formed;
3. Lack of nitrification and/or denitrification per Enos Stover (Daigger et al., 1998);
4. High capital cost; and
5. Foam control is required to ensure effective oxygen transfer (Metcalf and Eddy, 2002).

This process is relatively stable, self-regulating with respect to temperature, recovers quickly from minor process upsets, and is not greatly affected by temperature variations of outside air. Because the ATAD system is capable of producing Class A biosolids, it is growing in popularity, with a total of 35 ATAD systems known to be operating in North America in 2003. In excess of 40 plants are operating in Europe (Stensel and Coleman, 2000).

Typical Design Consideration for the Autothermal Aerobic Digestion System. Note that the design parameters that follow have been adapted, in part, from Stensel and Coleman (2000) and from the Water Environment Federation (1998).

Nitrification is Inhibited in the Autothermal Aerobic Digestion Process. Because of the high operating temperatures, nitrification is inhibited, and aerobic destruction of volatile solids occurs, as described by eqs 31.1 to 31.3, without the subsequent reactions, as described in eqs 31.4 to 31.6. Additionally, many, if not all, ATAD systems may be operating under microaerobic conditions, in which oxygen demand exceeds oxygen supply (Stensel and Coleman, 2000). As described elsewhere in this chapter, ammonia is released as a result of digestion. Because nitrification is inhibited in ATAD systems, the pH in the ATAD systems will typically range from 8 to 9. Ammonia-nitrogen produced will be present in the offgas and in solution, with concentrations of several hundred milligrams per liter in each.

Effect of Liquid Sidestreams that Contain Ammonia-Nitrogen. Most of the ammonia-nitrogen will be returned to the liquid process in sidestreams from the odor control and dewatering facilities. If the effluent limits on the liquid side are very low both on nitrogen and phosphorus, the recycle stream can have a negative effect on the plant performance. If the ATAD process is chosen in conjunction with a biological nutrient removal process, both the liquid sidestreams from the odor-control and dewatering systems need to be accounted for or treated separately.

Foam. A substantial amount of foam is generated in the ATAD process as cellular proteins, lipids, and oil-and-grease materials are broken down and released into solution. The foam layer contains high concentrations of biologically active solids that provide insulation. It is important to effectively manage the foam, either with foam cutters or spray systems, to ensure effective oxygen transfer and enhanced biological activity. A freeboard of 0.5 to 1 m (1.65 to 3.3 ft) is recommended (Stensel and Coleman, 2000).

Equipment Design. Table 31.2 shows recommended design patterns for ATAD digester systems.

Prethickening. Thickening or blending facilities may be required to maintain an influent to the ATAD reactor greater than 4% solids.

Basin Configuration. Two or more enclosed insulated reactors in series should be provided and equipped with mixing, aeration, and foam-control equipment.

Continuous or batch processing is acceptable. For compliance with pathogen regulations of Class A biosolids, the withdrawal and feeding of the sludge to the reactors is performed on a batch basis. In this case, the ATAD pumping system is designed to withdraw and feed the daily amount of sludge in 1 hour or less. The reactor is then isolated for the remaining 23 hours each day, at a minimum temperature of 55 °C in stage 2 before disposal.

Figure 31.1 shows data from one of the earliest full-scale ATAD systems in Germany, operating since 1980 (U.S. EPA, 1990). This figure illustrates typical results of various operating parameters during these studies. The system achieved approximately 33% reduction in volatile suspended solids (VSS) for the WAS feed source during the study period. A "sawtooth" temperature curve is evident in both reactors and is the result of batch reactor feeding. During treatment, the pH increased from approximately 6.5 to 8.0.

Post-Autothermal Aerobic Digestion Storage/Dewatering. Post-process cooling is necessary to achieve solids consolidation and enhance dewaterability. Typically, 14 to

TABLE 31.2 Recommended design parameters for ATAD digester systems (Stensel and Coleman, 2000).

Parameters	Range	Typical
Number of reactors	2 to 3	2
Prethickened solids	4 to 6%	4%
Reactors in series		Yes
Total HRT in reactors	4 to 30 days	6 to 8 days
Temperature—stage 1	35 to 60 °C	40 °C
Temperature—stage 2	50 to 70 °C	55 °C

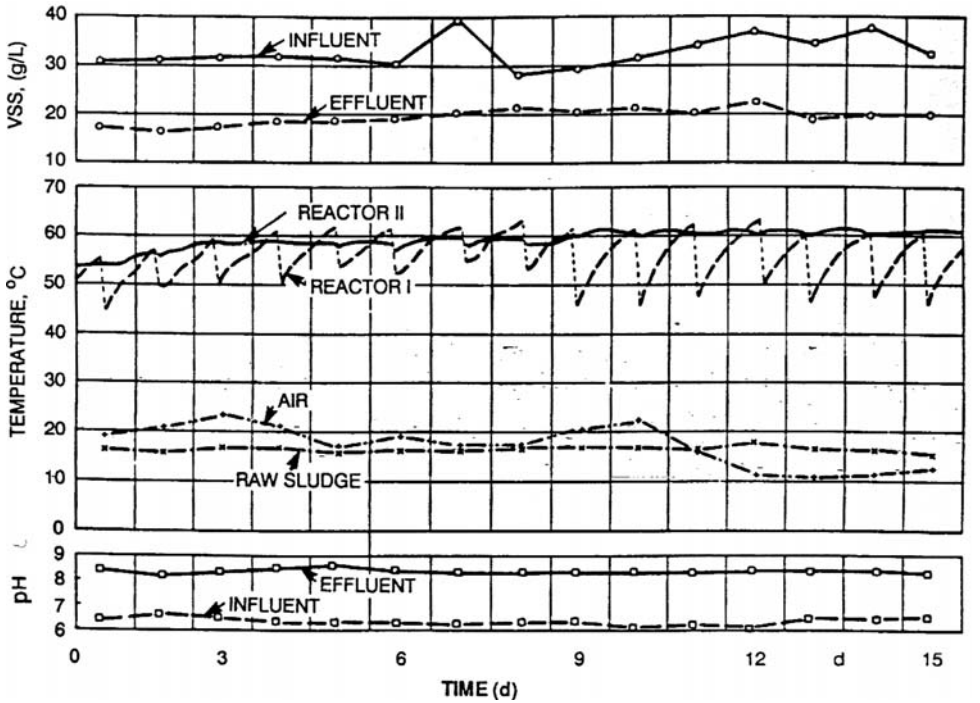


FIGURE 31.1 Data from the ATAD facility in Gemmingen, Germany (U.S. EPA, 1990).

20 days of retention time may be necessary, unless heat exchangers are used for cooling the processed biosolids.

If the reader is interested in more information on the ATAD process, the author suggests review of "Assessment of Innovative Technologies for Wastewater Treatment: Autothermal Aerobic Digestion (ATAD)" by Stensel and Coleman (2000). This document provides detailed information concerning the history, design, operation and maintenance, and performance of these systems, and can be used as an updated version of the Environmental Regulations and Technology document "Autothermal Thermophilic Aerobic Digestion of Municipal Wastewater Sludge" (U.S. EPA, 1990).

CRYOPHILIC AEROBIC DIGESTION. The operation of aerobic digesters at low temperatures (less than 20 °C) is known as *cryophilic aerobic digestion*. Although not widely used, research has been concentrating on optimizing the operation of these digesters. This research has suggested that the sludge age in the digester should be increased as the operating temperatures decrease, to maintain an acceptable level of suspended solids reduction.

CONVENTIONAL (MESOPHILIC) AEROBIC DIGESTION. Historically, the conventional aerobic digestion process was widely used to stabilize waste solids from municipal and industrial WWTPs (Grady et al., 1999). Its advantages include simple design and operation, moderate costs, and the provision of solids storage capabilities. Its disadvantages include high energy costs, reduced biological energy during cold weather, alkalinity depletion, and poor pathogen reduction. If SRT is sufficiently maintained in one or more aerated tanks, much of the biodegradable organic matter added to the digester can be stabilized. However, because of the completely mixed nature of the reactor environment, some biodegradable organic matter remains unstabilized (Grady et al., 1999). More importantly, operation in a completely mixed fashion results in bleedthrough of pathogens to the effluent. Nitrification of released ammonia-nitrogen results in consumption of alkalinity and low pH values, which inhibit digestion (Anderson and Mavinic, 1984; Daigger et al., 1997; Mavinic and Koers, 1979). As a result of these performance difficulties, relatively long SRT values were specified when solids disposal regulations were proposed and subsequently promulgated (Lue-Hing et al., 1998). Because of the above reasons, the interest in the conventional aerobic digestion process decreased.

Research was initiated in response to the new performance requirements for beneficial reuse (U.S. EPA, 1992), resulting in the identification of techniques that can improve process performance (Daigger and Bailey, 2000; Daigger et al., 1997). These techniques can be broadly grouped into the following three categories: (1) prethickening, which uses mechanical devices, such as gravity belt thickeners or gravity thickeners, to thicken before digestion; (2) staged operation, which uses either a tanks-in-series configuration or sequential batch reactor (SBR) operation to increase the plug-flow characteristic in the digester and reduce shortcircuiting; and (3) aerobic–anoxic operation, which cycles the oxygen-transfer device on and off to allow denitrification to occur (Daigger and Bailey, 2000).

DESIGN TECHNIQUES TO OPTIMIZE AEROBIC DIGESTION

PRETHICKENING. ***Advantages of Prethickening.*** The main advantages of this technique include the following:

1. Increased SRT and volatile solids destruction,
2. Accelerated digestion and pathogen destruction rate, and
3. Temperature elevation.

Increased Solids Retention Time and Volatile Solids Destruction. The characteristics of the waste sludge to be digested will be determined by the raw influent to the treatment system and by the treatment processes that precede aerobic digestion. The concentration of sludge to be digested is important to consider. Increasing feed sludge concentrations by thickening will result in longer SRTs with subsequent increased levels of volatile solids destruction.

Accelerated Digestion and Pathogen Destruction Rate. Because the quantity of water that must be heated is reduced, the heat released as a result of the oxidation of the biodegradable organic matter can result in elevated digester temperatures and accelerate digestion and pathogen destruction rates (Grady et al., 1999). The oxidation of biomass results in the release of its heat of combustion (approximately 3.6 kcal/g VSS destroyed) to the reactor.

Temperature Elevation. The resulting temperature increase can be significant. For example, if the feed concentration is 2% (20 000 mg/L), and 30% of the VSS is destroyed in an aerobic digester, sufficient heat is liberated to raise the temperature in the reactor by 21 °C if all of the released heat is conserved (Daigger and Bailey, 2000). The reason a temperature increase in conventional digesters is not typically observed is because, in some operations, the sludge is wasted from the activated sludge process to the digesters at 0.5 to 1.0% solids. The aeration system is shut down for 1 to 2 hours to allow the sludge to settle and the supernatant to form. The supernatant is then decanted, allowing additional sludge to be added; thus, the solids concentration typically increases to 1.5 to 2.0%. This technique reduces the volume of liquid; however, the heat released is used to heat a lot of water; thus, the temperature elevation is marginal.

If the potential exists to capture the heat generated by the volatile solids, it can be used to control the temperature of the reactor. This could be very beneficial in cold climates. Because conventional aerobic digestion typically operates in the range 15 to 35 °C, it is classified as a mesophilic process. On the other hand, it is also important to avoid excessive temperatures, especially in the summer months.

Categories of Prethickening. Prethickened aerobic digestion is divided into five major categories, as described below, based on the thickening treatment processes used (Table 31.3) (more detailed description of these treatment processes and their capabilities is included in Chapter 29).

Category A—Thickening Treatment Process: Batch Operation or Decanting of Aerobic Digester. Batch operation involves the practice of manually decanting digested sludge. Originally, aerobic digestion was operated as a draw-and-fill process, a concept still being used at many facilities. Solids are pumped directly from the clarifiers or SBRs to

TABLE 31.3 Thickening treatment process alternatives (Daigger and Bailey, 2000).

Category	Thickening treatment process
Category A	Batch operation or decanting of aerobic digester
Solids concentration range:	1.25 to 1.75%
Polymer required?	No
Category B	Continuous feed operation using gravity sedimentation, such as gravity thickener, after digestion
Solids concentration range:	1.5 to 2%
Polymer required?	No
Category C	Using gravity thickener in loop with aerobic digestion
Solids concentration range:	2.5 to 3%
Polymer required?	No
Category D	Using membranes for thickening in-loop with aerobic digestion
Solids concentration range:	3 to 3.5%
Polymer required?	No
Category E	Using any mechanical thickener, such as gravity belt thickener, dissolved air flotation (DAF mechanisms) or centrifuge, or drum thickener before aerobic digestion
Solids concentration range:	4 to 8%
Polymer required?	Yes (note that DAF units could also be operated with polymer and achieve 3 to 5% solids. Drum thickeners could be also be operated without polymer and achieve 2 to 3% solids concentration).

the aerobic digester. The time required for filling the digester depends on the tank volume available and the volume of waste sludge. When a diffused air aeration system is used, sludge undergoing digestion is aerated continually during the filling operation. When the sludge is removed from the digester, aeration is discontinued, and the stabilized solids are allowed to settle. The clarified supernatant is then decanted and returned to the treatment process. The thickened solids are removed at a concentration between 1.25 and 1.75% solids.

For batch-feed digesters, the typical operating steps are as follows:

1. Turn off the aeration equipment and allow the solids to settle. To avoid anaerobic conditions, limit the solid–liquid separation to several hours.

2. Decant as much supernatant as possible. For quality control, analyze a sample of the supernatant for pH and suspended solids. It is also recommended to monitor parameters such as VSS, ammonia-nitrogen, nitrate-nitrogen, and alkalinity of the supernatant for the system performance.
3. Draw off the thickened, digested sludge for second-stage digestion or for disposal. For quality control, sample the drawn-off sludge. The digested solids content will be significantly higher when primary sludges are digested. Primary clarifiers can typically produce sludge in the range of 2 to 5% solids concentration. Primary to secondary sludge fed to the digester system is typically in the range of 40:60 to 20:80 primary:secondary by volume, therefore the combined feed to the digester could vary both in digester concentration and volatile reduction.
4. If WWTP flexibility permits, add the new sludge feed to the digester in short, frequent periods of time. It is suggested that the volume and concentration of the sludge added each day be somewhat uniform. At some digester installations, sludge settling and drawoff are performed once per week, while sludge addition or feed is practiced daily. Therefore, the sludge volume in the digester increases daily, until the next decanting and drawoff period.

Disadvantages of this process include the following:

1. Basins are sized based on low solids concentration and high water content. Large volumes are required.
2. High capital cost.
3. High operating cost.
4. No control of alkalinity, temperature, ammonia, nitrates, and phosphorus, as offered by categories C through E (Note: The importance of controlling these parameters is explained, in depth, in the sections to follow. This list is only to be used as a quick reference checklist).
5. Difficult to meet stringent limits on supernatant effluent.

Category B—Thickening Treatment Process: Continuous-Feed Operation Using Sedimentation After Digestion. Category B is the thickening treatment process consisting of continuous-feed operation using sedimentation, such as a gravity thickener, after digestion. This is typically a continuous aerobic digestion process that closely resembles the activated sludge process. Solids are pumped directly from the clarifiers or SBR or MBR into the aerobic digester. The digester operates at a fixed level, with the overflow going to a solid–liquid separator. Thickened and stabilized solids are removed for fur-

ther processing. A lower solids concentration typically is obtained with continuous operation. The category B process can produce marginally better quality effluent than category A because the aerobic digestion basin is operated at a fixed level, and aeration transfer efficiency is optimized.

For continuous-feed digesters, the process can be improved by the following:

1. Adjusting the rate of settled return sludge to obtain the best balance between return sludge concentration and supernatant quality,
2. Adjusting the settling chamber's inlet and outlet flow characteristics to reduce shortcircuiting and unwanted turbulence that hinders solids concentration, and
3. Modifying the weir and piping arrangements.

Disadvantages of this process include the following:

1. Basins are sized based on low solids concentration and high water content. Large volumes are required.
2. High capital cost.
3. High operating cost.
4. No control of alkalinity, temperature, ammonia, nitrates, and phosphorus, as offered by categories C through E (Note: The importance of controlling these parameters is explained in depth in the following sections. This list is only to be used as a quick reference checklist).
5. Difficult to meet stringent limits on supernatant effluent.
6. If nitrification and denitrification is not controlled between the digester and thickener, it leads to anaerobic conditions and undesirable odors (Note: The importance of controlling these parameters is explained in depth in the following sections. This list is only to be used as a quick reference checklist).

Category C—Thickening Treatment Process: Using a Gravity Thickener in Loop with Aerobic Digestion. This process typically consists of two main phases—the in-loop phase and the isolation phase. This process usually includes four main basins, two digesters, one premix basin, and a gravity thickener. For feeds from SBRs and MBRs, additional basins are incorporated to the design to optimize flexibility; however, these four basins are still included as the main components of the process. During the in-loop phase, a digester, a premix, and a thickener operate in loop. The main results during the in-loop phase are the reduction of volatile solids, reduction of ammonia, and an increase in solids concentration. The in-loop thickener has two main functions—it thickens as well as denitrifies. The in-loop digester acts as a volatizer and reduces

the majority of volatile solids. During the isolation phase, no contamination occurs in a digester, and the digester's main function is to complete the additional pathogen reduction to meet the sludge requirements. The digesters are fed in a batch operation, either 8, 16, or 24 times per day; however, the process is considered a "modified batch process" because one digester is fed in short-batch intervals for an extended period of time—typically 10 to 20 days (equal to the length of the in-loop phase)—before it goes to the isolation phase (10 to 20 days). This process produces 2.5 to 3% solids.

Advantages of this process include the following (Note: For points 1, 2, 3, and 4, the importance of controlling these parameters is explained in the following sections. This list is only to be used as a quick reference checklist):

1. Process provides all the benefits of aerobic–anoxic operation.
2. Process provides all the benefits of staged operation.
4. Good control of alkalinity without the need to turn air on and off.
5. Can easily meet stringent limits on supernatant effluent on ammonia, nitrates, phosphorus, and total suspended solids (TSS).
6. Process provides better SOUR and pathogen reduction when compared to categories A and B as a result of true isolation.
7. Moderate capital cost.
8. Low operating cost.
9. No polymer required, achieving 3% solids.

Category D—Thickening Treatment Process: Using Membranes for In-Loop Thickening with Aerobic Digestion. Membrane technology is considered a fairly new process in the United States and has only been used in Europe and Japan for the last 16 years. The thickening applications are even more limited, with the oldest installations operating successfully with no odor issues, typical cleaning frequency of membranes, and no membrane replacements dated back to 1998. Applications range from 3 to 5% solids concentrations, operating in continuous or batch mode, in isolation and in series. The process incorporates a wastewater membrane, which is applicable for high solids. Membranes used for these applications are either flat plate, such as those manufactured by Enviroquip Kubota Company (Texas), or hollow fiber, such as those manufactured by Zenon Membrane Solutions (Oakville, Ontario, Canada). This process can be used in lieu of any of the processes listed in categories A through C; however, it is not recommended that the design solids exceed 3.5%.

Membranes can be fitted into existing basins to provide both thickening and digestion at the same time because airflow is required to clean the membranes.

Designs include two-, three-, four-, or five-basin configurations, operating in batch or in series. Figures 31.2 and 31.3 show two possible operating scenarios using membranes in loop with digestion to thicken to 3% solids. Figure 31.2 shows a five-stage batch operation setup, and Figure 31.3 shows a five-stage, in-series operation setup.

Advantages of this process include the following (Note: For points 1, 3, 4, and 5, the importance of controlling these parameters is explained in depth in the following sections. This list is only to be used as a quick reference checklist):

1. Provides the best control of supernatant effluent because there is no danger of solid overflow resulting in poor supernatant (separate scum removal is not required).
2. Requires small footprint, which is ideal for high-rate digestion.
3. Provides good temperature control.
4. Provides all the benefits of staged operation.
5. Provides all the benefits of aerobic–anoxic operation.
6. Provides better SOUR and pathogen reduction compared with categories A and B, as a result of true isolation.
7. Moderate capital cost (smaller footprint).

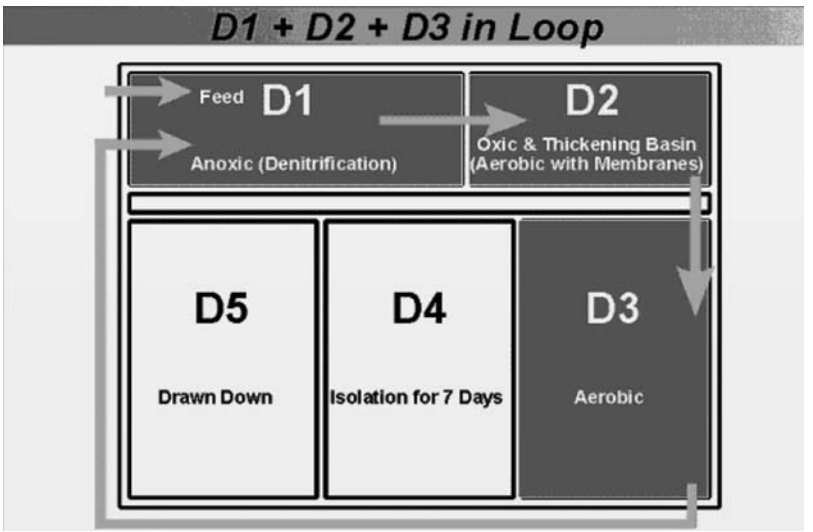


FIGURE 31.2 A five-stage batch operation setup using membranes for in-loop thickening as part of an aerobic digestion process (Daigger et al., 2001).

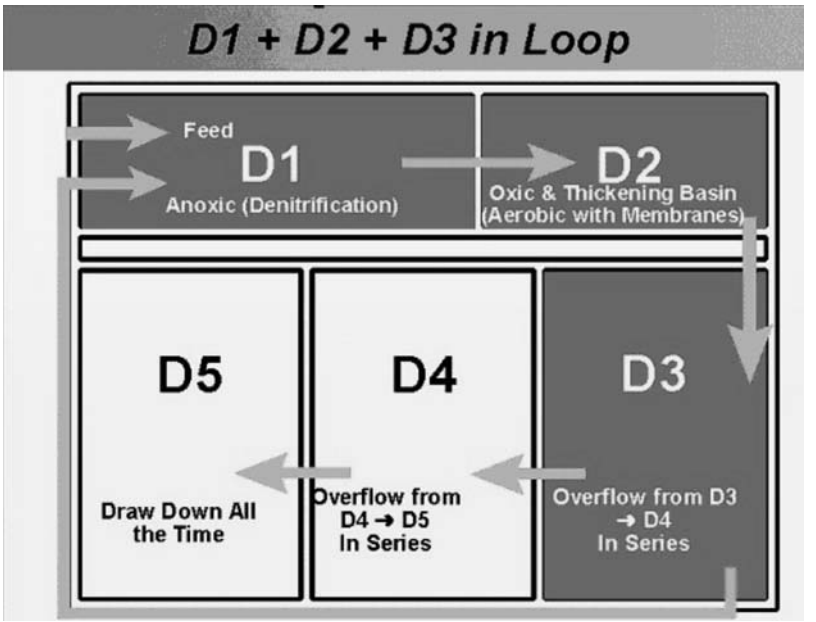


FIGURE 31.3 A five-stage, in-series operation setup using membranes for in-loop thickening as part of an aerobic digestion process (Daigger et al., 2001).

8. Low operating cost (less air is required for the process because the viscosity factor is lower; therefore, the airflow requirement is lower compared with thickened systems using polymer).
9. Following nitrification and denitrification, there is reduced phosphorus release. If a biophosphorus permit applies on the liquid sidestream, the permeate can be treated with alum or ferric chloride; therefore, the phosphorus can be fixed and removed with the sludge (please refer to the Aerobic–Anoxic Operation section of this chapter for more in-depth discussion on phosphorus).

Additional advantages that membranes offer above all other processes with respect to phosphorus removal include the following:

- Membrane plants produce zero TSS.
- It is important to note that the permeate from a membrane digester system is collected in the aerobic phase, as opposed to the supernatant or decant that is typically collected from an anoxic phase on the systems in all the other categories described above.

- Most membrane systems in thickening applications operate at approximately 0.5 to 1 mg/L dissolved oxygen, which is ideal for this application.
- Another factor that affects phosphorus, ammonia, and nitrogen is pH. Membrane systems include an anoxic zone to balance alkalinity, so pH balancing is always integral to the process.

Category E—Thickening Treatment Process: Using Any Mechanical Thickener Before Aerobic Digestion. Category E is the thickening treatment process using any mechanical thickener, such as a gravity belt thickener, dissolved air flotation mechanism, centrifuge, or drum thickener before aerobic digestion. This process uses mechanical prethickening devices that use polymers as conditioning agents to maximize thickening. The designer can choose the ideal mechanical device and desired operating solids concentration, such as 4, 5, or 6%, to maximize the reduction of the aerobic digestion basins. This process gives ultimate process control to the operator to meet performance in the summer and winter by modifying the schedule of the operation of the mechanical device as desired. For this process, two digesters in series are recommended, as a minimum (in-series operation will be addressed later in this chapter). Because of the flexibility and reliability of the process and the capital and operating cost savings, this process is also preferred in WWTP designs capable of handling more than 7600 m^3/d (2.0 mgd) in flow.

Advantages of this process include the following:

1. Provides the ultimate process control of treatment of solids.
2. Provides the capabilities to maximize reduction in volume by choosing the ideal machine and ideal solids concentration for the application.
3. Maximizes reduction in footprint, which is ideal for high-rate digestion (a deep tank is necessary).
4. Provides the best temperature control when flexibility is included in the design (cold weather not an issue with these systems, however, provisions may be required to prevent thermophilic conditions in the summer).
5. Provides all the benefits of staged operation.
6. Provides all the benefits of aerobic–anoxic operation.
7. Following nitrification and denitrification, there is reduced phosphorus release. If a biophosphorus permit applies on the liquid stream, treat the permeate with alum or ferric chloride. Phosphorus can be fixed and removed with sludge.
8. Provides excellent SOUR and pathogen reduction.
9. Moderate capital cost.

10. Low operating cost. The alpha values and transfer efficiency are lower in higher solids concentration digester of 4 to 6% compared with digesters operating in the range 2 to 3%. However, because of the reduced basin volume required for these systems, the airflow required for both process and mixing is comparable. Mixing requirements typically are higher than process air requirements for systems with lower solids concentration, so, in comparison, the overall operating horsepower for higher solids is less.
11. While in the prethickened mode, supernatant is not produced because the liquid in the digesters are in the thixotropic stage.

BASIN CONFIGURATION—STAGED OPERATION OR BATCH (MULTIPLE BASINS). Traditional aerobic digester basins have been designed as single basins, and, if multiple basins were supplied, they were typically operated in parallel.

As described below, multiple tanks in series or in isolation operated in a batch operation have proven to improve both the pathogen destruction and SOUR. For this reason, this chapter will focus on the staged operation systems.

The Environmental Regulations and Technology manual "Control of Pathogens and Vector Attraction in Sewage Sludge" (U.S. EPA, 1999a) offers the following comments on both batch and staged operation. Sludge can be aerobically digested using a variety of process configurations, including continuously fed or fed in a batch mode, in a single- or multi-stage. Batch operation will typically produce less volatile solids reductions for primary sludge than the other options because there are lower numbers of aerobic microorganisms in it. Single-stage completely mixed reactors with continuous feed and withdrawal are the least effective of these options for bacterial and viral destruction, mainly because organisms that have been exposed to the adverse conditions of the digester for a short time can leak through to the product sludge.

Probably the most practical alternative to a single-stage completely mixed reactor is staged operation, such as the use of two or more completely mixed digesters in series. The amount of processed sludge passing from inlet to outlet would be greatly reduced compared with single-stage operation. If the kinetics of the reduction in the pathogen densities is known, it is possible to estimate how much improvement can be made by staged operation.

Farrah et al. (1986) have shown that the decline in densities of enteric bacteria and viruses follow first-order kinetics. If first-order kinetics are assumed to be correct, it can be shown that a 1-log reduction of organisms is achieved in half as much time in a two-stage reactor (of equal volume in each stage) as in a one-stage reactor. Direct experimental verification of this prediction has not been carried out, but Lee et al. (1989) have qualitatively verified the effect.

It is reasonable to give credit for an improved operating mode. However, because not all factors involved in the decay of microorganisms' densities are known, some factor of safety should be introduced. It is recommended that for staged operation using two stages of approximately equal volume, the time required be reduced to 70% of the time required for single-stage aerobic digestion in a continuously mixed reactor. This allows a 30% reduction in time instead of the 50% estimated from theoretical considerations. The same reduction is recommended for batch operation or for more than two stages in series. Thus, the time required would be reduced from 40 to 28 days at 20 °C (68 °F), and from 60 to 42 days at 15 °C (59 °F). These reduced times are also more than sufficient to achieve adequate vector attraction reduction. Approval of this process as a Process to Significantly Reduce Pathogens (PSRP) by the permitting authority may be required in specific states in the United States. For more information on this topic, please refer to the Solids Retention Time × Temperature Product section.

The benefits of a two-stage reactor system in series or in isolation include the following (Note: Please see more information about points 5 and 6 in the Dissolved Oxygen and Oxygen Requirements section of this chapter):

1. Improvement in pathogen destruction;
2. Improvement in SOUR;
3. Capital cost reduction of aeration equipment;
4. Capital cost reduction of tankage;
5. Air flow reduction, as a result of process requirements in the first digester; and
6. Air flow reduction, as a result of mixing requirements in the second digester.

AEROBIC–ANOXIC OPERATION. This technique enables operators to successfully nitrify/denitrify, control pH, recover lost alkalinity, and optimize aerobic digestion, while saving energy.

Nitrification and Denitrification. As described in the Description of Aerobic Digestion Processes section of this chapter, the oxidation of biomass produces carbon dioxide, water, and ammonia, as described in eq 31.1.

Table 31.4 includes a summary of the nitrification and denitrification eqs 31.1 to 31.6 presented earlier in this chapter to facilitate the explanation of the process.

Ammonia is combined with some of the carbon dioxide to produce a form of ammonium bicarbonate. Often, partial nitrification occurs, and a portion of the nitrogen is left as ammonia. The system will nitrify until the pH drops enough that it begins to

TABLE 31.4 Summary of the nitrification and denitrification equations (Daigger et al., 1997).

$C_5H_7O_2N + 5O_2 \rightarrow 4CO_2 + H_2O + NH_4HCO_3$ Destruction of biomass in aerobic digestion	(31.1)
$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$ Nitrification of released ammonia-nitrogen	(31.2)
$C_5H_7O_2N + 7O_2 \rightarrow 5CO_2 + 3H_2O + HNO_3$ Complete nitrification	(31.3)
$2C_5H_7O_2N + 12O_2 \rightarrow 10CO_2 + 5H_2O + NH_4^+ + NO_3^-$ With partial nitrification	(31.4)
$C_5H_7O_2N + 4NO_3^- + H_2O \rightarrow NH_4^+ + 5HCO_3^- + 2N_2$ Denitrification using nitrate-nitrogen as electron acceptor	(31.5)
$C_5H_7O_2N + 5.75O_2 \rightarrow 5CO_2 + 0.5N_2 + 3.5H_2O$ With complete nitrification and denitrification	(31.6)

inhibit the nitrifying bacteria, as illustrated by eq 31.4 (with partial nitrification). This occurs where there is only an inconsequential amount of alkalinity in the sludge that is fed to the digester. In this case, there could be a mixture of both ammonia and nitrate produced at the same time, as is evidenced by a number of installations across the country. An example of this could be during the so-called "decant or supernating phase" of digestion, where an accumulation of ammonia in the sludge cannot be removed, because there is not enough alkalinity to drive the reaction, resulting in odors.

If the oxygen in the nitrate can be used as an oxygen source to stabilize biomass, as it is used in the liquid stream processes, then both nitrification and denitrification can be accomplished, as shown in eq 31.5. Oxidizing biomass with nitrates releases ammonia once again (as in eq 31.1) and also produces nitrogen gas plus bicarbonate, which is again a form of alkalinity.

Equation 31.6 shows a balanced stoichiometric equation of nitrification and denitrification. As shown in this equation, oxidized biomass is converted to carbon dioxide, nitrogen gas, and water.

Nitrification and denitrification can be achieved by the following:

1. Turning the air on and off (typically 75% on, 25% off), or
2. Running at low dissolved oxygen and creating conditions to allow simultaneous nitrification and denitrification to occur.

Both of these operating procedures are similar to those used in the liquid stream.

Benefits of the nitrification and denitrification process include the following:

1. Alkalinity recovery and pH balance,
2. Energy savings,
3. Dissolved oxygen and oxygen requirements,
4. Nitrogen removal, and
5. Phosphorus removal.

As shown from studies conducted in Kuwait in a controlled environment at 20 °C and an SRT of 10 days, the length of the anoxic stage was optimized at 8 to 16 h/d (Al-Ghusain et al., 2004). Figure 31.4 shows that total nitrogen removal in the filtrate is optimized at 8 hours of anoxic cycle (Al-Ghusain et al., 2004).

Alkalinity Recovery and pH Balance. If complete nitrification and denitrification occurs, from an alkalinity prospective, the following is true:

Destruction of biomass produces 1 mole of alkalinity	=	+1 mole of alkalinity
Nitrification destroys 2 moles of alkalinity	=	−2 moles of alkalinity
Denitrification produces 1 mole of alkalinity	=	+1 mole of alkalinity
Alkalinity consumption during nitrification and denitrification	=	0 moles of alkalinity

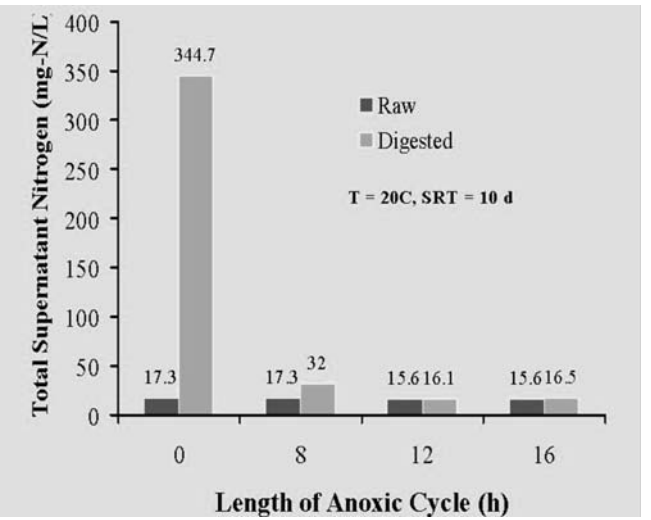


FIGURE 31.4 Evaluating the effect of digestion temperature on the concentration of total nitrogen in the filtrate shows that the highest concentration of total filtrate nitrogen occurred at 30 °C and the lowest at 20 °C (Al-Ghusain et al., 2004).

The end result and benefit of full nitrification and denitrification is that no alkalinity is consumed in the aerobic digestion process.

If sufficient alkalinity is available in the feed solids, an approximately neutral pH will be maintained. If complete nitrification and denitrification occurs by incorporating an anoxic cycle, the residual of ammonia and nitrate is typically in the range 10 to 20 mg/L (Hao and Kim, 1990; Hao et al., 1991; Matzuda et al., 1988; Peddie et al., 1990). This is one reason that pH is a primary indicator of controlling aerobic digestion processes and enables operators to optimize nitrification and denitrification techniques. If sufficient alkalinity in the feed is not available to balance the pH biologically, then an addition of chemicals to the digester will be required. Sodium bicarbonate can be added to the feed sludge, or lime or sodium hydroxide can be added to the digester directly to solve the problem. Figure 31.5 is from a study evaluating the effect of both

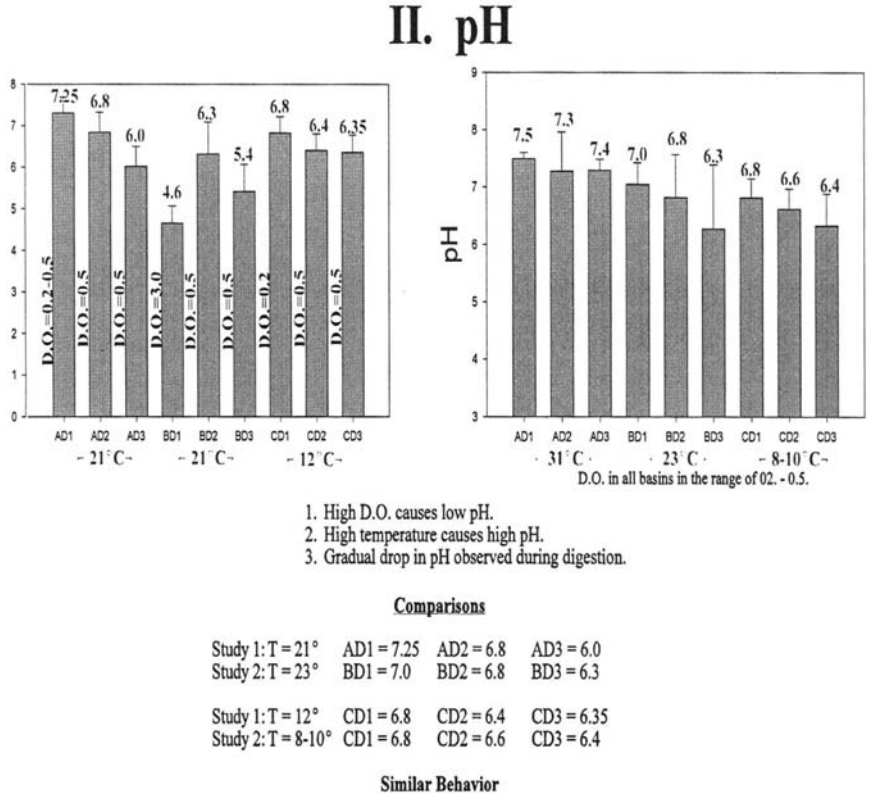


FIGURE 31.5 Effect of pH levels in an aerobic digester (D.O. = dissolved oxygen) (Daigger et al., 1999).

high dissolved oxygen and high temperature on pH fluctuation in a three-stage digester system (Daigger et al., 1999). Observations from the study were as follows:

1. High dissolved oxygen causes low pH. This is most obvious when we compare the pH in AD1 at 7.25 and in BD1 (high dissolved oxygen) at 4.6. Both basins operate at the same temperature (21 °C). This indicates that active nitrification converts the ammonia to acidic nitrate and causes low pH.
2. High temperature causes high pH. Once again, at a higher temperature, there is faster generation of ammonia from the heterotrophic protein degradation.

Energy Savings. The process oxygen requirement is also reduced from 7 moles oxygen/mole biomass destroyed for the fully aerobic process (eq 31.3), to 5.75 moles oxygen/mole biomass destroyed for the anoxic–aerobic digestion process (eq 31.6). If complete nitrification and denitrification occurs from the oxygen source, energy savings can be realized, as shown below:

Destruction of biomass requires	5 moles oxygen
Complete nitrification requires	7.00 moles oxygen
Complete nitrification and denitrification requires	5.75 moles oxygen
Net savings from nitrification and denitrification	1.25 moles oxygen

Approximately 18% of energy savings can be realized based on reduced process energy requirements because of reduced process oxygen requirements during the anoxic phase.

Dissolved Oxygen and Oxygen Requirements. The characteristics of the sludges pumped to the aerobic digesters will determine the oxygen requirements for the process. The oxygen requirements that must be satisfied are those of the microorganisms (cell tissue) in the digestion process and, with mixed sludges, the biochemical oxygen demand (BOD) in the primary sludge.

The viscosity of undigested WAS is much higher than water and changes with sludge concentration and temperature. Undigested sludges at 6% solids have four times the viscosity of digested sludge. Thus, during the critical first stage of digestion, when oxygen demand is highest and the sludge is most viscous, intense mixing is essential to ensure that oxygen transfer occurs.

When prethickened sludges are fed to the aerobic digester, the oxygen uptake rate in the first part of the digester is extremely high, with as much as 70 to 80% of the total oxygen requirement needed in the first 10 days SRT, if the temperature is approxi-

mately 17 to 20 °C. The aeration system must be designed so that there is enough built-in flexibility to ensure that the oxygen profile in each basin matches the oxygen demand. If adequate oxygen is not available, anaerobic conditions will occur in parts of the digester, and odors and ammonia released will remain in the system. When calculating air requirements, 0.9 kg oxygen/0.5 kg VSS (2 lb oxygen/lb VSS) should be allowed, based on the expected destroyed volatile solids quantity. Sufficient air should then be provided to ensure that 1 to 2 mg/L oxygen could be maintained during the aerobic phase, if required. This enables the nitrification phase to operate at high dissolved oxygen.

Care should be taken when relating clean water transfer efficiency to prethickened sludge applications. From an operator's point-of-view, it is important to remember that traditional oxygen transfer efficiency factors should be downgraded by at least 25 to 45% when compared with the performance of the same product used in the liquid sidestream. The viscosity correction factor makes an allowance for the additional airflow required to overcome the negative effects of thixotropic sludges. The system should be designed to provide adequate velocity gradient, shearing action, and intense mixing, all required to enable oxygen to be transferred to the waste of extremely viscous materials, such as 4 to 8% solids feed, as required for volatile solids reduction.

Maintaining adequate oxygen levels allows the biological process to take place and prevents objectionable odors. In aerobic digesters, a typical dissolved oxygen level range is from 0.1 to 3.0 mg/L. Inadequate dissolved oxygen levels result in incomplete digestion and, more importantly, odor problems. On the other hand, by using low dissolved oxygen, there is potentially large energy savings resulting from simultaneous nitrification and denitrification.

The effect of low dissolved oxygen in pathogen destruction and volatile solids destruction was evaluated and later reported (Daigger et al., 1999). As concluded from this study and shown in Figure 31.6, low dissolved oxygen did not have any negative effect on either pathogen destruction or volatile solids destruction. A summary of the results are as follows:

1. No apparent drawbacks in pathogen destruction and volatile solids reduction resulting from low dissolved oxygen operation,
2. Low dissolved oxygen gives large energy savings, and
3. High dissolved oxygen causes low pH.

Nitrogen Removal in Biosolids and Filtrate or Supernatant. Although ammonia and nitrogen reduction is not typically a goal of aerobic digestion, design-loading rates for land application of biosolids can be limited by pollutants, such as heavy metals, or

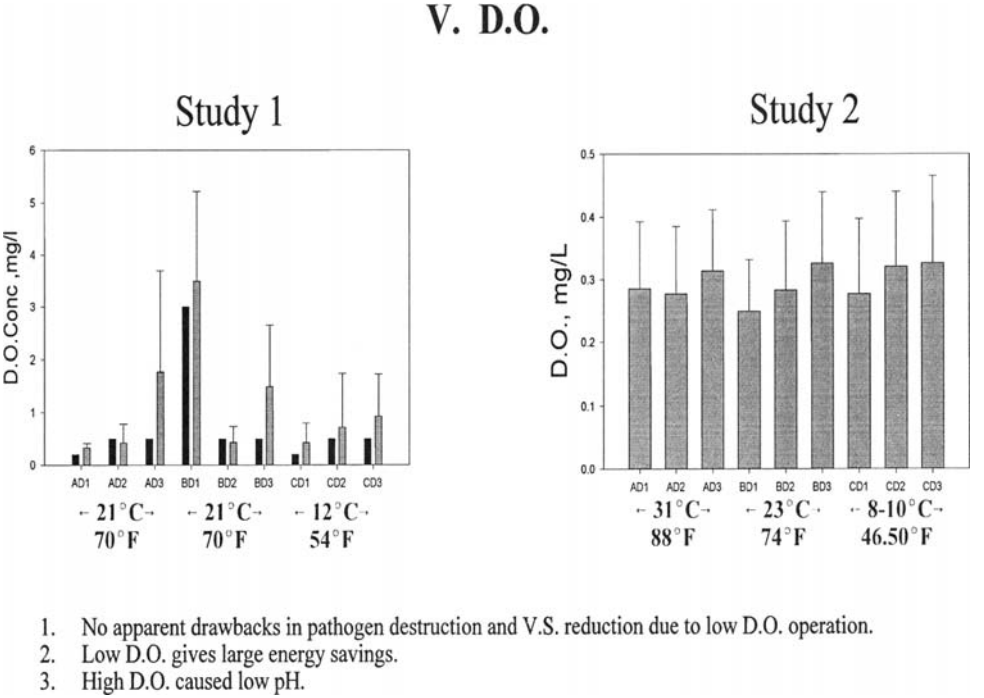


FIGURE 31.6 Effect of low dissolved oxygen in pathogen destruction and volatile solids destruction (D.O. = dissolved oxygen) (Daigger et al., 1999).

by nitrogen. The long-term loading of heavy metals is based on U.S. EPA 503 regulations (U.S. EPA, 1999b). The annual loading rate is typically limited by the nitrogen loading rate. These rates typically are set to match the available nitrogen provided by commercial fertilizers (Chang et al., 1995; Metcalf and Eddy, 2002). Because municipal biosolids represent a slow-release organic fertilizer, a combination of ammonia and organic nitrogen must be included in calculations of the application rate (Metcalf and Eddy, 2002). Conventional aerobic digestion operated in the aerobic–anoxic mode, providing full nitrification and denitrification, is the most ideal of the aerobic digestion processes to meet these requirements.

Another advantage of aerobic–anoxic sludge digestion is the ability to reduce the amount of nutrients, especially nitrogen in the filtrate or supernatant, thus reducing the load to the plant resulting from the recycle of filtrate for further treatment (Al-Ghusain et al., 2004). In a recent study, various forms of nitrogen were analyzed throughout the digestion period. The total nitrogen in the sludge filtrate (nitrite [NO_2], nitrate [NO_3], ammonium [NH_4], and organic nitrogen) was calculated for the reactors.

The data showed that there was no profound effect by the SRT (10 and 20 days), at an elevated temperature of 30 °C and anoxic time of 8 hours, on the concentration of total nitrogen in the reactor. Figure 31.4 shows the buildup of nitrogen species in the aerobic digester (with continuous aeration) in contrast to the much lower levels of nitrogen in the aerobic–anoxic digester at anoxic cycle lengths of 8, 12, and 16 hours, respectively. In the same study, the length of the anoxic cycle was evaluated at 20 °C and an SRT of 10 days, indicating that the use of an 8-hour anoxic cycle provides the optimum trade-off between energy saving and quality of sludge stabilization. Figure 31.7 shows the effect of the anoxic cycle on VSS removal (Al-Ghusain et al., 2004). In the same study (Al-Ghusain et al., 2004), the sludge dewaterability was tested using a filtration test on both aerobically digested sludge and aerobic–anoxic digested sludge. This study showed that aerobic–anoxic digestion reduces the resistance to filtration (i.e., improves sludge dewaterability).

Phosphorus Reduction in Biosolids and Biophosphorus. Biological phosphorus release occurs in the anaerobic zone of the liquid stream, where there is BOD uptake and phosphorus release. The aerobic zone provides the environment where BOD is oxidized and phosphorus is taken back up, increasing the population of high-phosphorus-content organisms, so that when the waste is removed, the waste sludge may have an

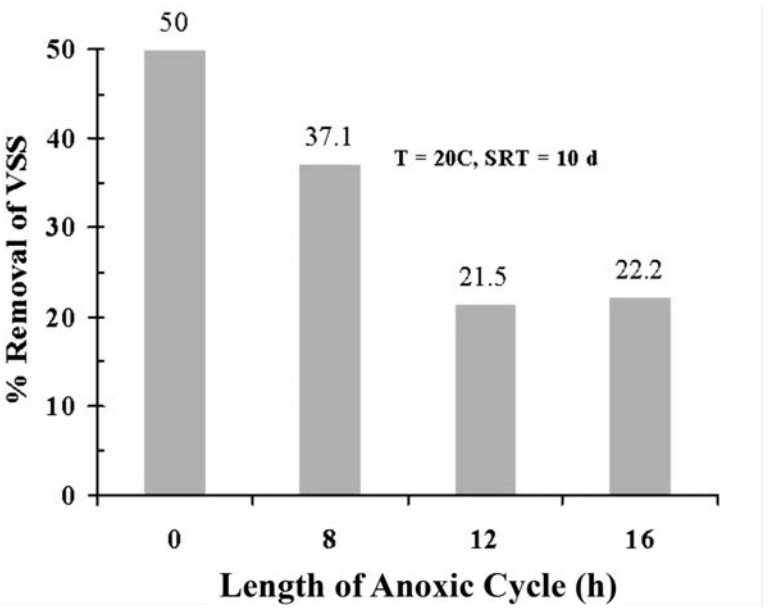


FIGURE 31.7 Effect of anoxic cycle on VSS removal (Al-Ghusain et al., 2004).

overall phosphorus content of 5 to 7%. In the aerobic digester, the organisms destroy themselves through digestion, so the phosphorus that is contained within them is released into solution. As a result, a high concentration of phosphorus may be found in solution. From an overall mass-balance prospective, the phosphorus coming into the digester ends up either in the waste sludge or in the effluent. If the phosphorus is not allowed to move forward with the sludge, then it will be recycled back to the head of the plant. Phosphorus will be released from both anaerobic and aerobic digestion; however, the release is lower from aerobic processes than from anaerobic processes.

It has been proven through experimental work of Lu Kwang Ju (Daigger et al., 2001) and in full-scale installations that cyclic operation of air on and off, or under low dissolved oxygen conditions (which provides simultaneous nitrification and denitrification), minimizes phosphorus release. As shown in Figure 31.8, when sludge was tested from a biophosphorus facility (Ozark WWTP, Kansas), if it was digested under fully aerobic conditions, the phosphorus release was in the range 120 to 150 mg/L. On the other hand, if the same sludge was digested under cyclic operation, it produced phosphorus in the range 70 to 90 mg/L after 500 hours of operation. The rate of phosphorus release and uptake decreases with time. For comparison, under similar cyclic operation

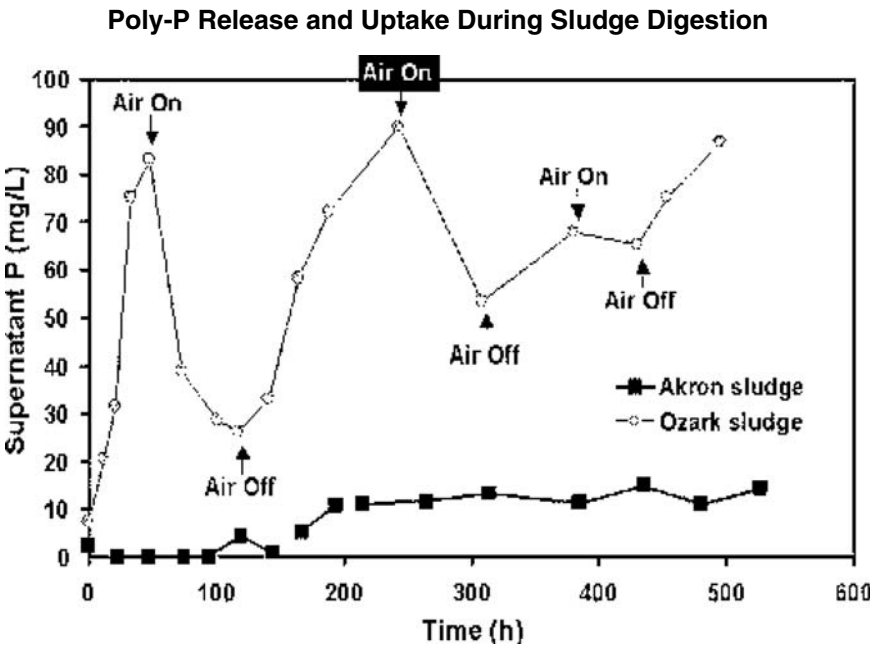


FIGURE 31.8 Polyphosphorus release and uptake of phosphorus during sludge digestion (Daigger et al., 2001).

on sludge from a nonbiophosphorus facility (Akron WWTP, Ohio), the sludge did not show any fluctuation in the phosphorus profile because this sludge did not have any biophosphorus in it; however, it was in the range 10 to 20 mg/L.

Another factor that affects phosphorus, ammonia, and nitrogen is pH. Conclusions from the same study (Daigger et al., 2001) showed that a pH less than 6.0 should be avoided because it encourages dissolution of the inorganic metal phosphates.

Option I: Liquid Disposal—No Restriction of Phosphorus on Land Application. Assuming that a system is designed as a two-stage-in-series, prethickened aerobic digester using a mechanical thickener that can thicken to 6% solids, the expected solids leaving the system would be approximately 3.6%. Figure 31.9 shows a typical prethickened application for liquid disposal with no phosphorus limit restriction on land application per Jim Porteous (Daigger et al., 2000). The necessary steps for option I are as follows:

1. The main design consideration, in this case is that the sludge being fed to the prethickening device remains aerobic.
2. To prevent anaerobic conditions, the sludge should be wasted directly from the liquid side stream to the prethickening device; or
3. If storage is required before prethickening, the detention time should be reduced to the minimum.

Option II: Dewatering, Post-Thickening, and Supernating, with Limit Restriction of Phosphorus on Land Application. This option assumes that a system is designed as a three-stage-in-series, prethickened aerobic digester using a mechanical thickener that can

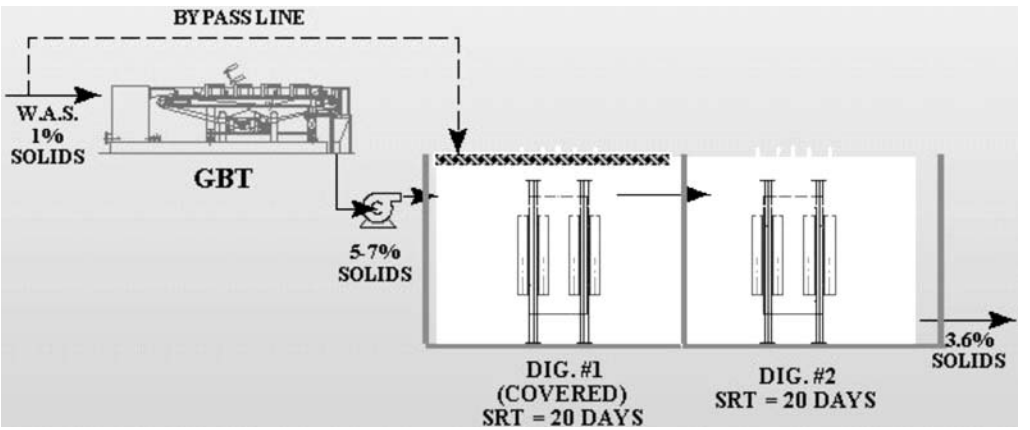


FIGURE 31.9 Option I: prethickened liquid disposal with no phosphorus limit restriction on land application (GBT = gravity belt thickener) (Daigger et al., 2000).

thicken to 6% solids; however, it is also designed to post-thicken. In this case, it is assumed that there is a restriction on land, and, at times, the prethickening device will be bypassed (during the summer). Figure 31.10 shows such a case of a dewatering option, with restriction of phosphorus on land application. The necessary steps for option II are as follows:

1. Phosphorus will be released during digestion and will be returned to the headworks.
2. Nitrification can be controlled in first digester to encourage struvite production, which is to be separated.
3. Add alum or ferric chloride to the supernatant and filtrate. Chemicals are only required for phosphorus removal. There is little else in the supernatant, so chemicals for phosphorus removal are minimized.
4. Phosphorus is now fixed and can be removed with the sludge.

TEMPERATURE CONTROL. If the potential exists to capture the heat generated by volatile solids destruction, the temperature of the reactor can be controlled.

Depending on geographical location and climatic conditions, tanks may or may not require covers. Covers are used in colder climates to help maintain the temperature of the waste being treated. Covers should not be used if they reduce evaporative cooling too much, and the liquid contents become too warm. When the liquid becomes too warm, offensive odors may develop, and the process effluent will have a very poor quality (California State University, 1991).

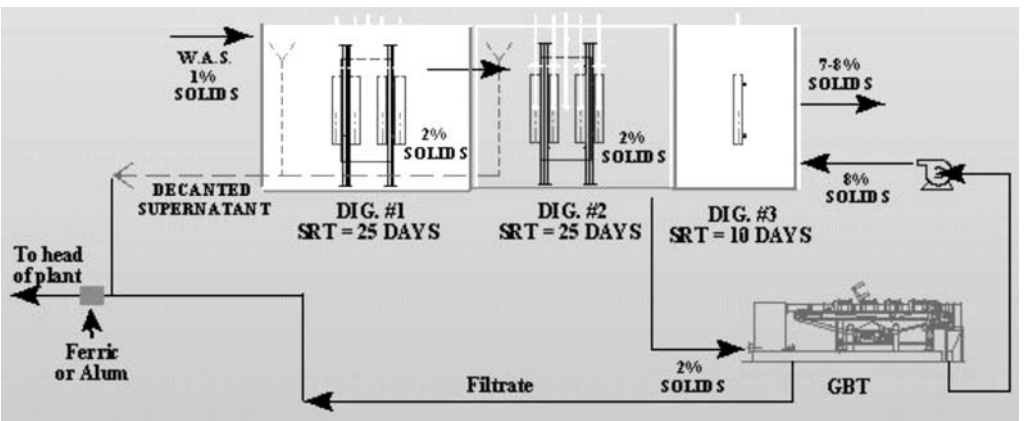


FIGURE 31.10 Option II: dewatering post-thickening, with phosphorus limit restriction on land application (GBT = gravity belt thickener) (Daigger et al., 2000).

The liquid temperature in an aerobic digester significantly affects the rate of volatile solids reduction and pathogen reduction. The rate of volatile solids reduction increases as the temperature increases. As with all biological processes, the higher the temperature, the higher the efficiency. At temperatures less than 10 °C (50 °F), the process is basically ineffective. Figure 31.11 shows highlights from a study focused on pathogen destruction and volatile solids performance of three-stage digester systems operated at temperatures in the range 8 to 31 °C. The following conclusions can be drawn from this study:

1. Above 12 °C, pathogens less than 2 000 000 can be achieved in 7 days; and
2. At temperature <10 °C, a minimum of 25 was required to achieve the same limits.

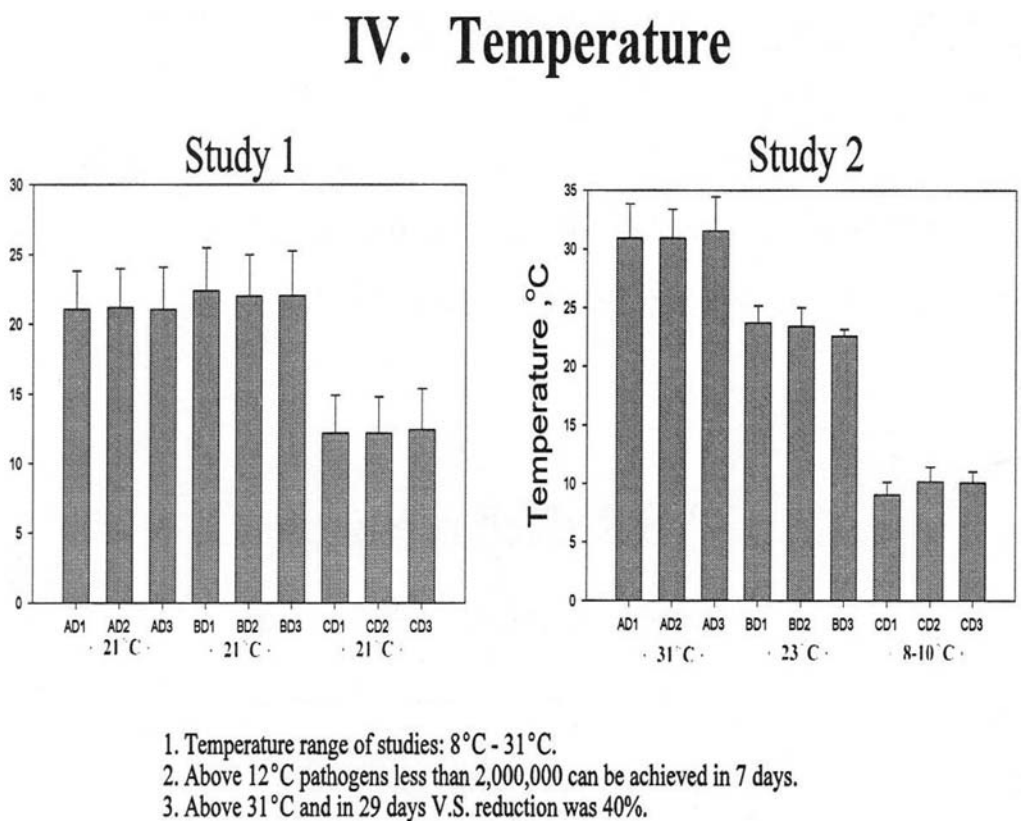


FIGURE 31.11 Study conclusions of temperature effect in the performance of aerobic digesters (Daigger et al., 1999).

The effect of temperature on volatile solids destruction is shown best on the full-scale installation data from Plum Creek, Colorado per Tim Grotheer (Daigger et al., 1997). This WWTP was a common-wall complete WWTP that was converted to a digestion system, as shown on the flow schematic in Figure 31.12. During this phase of the project, the waste was prethickened and fed to a five-stage-in-series digester system. No covers or insulation were supplied. During phase I of the project, even though the total SRT of the system was 54.5 days, the volatile solids reduction in February was only 16%, when the temperature was as low as 10 °C.

Figure 31.13 shows the volatile solids reduction for the entire system for each month, versus solids concentration and temperature. Figure 31.14 shows the volatile solids reduction for each month between each stage.

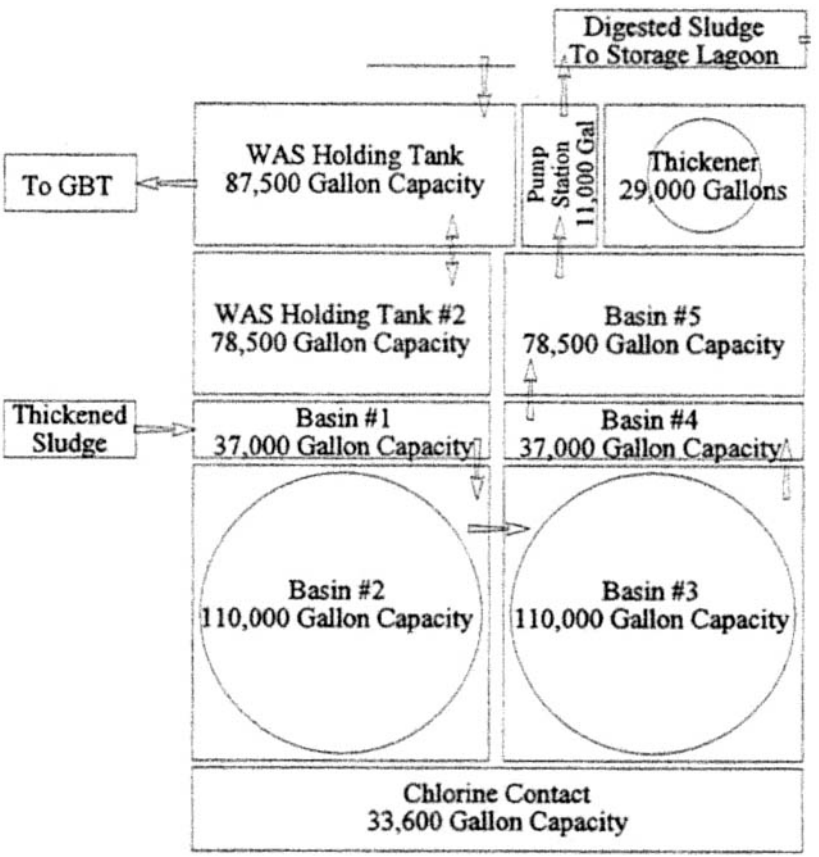


FIGURE 31.12 Flow schematic of sludge treatment process, Plum Creek, Colorado (GBT = gravity belt thickener; gal × 3.785 = L) (Daigger et al., 1997).

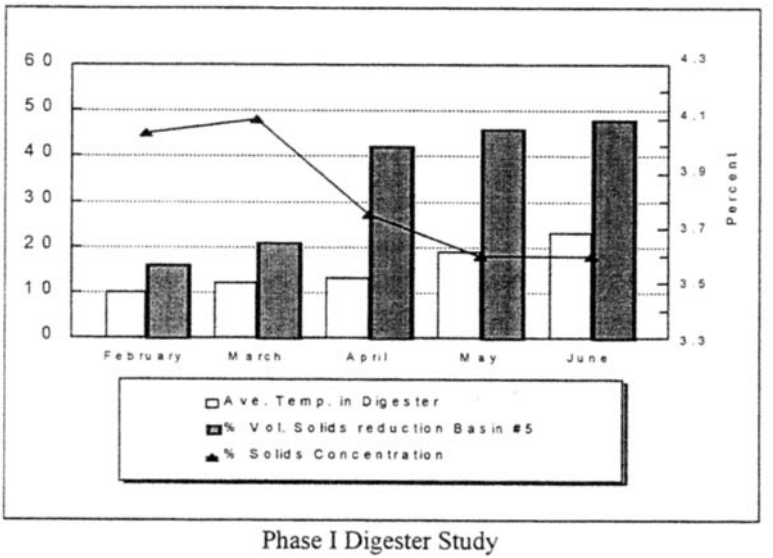


FIGURE 31.13 Volatile solids reduction of Plum Creek, Colorado, versus solids concentration and temperature (Daigger et al., 1997).

The study by Al-Ghusain (Al-Ghusain et al., 2004) evaluated the effect of temperature on volatile solids destruction at a low SRT of 10 days, with an anoxic cycle of 8 hours, as shown in Figure 31.14. This study agrees with the Plum Creek data, showing VSS destruction of 42.4% at 30 °C, as shown in Figure 31.15.

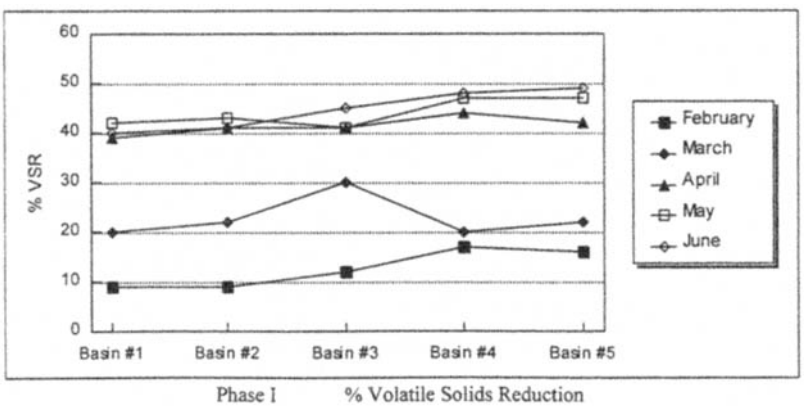


FIGURE 31.14 Volatile solids reduction (VSR) of each in-series stage, at Plum Creek, Colorado (Daigger et al., 1997).

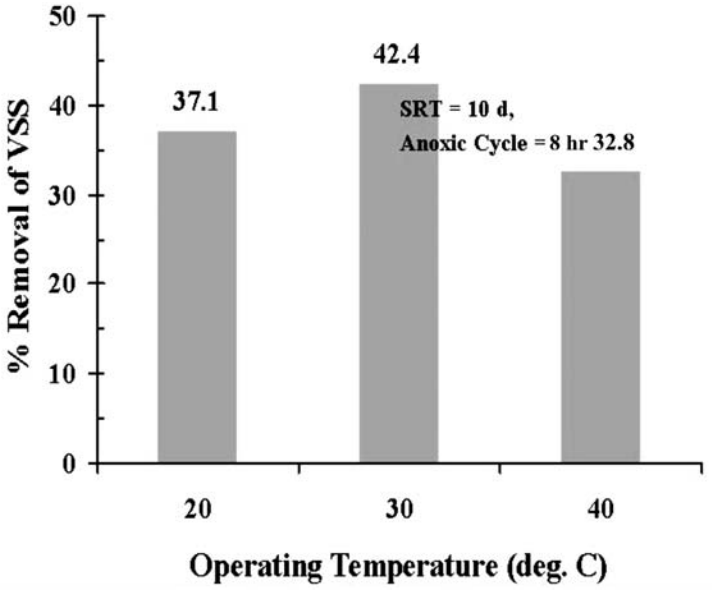


FIGURE 31.15 Effect of temperature on VSS removal with an anoxic cycle of 8 hours (Al-Ghusain et al., 2004).

Another study (Daigger et al., 2001) evaluated the reliability of two systems—one that provides in-loop thickening to achieve 3% solids in the digester compared with a system that prethickens to 3% solids. The focus of this study was to compare the capabilities of each system to maintain 20 °C liquid temperature in the digesters during the winter months, with waste of low temperature. Figure 31.16 highlights the finding from this evaluation. As shown in this figure, for an in-loop system, if the feed is as low as 10 °C, the digester basins and walls need to be insulated to maintain 20 °C in the digester. On the other hand, if the waste sludge is prethickened at the same concentration, covers are more than adequate to provide the same temperature elevation in the basins.

Part of this evaluation was to show that if the potential is there to capture the heat generated by the volatile solids, it is possible to control the temperature of the reactor. This could be very beneficial in cold-weather climates. Because conventional aerobic digestion is classified as a mesophilic process, it is optimized when the temperature is above 20 °C.

FLEXIBILITY OF THE SYSTEM. Flexibility should be built into the aerobic digester design, especially of a staged operation system, where two or more basins are

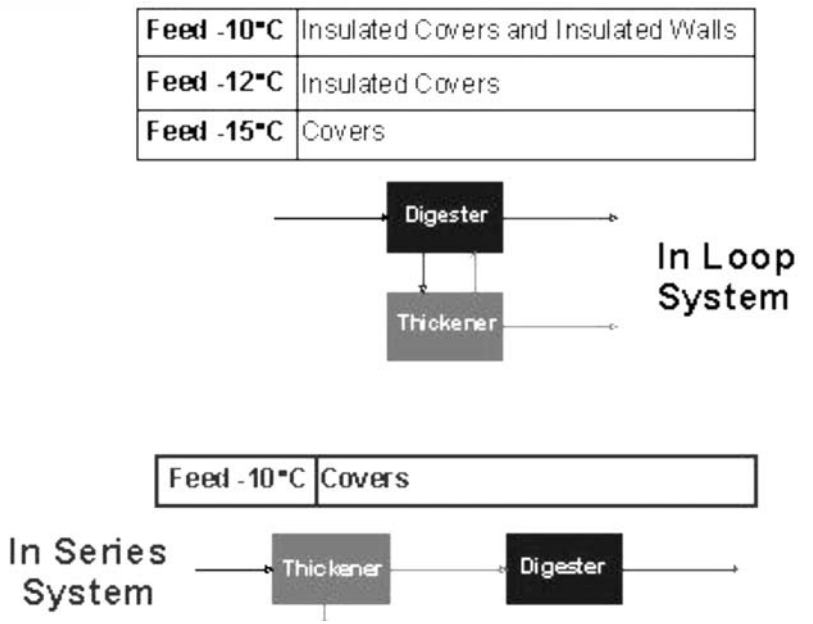


FIGURE 31.16 Cover requirements for cold-weather installations with 3% solids feed (Daigger et al., 2001).

incorporated to the design. In addition, if a mechanical prethickening device is used, at a minimum, bypass piping for the digesters should be included to allow for down time and service of the machine. This also allows the operator the flexibility to make process changes, if necessary, resulting from temperature fluctuations, sludge volume, strength of waste to the system, toxicity, and possible extreme weather events, such as heavy rain and snow.

As a minimum, the aerobic digester equipment, blowers, and thickening equipment should have the ability to operate as follows:

1. The option to operate the digesters both in series and in parallel operation.
2. The aeration system and blowers to be designed to allow for incremental aeration for nitrification and denitrification.
3. The aeration system and blowers to be flexible to allow for air to move from basin to basin, as required.
4. The aeration system and blowers to be flexible to allow for air to be provided in one digester while the other digester is off. The blowers should be capable of handling water-level variations.

5. The ability to feed unthickened solids in the summer in two out of three tanks and post-thickening before the third tank. For example, feed 1% solids to the first digester every day, as shown in Figure 31.17, and post-thicken before liquid haul.
6. The ability to have in-loop thickening of the digester content and then post-thicken. This is one way to reduce temperature in the digester during the summer. For example, bypass the prethickening device, and then feed the thickener directly from the first digester. The thickened sludge can either go back to the same digester or to the second digester. If a third digester is present, the sludge from the second digester will be post-thickened and stored in the third basin in a much higher concentration.
7. Bypass the prethickening process a few days a week, and continue prethickening the remaining days of the week. For example, prethicken 3 days per week at 6% suspended solids, and bypass the 0.7% suspended solids 4 days per week to

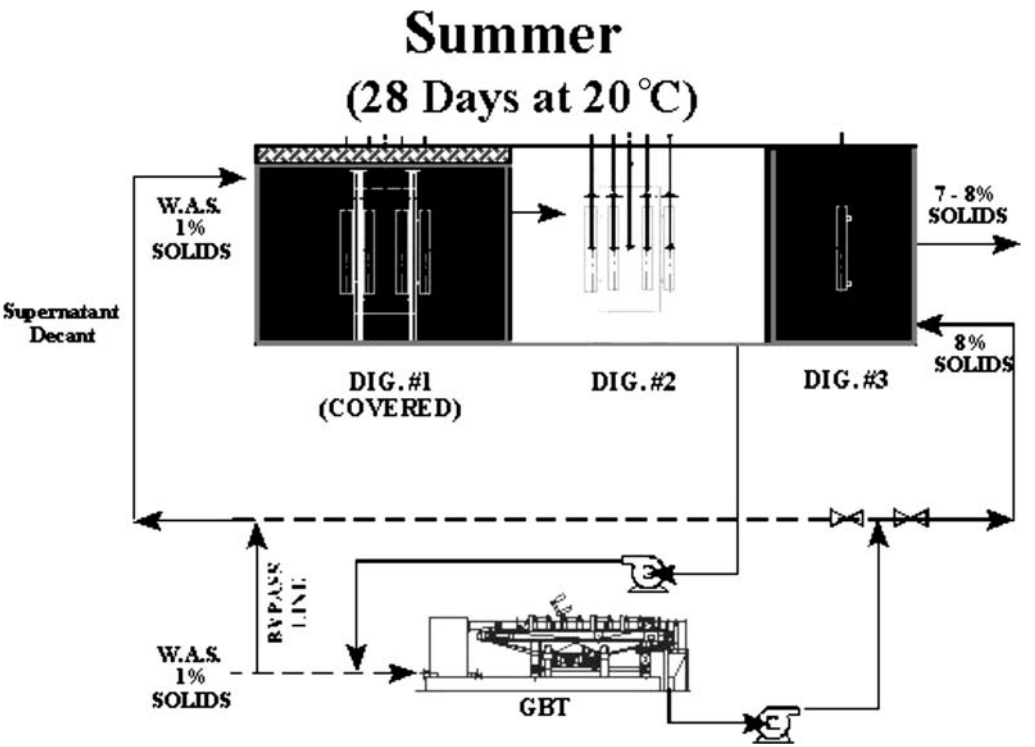


FIGURE 31.17 Reduce first stage to 1% solids in the summer to control temperature and post-thickener before liquid haul (GBT = gravity belt thickener) (Daigger et al., 1999).

the first digester. Figure 31.18 shows a schematic of the operation of a full-scale installation at Paris, Illinois as presented by Richard Yates (Daigger et al., 1997). As can be seen from this example, this approach is also applicable for digesters systems designed to treat a combination of primary and secondary WAS. For plants with high degradable solids, it is typical to have a summer and winter operation to optimize temperature control and process control.

8. The ability to prethicken and post-thicken. Figure 31.19 shows an example of a possible flow diagram that can provide the necessary piping and machinery to prethicken and post-thicken using the same prethickening device.

EQUIPMENT DESIGN AND SELECTION

TYPES OF REACTORS. Aerobic digesters are either open or closed tanks. Open tanks are more common; however, in the last decade, more designers use covered and deeper tanks. Common-wall construction with a basin wall height of 7.3 m (24 ft) and water level of 6.7 m (22 ft) is typical. If prethickening is included in the design, tanks are typically 6.1 m (20 ft) deep or more; refer to the Diffused Aeration Equipment section for explanation. For round structures, tanks are 6.1 to 9.1 m (20 to 30 ft) deep and 9.1 to 18 m (30 to 60 ft) in diameter.

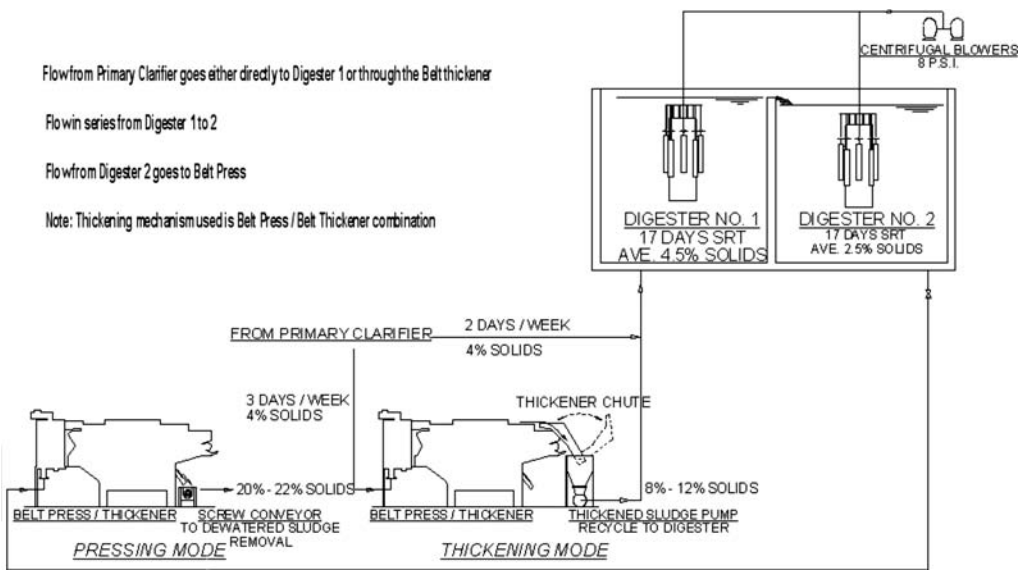


FIGURE 31.18 A schematic of the flow diagram of Paris, Illinois (8 psi = 55 kPa) (Daigger et al., 1997).

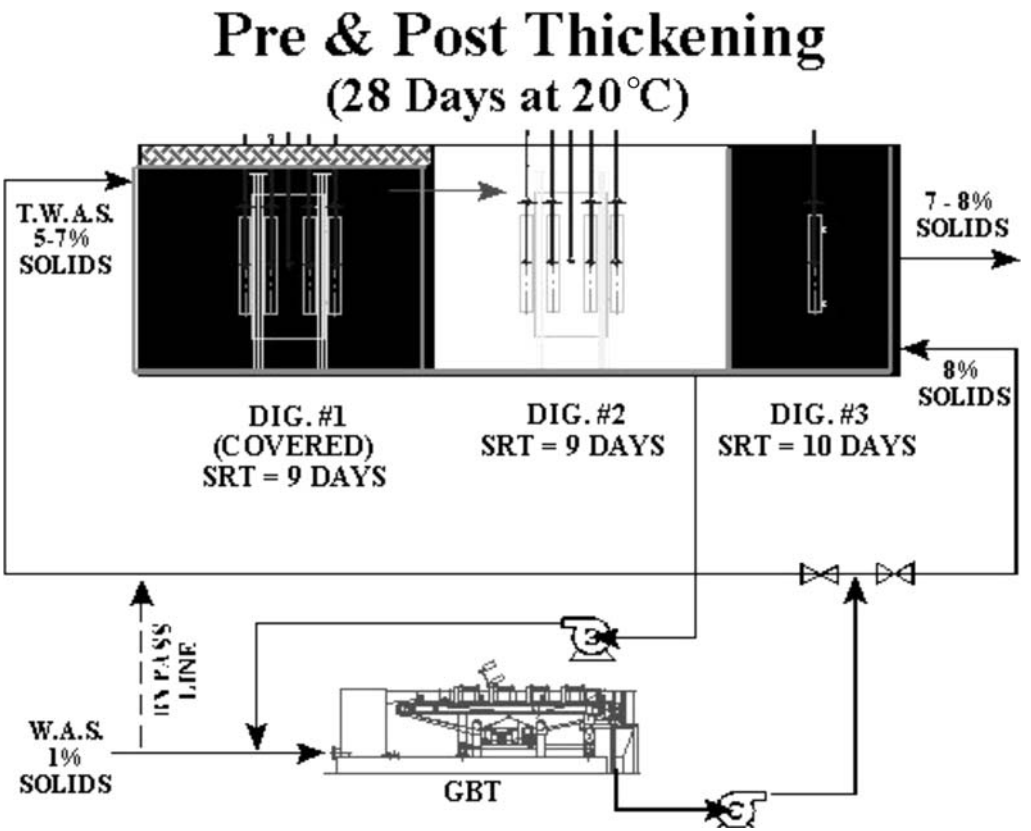


FIGURE 31.19 A schematic of a pre- and post-thickening system (T.W.A.S. = total waste activated sludge, GBT = gravity belt thickener) (Daigger et al., 1999).

Covers reduce freezing, heat loss, and surface evaporation. As described in the Temperature Control section, covers combined with prethickening can increase the performance of conventional aerobic digestion by increasing both the volatile solids reduction and pathogen destruction. Combined with flexibility, temperature elevations in the thermophilic stage can be avoided, and the process can be controlled all year. In general, if the digester liquid temperature can be maintained at 20 °C all year, after thickening, the covers are not required. If the temperature is expected to be below that, then economics typically favor covers.

Most aerobic digesters are constructed to allow the liquid level to fluctuate very little in the first tank to maximize transfer efficiency and mixing. Some aerobic digesters are designed with sloped floors so that digested sludge is drawn off the bottom;

others have a constant weir overflow design. Aerobic digesters are constructed of reinforced concrete and steel. In cold climates, steel tanks that are above ground should be insulated. If the steel and concrete tanks are below ground, they are fairly well-insulated by the soil if the groundwater is drained from the exterior of the tank walls.

At least two tanks should be installed to provide process flexibility and equipment flexibility, should any one tank need repairing. Increasing the aerobic digester size to produce an operating safety factor may create operational problems because of a loss of heat and increased energy requirements for mixing, as described in the Rules and Regulations section. The two schematics shown in Figures 31.20 and 31.21 are examples of two sludge treatment processes that are typical for dewatering and liquid disposal. Figure 31.20 shows a two-stage dewatering option, and Figure 31.21 shows a three-stage liquid disposal option.

PIPING REQUIREMENTS. Piping requirements should, at a minimum, include provisions for feeding sludge; decanting supernatant, where applicable; withdrawing digested sludge; and supplying air for aeration. If possible, piping arrangements for flushing out sludge lines with WWTP effluent should be provided.

When possible, piping should allow bypass of each digester basin. For more details, refer to the Flexibility of the System section of this chapter.

DIFFUSED AERATION EQUIPMENT. Equipment used for digestion to supply air and mixing includes conventional mechanical aerators, coarse-bubble diffusers, fine-bubble aeration, or jet aerators. The best device not only should be capable of

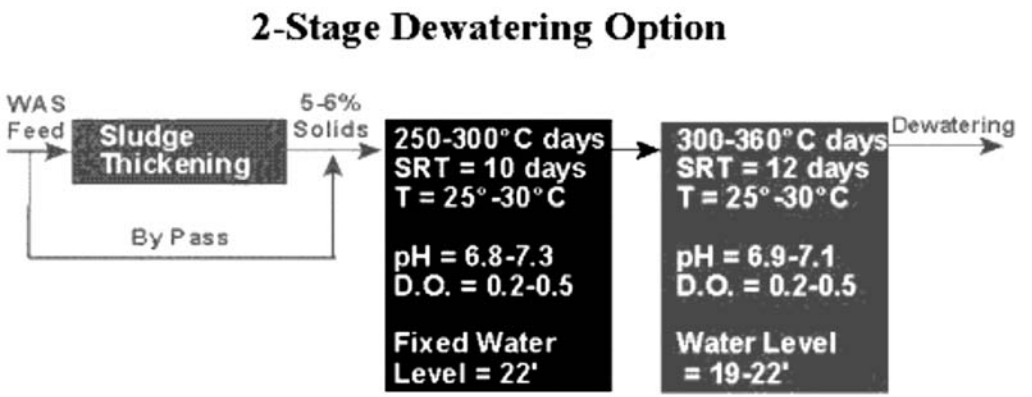


FIGURE 31.20 Two-stage sludge treatment dewatering option (D.O. = dissolved oxygen) (Daigger et al., 1999).

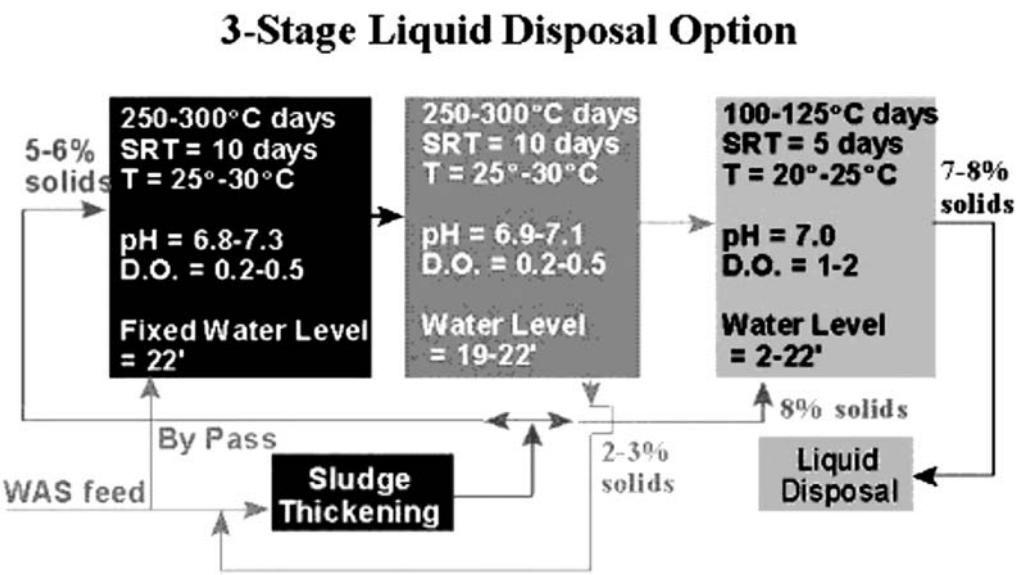


FIGURE 31.21 Three-stage sludge treatment liquid disposal option (D.O. = dissolved oxygen) (Daigger et al., 1999).

developing the required oxygenation and mixing, but should also provide flexibility (Water Environment Federation, 1998). In aerobic digesters, avoid fine-bubble ceramic diffusers because they are especially susceptible to clogging. Even though fine-bubble diffusers can work effectively in aerobic digesters aerated on a continuous basis, as stated by Jim Scisson, there are practical limitations to effectively operating an aerobic digester in an aerobic–anoxic mode (Daigger et al., 1998).

Typically, floor-covering, submerged-header air diffusers are found near the bottom of the digester, toward one side, to induce a spiral or cross-roll mixing pattern. The most widely used air diffusers are the small- and large-bubble types. Submerged header air diffused systems

1. Tend to add heat to the digester,
2 Are not greatly affected by foaming conditions, and
3. May require the entire assembly to be removed for cleaning if it becomes clogged or plugged during the anoxic operation.

An alternative to the floor-covering diffuser systems is a full range of high shear, nonclog aeration equipment designed specifically for high solids concentrations in

the range 4 to 8% solids concentration. This aeration system is combined with an adjustable, above-water orifice to allow for profiling the air requirements to meet demand, and nonclog diffusers ensure that plugging will not occur during the anoxic operation. The shear tube and draft tubes that are also incorporated into the design have proven to provide the type of rapid mixing and shearing action necessary to transfer oxygen and achieve volatile reduction with high solids. The limitation of this system is that it works better when the liquid depth is greater than 6.1 m (20 ft). Figure 31.22, per Richard Yates, shows an installation of a system of this kind. Figure 31.23 shows the plan and section views of the technical drawings for the same project.

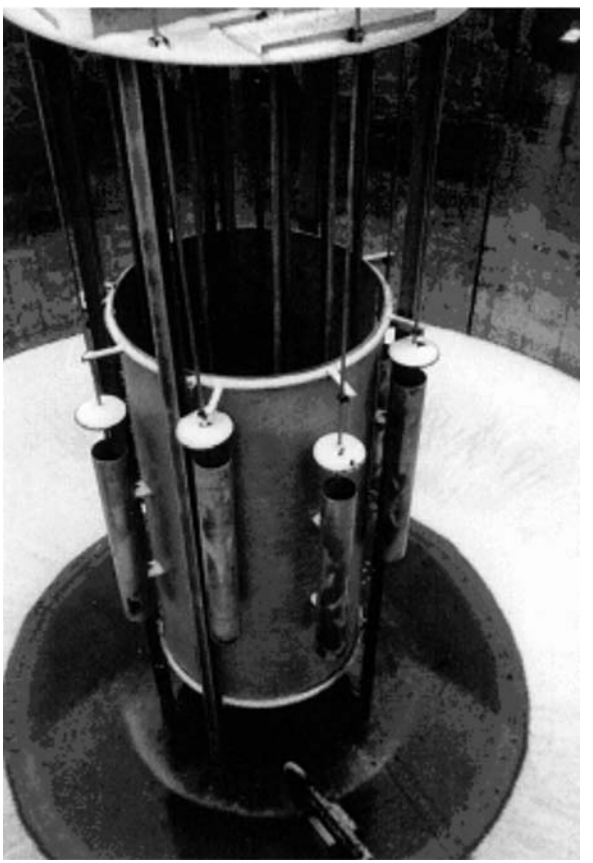


FIGURE 31.22 Typical installation of National Aeronautics and Space Administration (Washington, D.C.) draft tube at Paris, Illinois. Picture taken after conversion from anaerobic to a prethickened two-stage, in-series, aerobic digester system, treating a combined primary and secondary waste (Daigger et al., 1997).

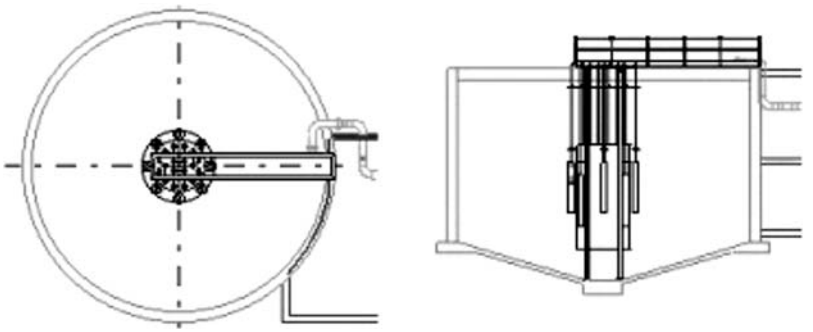


FIGURE 31.23 The plan and section views of a digester basin at Paris, Illinois. The digester basin is 14 m (45 ft) in diameter by 9.4 m (31 ft) deep (Daigger et al., 1997).

In summary, single-drop aeration with shear tubes or draft tubes systems

1. Are specifically designed for higher solids concentrations (4 to 8% suspended solids),
2. Tend to add heat to the digester,
3. Do not require maintenance because they are nonclog systems, and
4. Require deep tanks with greater than 6.1 m (20 ft) of liquid depth.

MECHANICAL SURFACE AERATORS. Both low- and high-velocity mechanical surface aerators, in either free-floating or fixed installations, are efficient in oxygen transfer (amount of oxygen fed by the aerator that has been absorbed by the sludge). Typically, mechanical surface aerators

1. Supply oxygen efficiently to aerobic digesters, if the desired solids concentration in the basin is less than 2.5% solids;
2. Have minimal maintenance requirements;
3. Are greatly affected by foaming conditions; and
4. Are greatly affected during cold weather by ice buildup.

SUBMERGED MECHANICAL AERATORS. Submerged mechanical aerators include a rotating submerged impeller mounted on a drive shaft extending vertically into the aeration basin. Compressed air is supplied beneath the impeller, where it is sheared into bubbles and pumped into the basin (Water Environment Federation, 1998).

Generally, submerged mechanical aerators are unaffected by foaming or icing conditions.

BLOWERS. Centrifugal blowers and rotary positive displacement air blowers are suitable for aerobic digestion. As a minimum, for a two-stage digester system, three blowers are recommended. If rotary positive displacement blowers are selected, then as a minimum, two out of the three blowers should be complete with dual-speed or variable-speed motors to provide maximum flexibility and process optimization. Examples for such a system include a blower designated for the first digester to operate at both maximum and design airflow (dual-speed motor is included in this machine), a blower designated for the second digester to operate at design and minimum airflow, and a standby blower that can be used to supply air to either basin at maximum and design airflow (dual-speed motor is included in this machine also).

Figure 31.24, per Glen Daigger, shows a flow schematic of a typical three-stage, prethickened digester system with a total of 30 days SRT operated at 20 °C. This diagram shows the recommended airflow requirement between the three stages and blower requirements (Daigger et al., 1999).

PUMPS. A number of different types of pumps have been used to transfer sludge to aerobic digesters. Both positive displacement pumps and centrifugal pumps have been used successfully for this purpose. Airlift pumps and nonclog pumps draw off the thickened, digested sludge for transferring between basins, dewatering, or disposal.

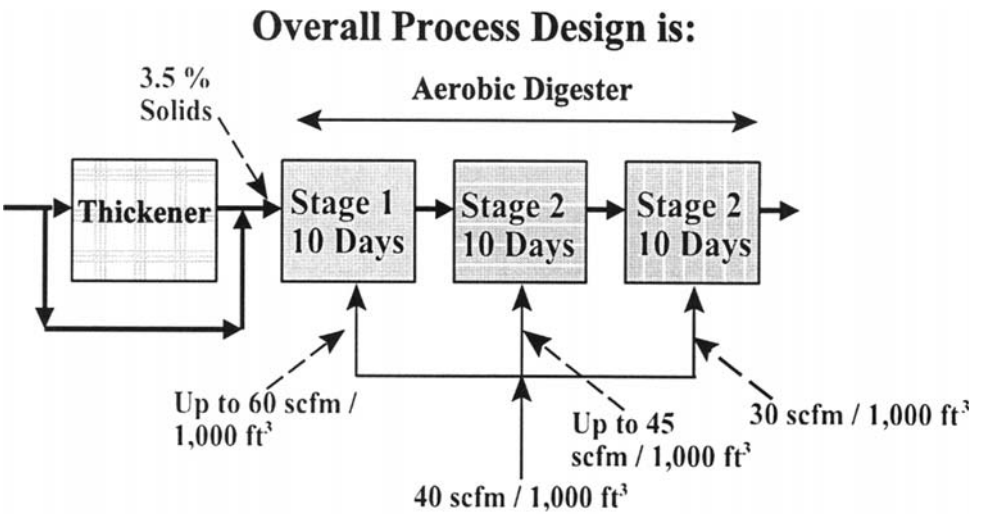


FIGURE 31.24 Airflow distribution and blower requirements for a three-stage, prethickened aerobic digester system (1 scfm/1000 cf = 0.06 $m^3/m^3 \cdot h$) (Daigger et al., 1999).

An extensive section on pump selection is included in Chapter 8 of this book. Please refer to that chapter for more details.

MIXING AND AERATING EQUIPMENT. Various aeration systems have been used in ATAD systems, including U.S. Filter floor-mounted jet aspirator or jet aeration (U.S. Filter [Siemens], Warrendale, Pennsylvania), Fuchs side-mounted aspirating aeration (Fuchs, Harvey, Illinois), Turborator Technology top-mounted aspirator aeration and pump and venturi system (Burnaby, British Columbia, Canada) (Shamskhorzani, 1998). With all air aspirating systems, the equipment provides both mixing and oxygen transfer (Figures 31.25 and 31.26).

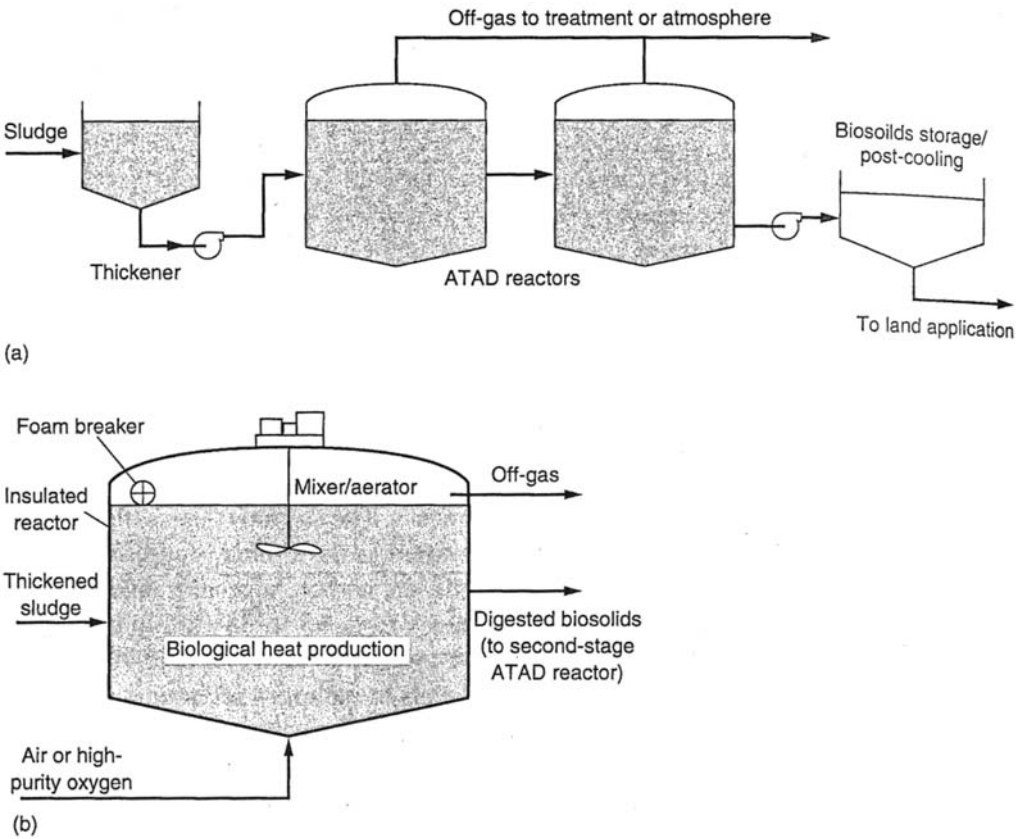


FIGURE 31.25 A typical ATAD system schematic and reactor schematic (Metcalf and Eddy, 2002).

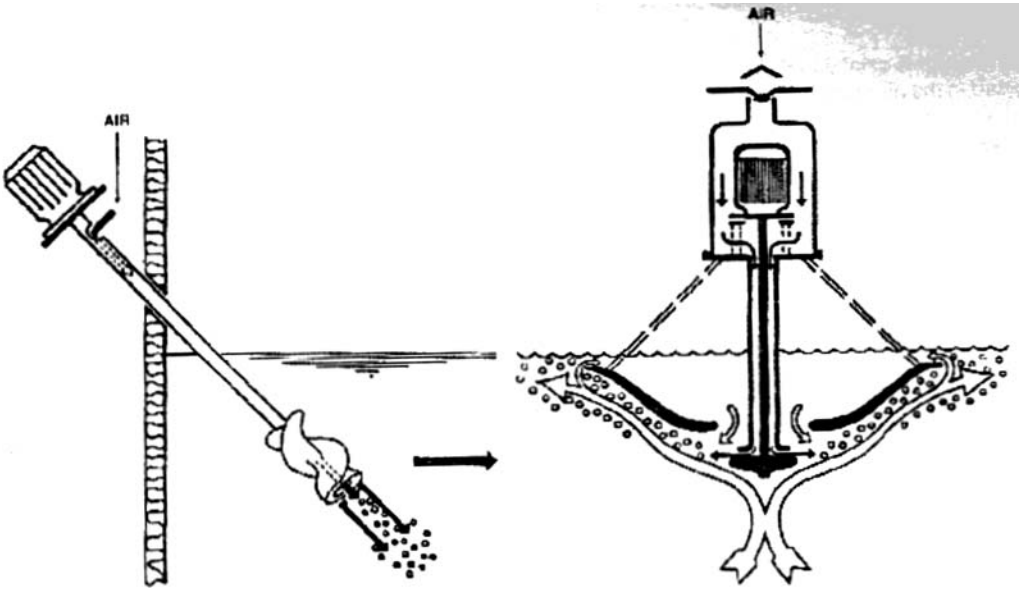


FIGURE 31.26 A schematic of an aerator used in an ATAD system (U.S. EPA, 1990).

CONTROL EQUIPMENT. Aerobic digestion systems often incorporate automatic pH control equipment. The typical automatic pH control system consists of a pH electrode placed within the digester that measures the pH and provides a signal to chemical feed pumps if the desired pH range is not being achieved. The pH control systems can also be used to control the blowers to provide a controlled airflow to the basins, which will provide the operator with the capabilities to optimize the process and operate in a simultaneous nitrification and denitrification mode. Another way that the pH system can be used is to turn the blowers on and off to provide a true aerobic–anoxic operation.

THICKENING EQUIPMENT. The thickening equipment recommended for aerobic digestion is divided into three categories and is described in the Prethickening section of this chapter. Because Chapter 29 is dedicated to this subject in its entirety, please refer to Chapter 29 for more details.

PROCESS PERFORMANCE

RULES AND REGULATIONS. ***Standards for the Use or Disposal of Sewage Sludge***. The Standards for the Use or Disposal of Sewage Sludge (40 *CFR* Part 503; U.S.

EPA, 1999b) regulate the use and disposal of biosolids from WWTPs. Limitations are established for items such as contaminants (mainly metals), pathogen content, and vector attraction.

The regulations addressed by 40 *CFR* Part 503 (U.S. EPA, 1999b) were promulgated in 1993 and revised in 1999 by the U.S. Environmental Protection Agency (U.S. EPA) (Washington, D.C.). The modifications and clarifications of the rules are described in the Environmental Regulations and Technology document, "Control of Pathogens and Vector Attraction in Sewage Sludge", as revised by the Pathogen Equivalency Committee (U.S. EPA, 1999a). The regulations cover specifically (1) land applications of biosolids, (2) surface disposal of biosolids, (3) pathogen and vector reduction in treated biosolids, and (4) incineration.

The regulations on land applications and vector reduction will be explored in this chapter to provide a better understanding of the effect of these rules on aerobic digestion systems.

Regulation of Land Application. Land application relates to biosolids reuse and includes all forms of applying bulk or bagged biosolids to land for beneficial uses at agronomic rates (i.e., rates designed to provide the amount of nitrogen needed by crop or vegetation, while minimizing the amount that passes below the root zone). The regulations establish the following levels of quality:

1. Two levels, with respect to heavy metals concentrations;
2. Two levels, with respect to pathogen densities (class A and class B); and
3. Two types of approaches for meeting vector attraction, one being the biosolids processing of choice, and the other the use of a physical barrier.

Definition of Biosolids. *Biosolids* is defined as a wastewater product that is both organic and semisolid and becomes suitable for beneficial use after biological or chemical stabilization.

Class A biosolids are biosolids in which the pathogens (including enteric viruses, pathogenic bacteria, and viable helminth ova) are reduced below required detectable levels (WEF, 1995) Class A biosolids must meet all the specific criteria to ensure that they are safe to be used by the general public and for nurseries, gardens, and golf courses.

The process that most likely will qualify for class A biosolids covered in this chapter is the thermophilic process. Although the regulations for class A are very elaborate,

and a number of options are available, the class A biosolids criteria that a thermophilic aerobic digestion system will most likely be designed to meet are as follows:

1. A fecal coliform density could be less than 1000 MPN/g total dry solids, or
2. Salmonella sp. density of less than 3 MPN/4 g total dry solids (3 MPN/4 g total solids).
3. In addition to meeting requirement 1 or 2, the biosolids should be treated by one of the prescribed processes that reduce pathogens beyond detectable levels, described as processes to further reduce pathogens (PFRPs). Thermophilic aerobic digestion that, by definition, processes liquid biosolids agitated either with air or oxygen to maintain aerobic conditions, with a mean cell residence time of 10 days at 55 to 60 °C, qualifies as an acceptable PFRP process.

Class B biosolids are biosolids in which the pathogens are reduced to levels that are unlikely to pose a threat to public health and the environment under specific use conditions (WEF, 1995). Class B biosolids cannot be sold or given away in bags or other containers or applied on lawns or home gardens. They are typically used for applications to agricultural land or disposed of in a landfill.

The process that most likely will qualify for class B biosolids covered in this chapter is the conventional aerobic digestion process. Although the regulations for class B are elaborate, and a number of options are available, the class B biosolids criteria that a mesophilic conventional aerobic digestion system will most likely be designed to meet are the following:

For a single digester basin, the following criteria could be met:

1. Meet one of the two pathogen reduction requirements, either
   - 60 days detention at 15 °C or 40 days at 20 °C, or
   - Meet fecal coliform density of less than 2 000 000 MPN/g total dry solids.
2. Meet one of the two vector attraction reduction requirements, either
   - Meet at least 38% reduction in volatile solids during biosolids treatment, or
   - Meet a SOUR at 20 °C (68 °F) of less than 1.5 mg oxygen/g total solids · h.
3. Sludge can also be accepted as suitably reduced in vector attraction when it shows less than 15% additional volatile solids reduction after 30 days additional batch digestion at 20 °C (68 °F).

For a two stage or more digester system, the following criteria could be met:

1. Meet *both* of the pathogen reduction requirements:
   - Meet fecal coliform density of less than 2 000 000 MPN/g total dry solids, AND
   - Provide 42 days detention at 15 °C or 28 days detention at 20 °C. In this case, because approval of the process as a PSRP equivalent alternative is required by the permitting authority, the plant operator should demonstrate experimentally that microbial levels in the product from their sludge digester are satisfactorily reduced and meet one of the Vector Attraction Reduction requirements listed above.
2. Meet the vector attraction reduction requirements, either
   - Meet at least 38% reduction in volatile solids during biosolids treatment, or
   - Meet a SOUR at 20 °C (68 °F) of less than 1.5 mg oxygen/g total solids·h.

PARAMETERS USED TO EVALUATE PERFORMANCE OF AEROBIC DIGESTERS. The following parameters are used to evaluate the performance of aerobic digesters:

1. SOUR,
2. Pathogen reduction,
3. Volatile solids reduction and solids reduction,
4. Solids retention time × temperature product (days °C),
5. Nitrogen removal in biosolids,
6. Phosphorus reduction in biosolids and biophosphorus,
7. Sludge dewatering characteristics, and
8. Supernatant quality of recycled sidestreams.

Standard Oxygen Uptake Rate. The rate of oxygen use by the microorganisms depends on the rate of biological oxidation. The SOUR of 1.5 mg oxygen/g total solids·h at 20 °C (68 °F) was selected by U.S. EPA to indicate that an aerobically digested sludge has been adequately reduced in vector attraction.

The oxygen uptake rate is used to determine the level of biological activity and the resulting solids destruction occurring in the digester. The SOUR is becoming a more common testing procedure for most operators instead of using the traditional volatile solids reduction. However, the volatile solids reduction test still remains the preferred choice for anaerobic digestion, because the SOUR does not apply to anaerobically digested solids.

The SOUR is a quick test and is independent of the initial value in the system or reduction of SOUR in the upstream process. On the other hand, volatile solids reduction is a percentage of the incoming volatile level to the digester system. During active aerobic digestion, if primary sludge is added to the first digester, it may exhibit an uptake rate ranging from 10 to 30 mg oxygen/g total solids·h. For staged operation, however, a typical rate of oxygen uptake is from 3 to 10 mg oxygen/g total solids·h in the first stage digester as compared with a range of 10 to 20 mg oxygen/g·h in the active phase of the activated sludge process.

An oxygen uptake rate for a well-digested sludge from the aerobic digestion process ranges from 0.1 to 1.0 mg oxygen/g total solids·h, well below the required 1.5 mg oxygen/g·h by U.S. EPA standards.

PATHOGEN REDUCTION. As mentioned earlier in this chapter, pathogen reduction is similar to solids reduction in that little pathogen reduction can be expected at temperatures less than 10 °C (50 °F), while significant reduction may be achieved at temperatures higher than 20 °C (68 °F). Even though it is acceptable by U.S. EPA standards to operate at 15 °C (59 °F), for economic reasons and performance reliability, the author recommends designing and operating the plant at a minimum of 20 °C (68 °F).

VOLATILE SOLIDS REDUCTION AND SOLIDS REDUCTION. Aerobic digestion results in the destruction of VSS. In addition, if a membrane thickening digestion option is selected, fixed suspended solids (FSS) can also be reduced. This occurs because both the organic and inorganic material in the biodegradable suspended solids are solubilized and digested. However, the components of VSS and FSS are not equal. Consequently, they will not generally be destroyed in the same proportion.

Primary solids and WAS from a system with a short SRT will contain relatively high fractions of biodegradable material, as opposed to WAS from a system with a long SRT, which will contain a low fraction of biodegradable material and a high fraction of biomass debris (Grady et al., 1999).

As mentioned earlier in this section, the destruction of biodegradable suspended solids is very much affected by temperature and can be characterized as a first-order reaction. This occurs because the decay of active biomass is a first-order reaction. The decay coefficient of relatively high active biomass is independent of the SRT at which the waste solids were produced. This is because the decay coefficient for the biodegradable suspended solids is influenced strongly by the decay coefficient for heterotrophic bacteria, which is relatively constant.

In a study performed to determine the minimum SRT required to meet class B requirements by meeting both pathogens and volatile solids reduction operating at

minimum temperatures as concluded by Lu Kwang Ju (Daigger et al., 1999), two systems were evaluated. One system included two basins in series and the other, three basins in series. Table 31.5 shows the volatile solids reductions at different temperatures and different SRTs.

The sludge used in this study had a very low digestible fraction. It was concluded that even though the pathogen destruction was met in all the systems, an SRT of 29 days was required to exceed the required 38% volatile solids reduction. This confirms that volatile solids reduction is dependent on the source of the sludge, and if it has a very low fraction of digestible organic content, it is difficult to meet the minimum requirements by U.S. EPA.

For full-scale data on this subject, please refer to the Temperature Control section.

Solids Retention Time × Temperature Product. A significant factor in the effective operation of aerobic digesters, the SRT is the total mass of biological sludge in the reactor, divided by the mass of solids that are removed from the process on a daily average. Typically, increased SRT results in an increase in the degree of volatile solids reduction.

Based on the discussion above, with respect to temperature, degradable sludge and nondegradable sludge and the effect it can have on volatile solids reduction, the SRT × temperature product (days °C) curve can be used to design digester systems, taking into consideration not only the total days °C that the digester system will have to meet, but also the quality of the source. The original U.S. EPA SRT × temperature curve, developed in the late 1970s (U.S. EPA, 1978, 1979), was updated (Daigger et al., 1999) by incorporating data from two extensive pilot studies by Lu Kwang Ju (Daigger et al., 1999) conducted over 3 years with data from three full-scale installations. Figure 31.27 shows a process design based on 600 days °C, assuming the feed has relatively

TABLE 31.5 Volatile solids (VS) reduction at minimum operating temperatures and minimum SRT (Daigger et al., 1999).

	VS reduction Data from both Studies in all basins					
°C	**8–10 °C**	**12 °C**	**21 °C**	**21 °C**	**23 °C**	**31 °C**
2 basins in series # of days	19.25	13.75	13.75	13.75	19.25	19.25
VS Removal	27%	31%	31%	31%	28%	31%
3 basins in series # of days	29.25				29.25	29.25
VS Removal	28%				32%	40%

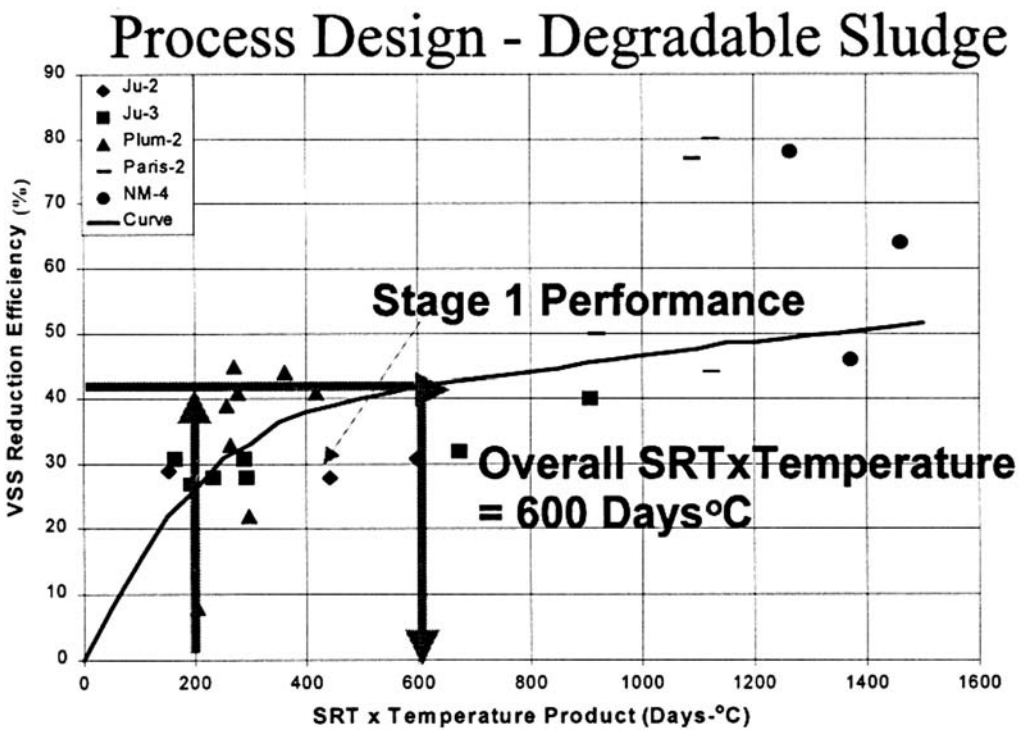


FIGURE 31.27 Selection of SRT × temperature (days °C) product for feed with high degradable solids content (Daigger et al., 1999).

high degradable solids content; and Figure 31.28 shows an alternative operation if the feed sludge has low degradable solids. Both systems can coexist, from a design standpoint, if prethickening is incorporated to the design into allow an increase or decrease of SRT as necessary.

Nitrogen Removal in Biosolids. As mentioned earlier in this chapter, the conventional aerobic digestion process, operated in the aerobic–anoxic mode, provides full nitrification and denitrification and a reduction in total nitrogen. The annual design loading rates for land application of biosolids is typically limited by the nitrogen loading rate. Because nitrification is inhibited in the ATAD process, the most ideal process to meet these requirements is the conventional process operated in the aerobic–anoxic mode.

Phosphorus Reduction in Biosolids and Biophosphorus. Phosphorus is released in both anaerobic and aerobic digestion; however, if the conventional aerobic digestion

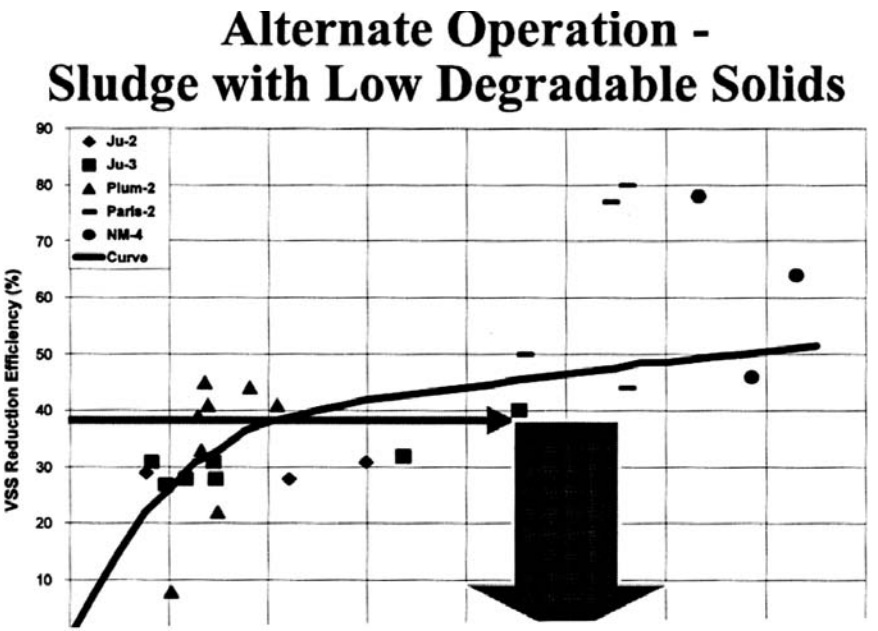


FIGURE 31.28 Selection of SRT × temperature (days °C) product for feed with low degradable solids content (Daigger et al., 1999).

process is operated in the aerobic–anoxic mode or under low dissolved oxygen conditions, the phosphorus release is minimized. As of 2005, there was a land application limit on phosphorus in very limited areas, where the land is saturated with phosphorus. If such rules apply in your area of interest, please follow the guidelines in the Phosphorus Reduction in Biosolids and Biophosphorus section under Aerobic–Anoxic Operation (aerobic–anoxic operation provides phosphorus reduction in biosolids and biophosphorus) and in the Category D—Thickening Treatment Process: Using Membranes for In-Loop Thickening with Aerobic Digestion section of this chapter.

Sludge Dewatering Characteristics. When compared with other type of sludges, the dewatering characteristics of the traditional aerobically digested sludges are typically worse than those of anaerobically treated sludges. In general, it has been observed that sludge type has the greatest effect on the quantity of chemicals required for chemical conditioning.

Factors affecting the selection of the type and dosage of conditioning agents are the properties of solids and type of mixing and dewatering devices to be used. Important solids properties include source, solids concentration, age, pH, and alkalinity. Sources such as primary sludge and WAS (digested and nondigested) are good indicators of

the range of probable conditioner doses required. Solids concentrations will affect the dosage and dispersal of the conditioning agent. The pH and alkalinity may affect the performance of the conditioning agents, in particular, the inorganic conditioners.

Sludges that are difficult to dewater and require larger doses of chemicals generally do not yield cake as dry as other sludges and have a poorer quality of filtrate or centrate (Metcalf and Eddy, 2002). Table 31.6 shows typical levels of polymer addition for belt-filter press and solid-bowl centrifuge dewatering. As shown in this table, anaerobically treated primary sludge and aerobically treated WAS, when compared with aerobically treated primary sludge and WAS, required similar quantities of polymer addition.

The data presented in Table 31.6 was accumulated before the adoption of the aerobic–anoxic operation of aerobic digestion processes (aerobic–anoxic operation techniques were adopted in the mid-1990s across the United States). Since then, a number of plants have shown improvement in their sludge characteristics when modifications were made from traditional conventional aerobic digestion to aerobic–anoxic operation. Based on preliminary reports conducted by Stensel and Bailey (2000) in Paris, Illinois, aerobically digested sludge operated in aerobic–anoxic mode produces less solids than aerobically digested sludge operated in full aeration.

Supernatant Quality of Recycled Sidestreams. Careful monitoring of solid–liquid separation in the continuous and batch-feed digesters increases the performance of an aerobic digester. The supernatant liquid or filtrate should be low in soluble BOD, TSS, and nitrogen, for both batch and continuous-flow operations. Table 31.7 lists characteristics of "acceptable" supernatant values from aerobic digestion processes (Metcalf and Eddy, 2002).

TABLE 31.6 Typical levels of polymer addition for belt-filter press and solid-bowl centrifuge sludge dewatering (Metcalf and Eddy, 2002).

Type of sludge	Belt-filter press (g/kg [lb/ton] dry solids)	Solid-bowl centrifuge (g/kg [lb/ton] dry solids)
Primary	1 to 4 (2 to 8)	0.5 to 2.5 (1 to 5)
Primary and waste activated	2 to 8 (4 to 16)	2 to 5 (4 to 10)
Primary and trickling filter	2 to 8 (4 to 16)	—
Waste activated	4 to 10 (8 to 20)	5 to 8 (10 to 16)
Anaerobically digested primary	2 to 5 (4 to 10)	3 to 5 (6 to 10)
Anaerobically digested primary and air waste activated	1.5 to 8.5 (3 to 17)	2 to 5 (4 to 10)
Aerobically digested primary and air waste activated	2 to 8 (4 to 16)	—

TABLE 31.7 Acceptable characteristics of supernatant from aerobic digestion systems (Metcalf and Eddy, 2002).

Parameter	Acceptable range	Acceptable values
pH	5.9 to 7.7	7.0
5-day BOD, mg/L	9 to 1700	500
Filtered 5-day BOD, mg/L	4 to 173	50
Suspended solids, mg/L	46 to 2000	1000
Kjeldahl nitrogen, mg/L	10 to 400	170
Nitrate-nitrogen, mg/L	— 30	
Total phosphorus, mg/L	19 to 241	100
Soluble phosphorus, mg/L	2.5 to 64	25

Although the values are considered "acceptable" values, using the techniques described in this chapter, the process can be controlled and optimized to provide supernatant of higher quality than what is described in Table 31.7. To improve these parameters, it is necessary to operate in aerobic–anoxic operation. Controlling the availability of necessary quantities of carbon source required for denitrification to allow for full nitrification and denitrification will enhance supernatant quality. Maintaining a neutral pH of 7.0 will also enhance nitrification and denitrification. For additional information, refer to Figure 31.4 for the effect of both lengths of anoxic cycles and temperature, with respect to total nitrogen levels in the filtrate.

Table 31.8 shows data from a category C sludge treatment process installation in the city of Stockbridge, Georgia, as described in the Category C—Thickening Treatment Process: Using a Gravity Thickener in Loop with Aerobic Digestion section of this chapter. As described in this section, the thickener and aerobic digester are operating in loop, nitrification occurs in the digester, and denitrification and pH recovery occur in the thickener. Thickener blanket data indicate good settling. Average data for TSS, ammo-

TABLE 31.8 Data from a category C process at the Stockbridge, Georgia WWTP (Stege and Bailey, 2003).

Parameter	Actual data from a category C process treatment	Compared with acceptable typical values from Table 31.7
pH	6.5 to 7.1	7.0
Suspended solids, mg/L	10 to 50	1000
Total Kjeldahl nitrogen, mg/L	2.5 to 4	170
Nitrate-nitrogen, mg/L	—	30
Total phosphorus, mg/L	0.3	100
Thickener blanket	8 to 13.5	10

nium, and phosphorus indicate both nitrification and denitrification and phosphorus removal with TSS removal. The sludge blanket during the collection of these data points varied between 2.4 and 4.1 m (8.0 and 13.5 ft). For comparison, data presented by Elena Bailey (Stege and Bailey, 2003) were used to produce Table 31.8, demonstrating how optimizing the techniques affects supernatant quality.

PROCESS CONTROL

The important factors in controlling the operations of aerobic digestion are similar to those for other aerobic biological processes. The primary process indicators for monitoring aerobic digesters on a daily basis are temperature, pH, dissolved oxygen, odor, and settling characteristics, if applicable. Ammonia, nitrate, nitrite, phosphorus, alkalinity, SRT, and SOUR are secondary indicators that are useful in monitoring long-term performance and for troubleshooting problems associated with the primary indicators.

All the parameters, both primary and secondary indicators, either affect or are used to monitor the operational performance of the process. While control and monitoring of these parameters is important, the degree of control that can be exercised on each parameter varies. Monitoring helps control process performance and serves as a basis for future improvements.

Table 31.9 provides a list of both the primary and secondary monitoring parameter indicators. Analysis frequency should be increased during startup and during those times when large changes are made to operating conditions, such as sludge flowrate, sludge source, change in polymer, large increase or decrease in solids concentration of feed, or large increase or decrease in temperature of feed.

TABLE 31.9 Recommended values for primary and secondary monitoring parameters (Stege and Bailey, 2003).

		Operating range		
Monitoring parameter	**Frequency**	**Minimum**	**Nominal**	**Maximum**
Temperature, °C	Daily	15	20	37
pH	Daily	6.0	7.0	7.6
Dissolved oxygen, mg/L	Daily	0.1	0.4 to 0.8	2.0
Alkalinity, mg/L as calcium carbonate	Weekly	100	>500	—
Ammonia-nitrogen, mg/L	Weekly	—	<20	40
Nitrate, mg/L	Weekly	—	<20	—
Nitrite, mg/L	As required	—	<10	—
SOUR, mg oxygen/h/g total solids	As required	—	<1.5	—
Phosphorus, mg/L	As required		<5	

PROCESS STARTUP

GENERAL GUIDELINES FOR PROCESS STARTUP. The following are general guidelines for process startup:

1. To start an aerobic digester smoothly, do not overload the digester. Proceed carefully by adding feed sludge to the digester on a regular schedule and operating the aeration system equipment continuously when sludge is being fed to the system.
2. An aeration system with adequate capacity ensures dissolved oxygen concentrations of 0.5 mg/L or more. In the startup phase, it will be higher than that, so take care not to cause foaming problems by overaerating.
3. If the initial volume of sludge does not provide sufficient liquid volume to operate the aeration system effectively, additional sludge or plant influent may be fed to obtain the needed volume. The daily sludge feed is then added on a regular schedule, preferably during as long a period as possible.
4. The primary process indicators for monitoring the aerobic digesters on a daily basis are temperature, pH, dissolved oxygen, odor, and settling characteristics, if applicable. Ammonia, nitrate, nitrite, phosphorus, alkalinity, SRT, and SOUR are secondary indicators that are useful in monitoring long-term performance and for troubleshooting problems associated with the primary indicators. All these parameters need to be closely monitored during startup to optimize the system.
5. The startup of aerobic digestion of primary feed sludges takes a substantially longer time and more oxygen than digestion of WAS. The degree of aerobic digestion depends on the concentration of solids in the digester and on the rate of solids feed. For routine monitoring, the total VSS may be used in place of TSS. As organic loading increases, the required SRT and total oxygen requirements increase and have a direct bearing on process efficiency. For a complete-mix, continuous-flow digester, the volumetric loading rate and detention are used to indirectly reflect solids destruction.
6. Regular loading, rather than periodic slug doses or large inputs, improves most biological process efficiencies. Regular feeding reduces both volume and aeration equipment requirements; however, batch-type operations often are used in the aerobic digesters.
7. If digesters are prethickened using a mechanical thickener, such as a gravity belt thickener, drum thickener, or dissolved air flotation unit, supernatant should not be returned to the head of the plant at any time. If, on the other hand, an in-loop digester-thickener process or a membrane thickening system

is used, the supernatant or permeate from these systems will be recycled to the head of the plant. During startup, it is important to make sure that the digester supernatant quality does not impose an excessive solids recycle load at the head of the plant, and the quantities of ammonia, nitrates, and/or phosphorus are within acceptable limits.

PREFERRED PROCEDURE FOR STARTUP. The following two examples are prepared by the author as examples of a step-by-step procedure during startup. Both examples assume that the design incorporates two digesters in series, a gravity belt thickener is used to prethicken to 6% solids 5 days per week, and primary sludge is also added directly in the first digester.

Preferred Choice for Process Startup. The following steps describe the preferred choice for process startup:

1. Step 1. Use clean water to fill both digesters completely.
2. Step 2. Test all the aeration equipment, blowers, and bypass lines to make sure that all the design features required in the Flexibility of the System section of this chapter do, in fact, work.
3. Step 3. Drain 1.5 m (5 ft) from digesters 1 and 2.
4. Step 4. Set up feed and transfer piping to operate in series.
5. Step 5. Prethicken WAS using the gravity belt thickener 3 times per week. For 2 days per week, bypass the gravity belt thickener. If primary sludge is scheduled to be aerobically digested as well, it is recommended to avoid introduction of the primary solids to the digesters the first 10 days of operation. Allow for the process to stabilize by creating a healthy population of nitrifiers before addition of primary sludge.
6. Step 6. Add all the feed to digester 1.
7. Step 7. When digester 1 is full, transfer flow to digester 2.
8. Step 8. Continue operating in series.
9. Step 9. After step 8 is accomplished, start operating the gravity belt thickener on full schedule.

Second Choice for Process Startup. The following steps describe the second choice for process startup:

1. Step 1. Use WAS to fill both digesters completely.
2. Follow steps 2 to 9 as described in the Preferred Choice for Process Startup section above.

OPERATIONAL MONITORING

For the most part, aerobic digestion is a self-regulating process, unless the process is overloaded or the equipment is inoperative. Routine operational surveillance includes analytical testing and periodic checks of electrical and mechanical equipment, such as seals, bearings, timers, and relays.

From an operator's point-of-view, there are two interrelated types of issues that typically could require troubleshooting—equipment and process. Sometimes, equipment malfunction could cause a process upset, and, at other times, because of process conditions, equipment could malfunction. The following troubleshooting guide is categorized based on primary causes of the problem.

EQUIPMENT TROUBLESHOOTING. ***Clogging of Air Diffusers.*** A buildup of rags or grit on the diffusers causes diffuser clogging when the aeration system is shut off to concentrate the digested sludge before supernatant, decanting, sludge withdrawal, or after denitrification. If the air is off for a long period of time (sometimes 6 to 12 h/d), rags and grit within the digester may lodge on and inside the diffuser mechanisms. When aeration is resumed, the particulates clog the diffusers and eventually will reduce the air discharge, causing an increase in the blower discharge pressure. As mentioned in the Equipment Design and Selection section, fine-bubble diffusers are not recommended for digestion application because they are especially susceptible to clogging problems.

Effective maintenance prevents or cures clogging. While the elimination of diffuser clogging is difficult, equipment modification can reduce its frequency and severity. Jet aerators can be equipped with a self-cleaning system. Alteration of the air header, so that the diffusers may be withdrawn for service without emptying the tank, may also be used. Another alternative would be to use diffusers with above-water orifices, each complete with individual drop pipes. The chance for clogging is reduced because the orifices are located out of the liquid. Otherwise, during the denitrification or anoxic stage, the air is off and solids will accumulate in the pipes.

For systems in which mechanical prethickening is used, the mixing air requirement in the first digester (for in-series digester systems) is the dominating design criterion and should be optimized. The ability to maintain suspended solids in suspension is important, so shear tubes or draft tubes are recommended in these applications.

Figure 31.29 shows a typical system of this type. This project incorporates prethickening with a gravity belt thickener to as much as 8%, has four basins in series, and is covered and insulated because of the high altitude and low winter temperatures. A

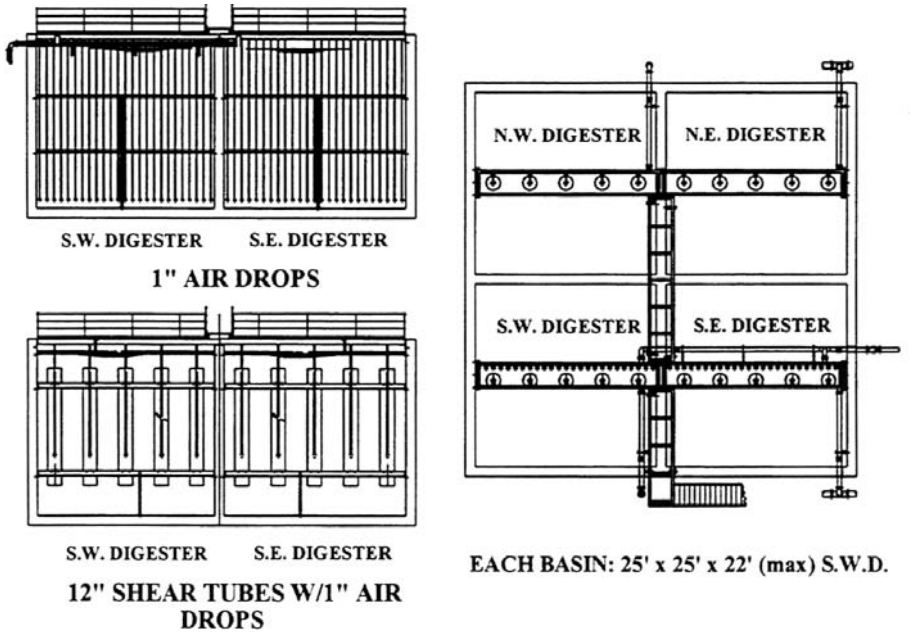


FIGURE 31.29 High solids operation at Los Lunas, New Mexico, in four-stage, prethickened, covered, and insulated digester system (ft × 0.3048 = m; in. × 25.40 = mm) (Daigger et al., 1997).

dual-type aeration system was provided on this project, as shown in the figure, to allow for high- and low-water-level operation (Daigger et al., 1997).

Blowers and Valves. An inefficient aeration system or excessive organic loading to the digester can cause a low dissolved oxygen concentration. Blower, mechanical aerator, or aeration diffuser deterioration results in a loss of aeration efficiency. It is important to routinely check and monitor the air delivery rate and pipeline pressures for potential problems; record the position of all air valves; investigate suspected clogging, leaks, and excessive pressure; and occasionally check the horsepower delivered to mechanical aeration shafts to determine their condition.

Mechanical Aerators. Mechanical aerator efficiency decreases if the liquid level exceeds specified upper and lower operational limits. Consult the manufacturers' engineering data and the operations and maintenance manuals for recommended liquid-level limits.

Freezing. Extended subfreezing weather may lead to ice formation on the liquid surface and on the mechanical aeration equipment. To prevent malfunction and possible breakdown during the winter, examine open digesters for ice formation. Break the ice and remove it before it damages digester appurtenances by wind action or expansion forces. Use warm air to thaw mechanical aerators troubled by ice formation. In extremely cold climates, it may be necessary to construct temporary covers to deter freezing.

Solids Deposition. Deposition may occur when gritty materials enter the digester and when the aeration and mixing devices do not create enough turbulence to resuspend the solids following a supernatant decanting sequence. Solids deposition can be prevented by improving the operation of the grit chamber, if one exists, or by using more powerful aeration and mixing equipment. Adding fillets to tank bottoms helps reduce solids buildup.

PROCESS TROUBLESHOOTING. The operator can evaluate the performance of the aerobic digester by following the guidelines described in the Process Control section; refer to Table 31.9 for the recommended acceptable values. If, during a check, an operator finds any of these parameters to show unusual values, the following troubleshooting guidelines could be used to identify problems with an aerobic digester system.

Increased Organic Loading. Increased organic loading can cause problems when the rate of oxygen required for aerobic digestion reaction is greater than the rate at which oxygen can be transferred to the sludge liquid by the WWTP's aeration system. Typically, the problem can be solved by reducing the organic loading rate and increasing the SRT. This is done by decreasing the influent sludge mass, total volume added, and amount of sludge withdrawn from the digester.

Excessive solids levels in the digester can also cause low dissolved oxygen concentrations. When suspended solids levels reach or exceed 3.5 to 4%, oxygen transfer efficiencies are reduced. This reduction may cause operational problems because of low dissolved oxygen concentrations, depending on the capacity of the aeration system.

Nuisance Odor from Digested Sludge. Inadequate dissolved oxygen is the primary cause of odor from the aerobic digestion process. To correct odor problems, first increase the dissolved oxygen concentration by additional aeration. Second, reduce the organic loading. If both of these fail, the addition of chemicals, such as potassium permanganate or hydrogen peroxide, to help oxidize the odor-causing compounds in the

digester, may be needed. This is considered an expensive and temporary solution to the problem. Odor control chemicals can be added to small volumes of sludge on a bench-scale test and proportioned to the digester volume to determine the amount of chemicals needed in the digester.

Excessive Foaming. Foaming can be caused by factors as simple as organic overloading or as complex as filamentous bacterial growth. To reduce foaming, decrease organic loading, install foam-breaking water sprays, reduce excess aeration rates, and use defoaming chemicals. To avoid dilution of the digester contents, operate water sprays sparingly.

Curing filamentous bacterial growth is a difficult task that should be handled at the aeration basins. Some operators have added oxidants, such as chlorine and hydrogen peroxide, both with and without beneficial results. Shocking the system with several hours of anaerobic conditions has also been tried. In most cases, limited sprays and defoaming agents control the foam until natural forces can cause a shift to a nonfilamentous type of bacteria.

Low pH (High Ammonia). The intent of this chapter is to encourage the reader to optimize digestion by using all the techniques available. Assuming that aerobic–anoxic operation is incorporated into the design, then a neutral pH of 7.0 is achieved during the nitrification and denitrification process.

When biomass is fed to the system, an increase in pH will be shown, as a result of the oxidation of biomass and production of ammonia. This event could occur once per day if a gravity belt thickener is used to prethicken; or 8 times per day, which is considered a typical wasting cycle of SBR and MBR systems; or 24 times per day, if a gravity thickener in loop is used in a batch operation. Both healthy nitrifiers and adequate alkalinity are required for nitrification. The pH could increase from initially 7.0 to 7.5 and then decrease to 7.0 again. When additional oxygen is provided to the system to oxidize the produced ammonia, the byproduct is hydrogen, indicating an acidic environment, or a drop in pH below 7.0. If denitrification or addition of chemicals is not added to the process to balance the lost alkalinity, then a drop in pH will continue. If, on the other hand, an anoxic cycle is incorporated into the digester, it is possible to recover the lost alkalinity and increase the pH without the use of chemicals.

Low Dissolved Oxygen. An acceptable range of dissolved oxygen is anywhere from 0.1 to 2, with a target of 0.5. Anything above a 0.1 is considered a positive dissolved oxygen; however, typically, dissolved oxygen probes are neither accurate nor reliable

ways to control dissolved oxygen, so a minimum reading of 0.3 is suggested. The dissolved oxygen reading should be evaluated with the ammonia concentration.

Clogging of diffusers, blower malfunction, or organic overload could cause low dissolved oxygen. In this case, check the equipment specifications, air deliveries, pipeline pressures, valving, and organic load. Clean diffusers, repair equipment as necessary, and, if the cause is organic load, reduce the feed to the digester, if possible, or reduce the solids concentration to the digester, reducing the oxygen demand and increasing the residual dissolved oxygen.

DATA COLLECTION AND LABORATORY CONTROL

DATA COLLECTION. Consistent data collection and process control through laboratory analyses are essential in the efficient operation of the treatment system. Analyses for total solids, volatile solids, dissolved oxygen, ammonium, nitrate, phosphorus, pH, temperature, flowrate, airflow rates, solids concentration, fecal coliforms, SOUR, and alkalinity of the raw and digested sludges provide the minimum surveillance for operating the aerobic digester. However, additional analyses would be warranted if operational problems arise.

The author highly suggests an in-depth reading of the Environmental Regulations and Technology document "Control of Pathogens and Vector Attraction in Sewage Sludge", produced by U.S. EPA's Pathogen Equivalency Committee (U.S. EPA, 1999a). The intent of this book is to give better understanding and guidance to the analytical procedures of fecal coliform tests and salmonella, and provide a more in-depth explanation of the basic concepts related to pathogens and vector attraction, as specified under 40 *CFR* Part 503 (U.S. EPA, 1999b).

MAINTENANCE MANAGEMENT PROGRAM. The planned maintenance program for the aerobic digester is similar to the maintenance program for the activated sludge process. Plot key elements include identification of maintenance tasks, scheduling, staffing, and a record system on trend charts. These charts plot various values according to time and show the trends in process changes.

MAINTENANCE TASKS. The key components that require regular attention in most aerobic digestion systems include

1. Aeration or oxygen supply system,
2. Mixing and pumping equipment, and
3. Instrumentation and control equipment.

Aeration and Oxygen Supply System. The principal requirement for the aeration or oxygen supply system is the inspection and service of the diffuser equipment. Once per year, schedule a diffuser mechanism inspection. If it is necessary to drain the tank for inspection and service, summer may be the best time because it is easier to restart.

Maximize the SRT during the spring and early summer before any diffuser inspection. Lower the mixed liquor concentration in the activated sludge tank just before the inspection to allow solids to be stored in the activated sludge process.

During the inspection, discharge the digested sludge to the drying beds or dewatering mechanism and accumulated solids in the aeration tank. Schedule material and manpower so that the tank is returned to service within 2 to 3 days. Restart digestion by seeding from other digesters or by the previously described startup procedure.

Mixing and Pumping Equipment. Annually, inspect the mixing and pumping equipment for worn blades and impellers. Replace faulty components and record critical parts for inventory. Service the seals, packing, and points of lubrication as frequently as recommended by the manufacturer.

Instrumentation and Control Equipment. Use a trained service representative to maintain the instrumentation and control components. Consider using the training courses available from equipment suppliers. Contract maintenance may also be available.

SCHEDULING. Assign specific maintenance tasks to individual staff members. Select staff on the basis of training and experience. An overall WWTP training program provides for upgrading the capabilities of both primary and backup staff members.

RECORDS. The importance of maintaining adequate operation and maintenance records cannot be overemphasized. The purpose of recording data is to track operational information that will identify and enable duplication of optimum operating conditions. The types of records include volume of sludge wasted to the digester, percentage of feed solids, volume of digested solids removed from the digester, and percentage of solids of sludge removed. If sludge is hauled to a site, keep records of hauling cost on a monthly basis.

Additional information includes dissolved oxygen data and pH, ammonia, nitrates, and/or phosphorus, SOUR and/or VSS reduction, pathogen reduction, alkalinity, and salmonella.

Keep a monthly report form. In WWTPs where the aeration system capacity is marginally adequate in providing desirable dissolved oxygen levels in the digester, record dissolved oxygen level data on a trend chart.

If chemicals are added to the digester for pH or odor control, record the type and amount of chemicals added.

If mechanical aerators are used, record power outage. In the case of diffused air systems, airflow records may be of interest. If airflow meters are not available, records of power consumption may be useful. Experimenting with the aeration system often leads to significant savings in power costs.

If the operator has chosen a two-stage digestion process because approval of the process as a PSRP equivalent alternative is required by the permitting authority, the plant operator should demonstrate experimentally that microbial levels in the product from their sludge digester are satisfactorily reduced. A record of pathogens has to be submitted and, once the performance is demonstrated, the process would have to be operated between monitoring episodes at time–temperature conditions at least as severe as those used during their tests.

To save time, use a simplified recording system. Increase completeness by using preprinted forms, computer data entry, or color-coded systems. Design the system as a permanent method to link routine and unscheduled maintenance with inspection procedures, equipment replacement, and accountability. Keep records where they are readily available to all WWTP personnel.

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Chapter 32

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Effective sludge processing is crucial to the reliable operation of a municipal wastewater treatment plant (WWTP). Because WWTPs have become more efficient at producing high-quality effluents, increased quantities of sludge are being generated. The solids treatment processes—thickening, dewatering, stabilization, and disposal—represent a major portion of the cost of wastewater treatment.

Sludge stabilization processes further treat the sludge to reduce odors or nuisances, to reduce the level of pathogens, and to facilitate efficient disposal or reuse of the product. This chapter focuses on the conventional methods of sludge stabilization other than anaerobic and aerobic digestion. Chapters 30 and 31 of this manual discuss anaerobic and aerobic methods. This chapter discusses the following stabilization methods:

- Composting,
- Lime stabilization,
- Thermal treatment,
- Heat drying, and
- Incineration.

All of these stabilization methods (other than incineration) are considered acceptable processes and are widely used for treating sludge to Class A or Class B levels for beneficial reuse and disposal, as referenced in the U.S. Environmental Protection

Agency's 40 *CFR* 503 regulations. The 503 regulations require documentation that one of these processes is used when meeting one of the alternatives listed for pathogen reduction in 503.32(a) for Class A sludge and 503.32(b) for Class B sludge. The resultant product has been referred to in this text as biosolids.

In addition, the 503 regulations reference the U.S. EPA guidance manual *Control of Pathogens and Vector Attraction in Sewage Sludge* (U.S. EPA, 1992) for calculation procedures that are acceptable for mass volatile solids reduction that is required for 503.33—Vector Attraction Reduction.

COMPOSTING

DESCRIPTION OF PROCESSES. Composting is a managed method for the biological decomposition of organic materials. Composting is one of the typical stabilization processes and is most frequently used to stabilize raw sludge; hoewever, applications for further stabilizing digested sludge are also typical. For many years, composting has been used to convert dewatered wastewater sludge into a stable, odorless, humus-like product. The practice of composting has grown largely because of rising costs of, or increasing restrictions on, the alternatives to composting such as landfill, ocean disposal, and incineration. Most solids composted in the U.S. are used for soil conditioning or horticultural application (WEF, 1995).

The four principal objectives of composting are

- Biological conversion of putrescible organics to a stabilized form;
- Pathogen destruction (the heat generated during composting results in disinfection but not sterilization of the end product);
- Mass reduction of the wet sludge quantity through moisture and volatile solids removal (although when a bulking agent is added to facilitate the composting process, overall volume may increase); and
- Production of a usable end product.

As a result of composting, the resulting product becomes a more attractive material for reuse. If the composted solids are sold, the revenues can help offset the composting reduction costs.

Figure 32.1 shows a typical flow diagram for a composting process. Providing a suitable environment in the compost mass requires the initial compost mixture to have a solids content of 40 to 50%. To attain this solids level, raise the carbon to nitrogen ratio (C:N), and provide the desired structural properties of the compost mass (promoting adequate air circulation). A bulking agent is often added. As the organic material in the

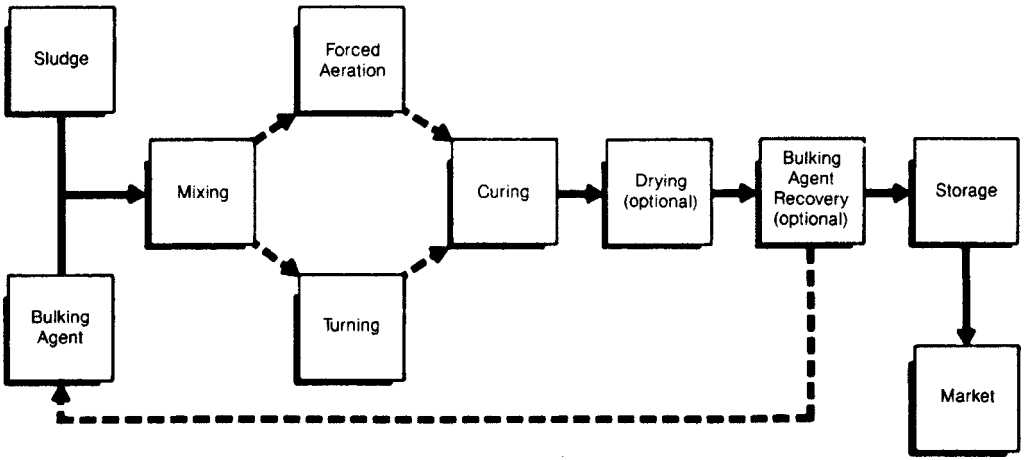


FIGURE 32.1 Compost process flow diagram.

sludge decomposes, the compost heats to temperatures in the pasteurization range of 122 to 158 °F (50 to 70 °C) and destroys most enteric pathogenic organisms.

The quality (that is, the concentrations of certain metals and organic pollutants) of the composted material will determine its suitability for use as a soil amendment. Compost quality needs monitoring on a regular basis to ensure compliance with applicable regulatory standards.

Composting may proceed under either aerobic or anaerobic conditions. Most composting operations seek to maintain aerobic conditions throughout the compost mass. Aerobic conditions accelerate material decomposition and result in the temperatures necessary for pathogen destruction. Anaerobic conditions can produce significant foul odors that are not generated when aerobic conditions are maintained throughout the compost mass.

Composting can be performed by reactor or nonreactor systems. Nonreactor systems are often referred to as open systems. Reactor systems are often referred to as in-vessel, enclosed, or mechanical compost systems. Reactor systems may be classified according to reactor type, solids-flow mechanisms, bed conditions in the reactor, and the method of air supply.

Composting with nonreactor systems is a labor-intensive process involving the addition of a bulking agent, mixing, windrowing or pile building, screening, and other activities. Some of these operations, however, may be automated. With in-vessel systems, most, if not all, operations are automated. The potential for odor generation exists

at all composting facilities, especially at poorly designed and operated sites. Also, the potential exists for the generation of significant quantities of dust, which might possibly spread pathogens.

Nonreactor Systems. Nonreactor systems include the windrow system (see Figure 32.2) and the aerated static pile (see Figure 32.3). In the windrow system, aerobic conditions are maintained through convective air flow and periodic turning. The windrow is turned daily except when it is raining. Through several turnings or mixings, the sludge is subjected to the higher interior temperatures for pathogen reduction and stabilization of the organic material. In the static pile system, blowers attached to pipes located in the base of the piles either blow or pull air through the compost pile. After composting for 3 weeks, including 3 days at a minimum temperature of 55 °C (131 °F), the windrow or compost pile is torn down and placed in curing.

Reactor Systems. In a reactor-type composting system, the sludge and the bulking agent are mixed and then aerated in silos (see Figure 32.4), rotating drums (see

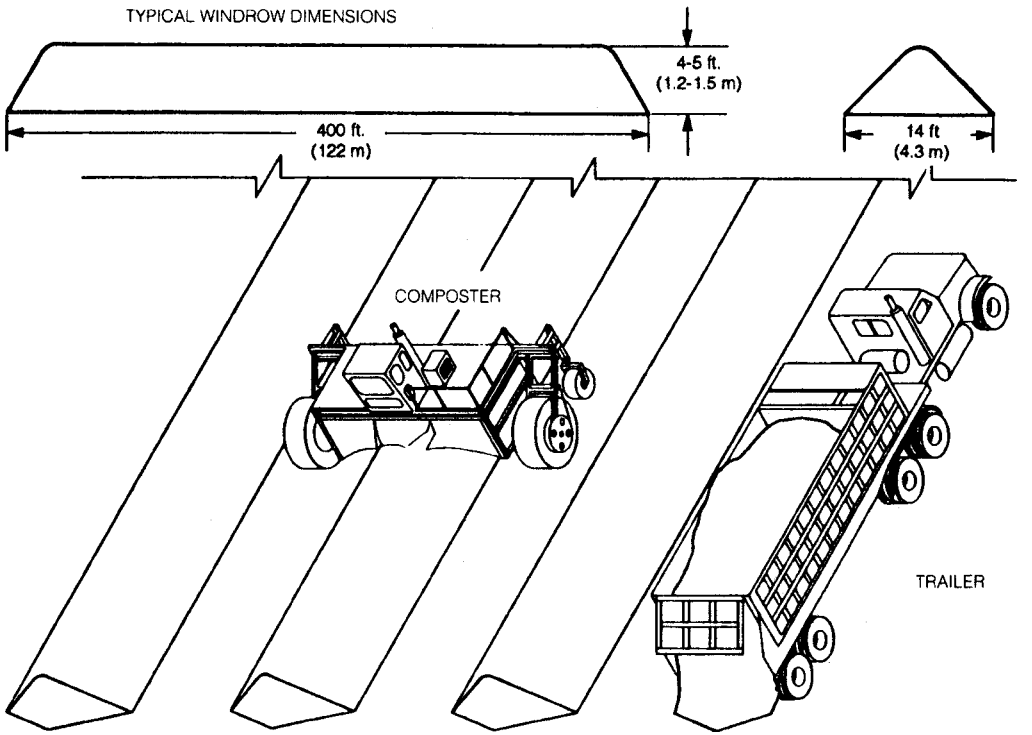


FIGURE 32.2 Windrow composting system.

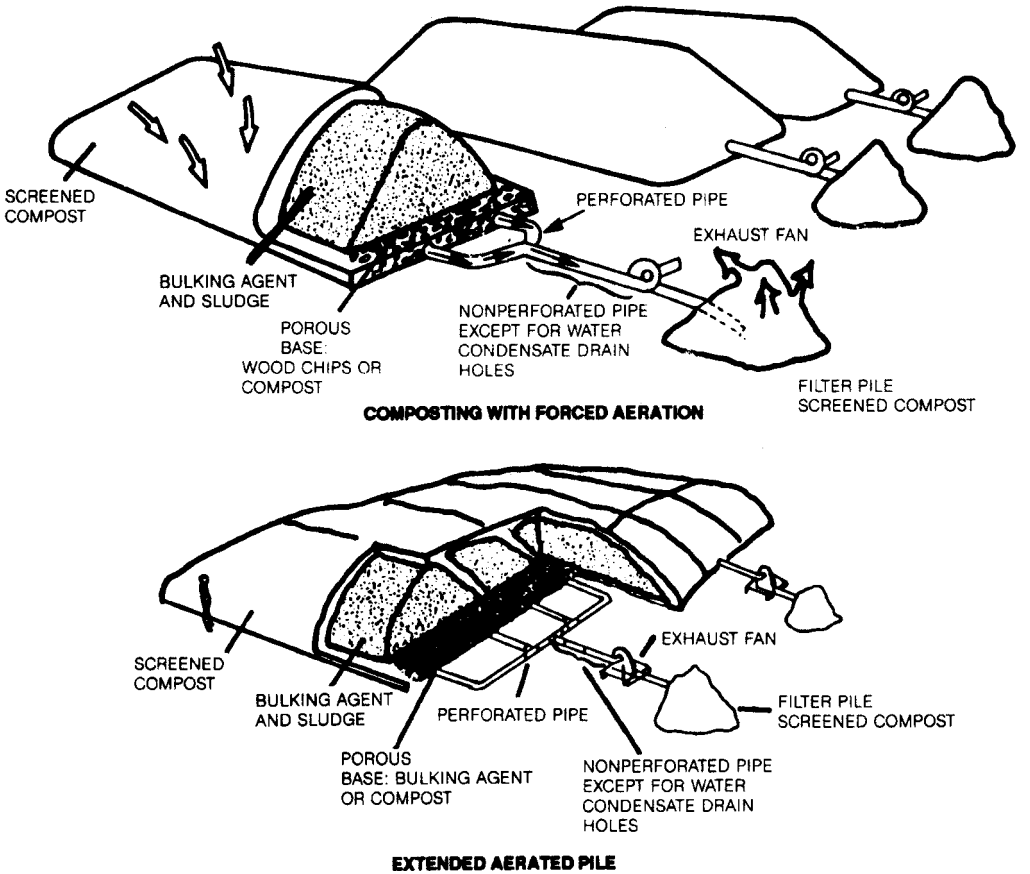


FIGURE 32.3 Two variations of a static pile composting system.

Figure 32.5), or horizontal beds (see Figure 32.6). In these systems, composting takes place in a stationary mode, by plug flow, or in an agitated bed. Regulated aeration controls the oxygen concentration and the temperature regime. Composted material typically is removed after approximately 14 days and placed in curing.

Facilities. The basic facilities for a composting operation include a paved working area; an aeration system; equipment for moving the sludge, bulking agent, and compost; equipment for screening and separating the bulking agent; odor control facilities; areas for bulking agent storage, compost storage, and compost curing; and a system to control runoff (WEF, 1995).

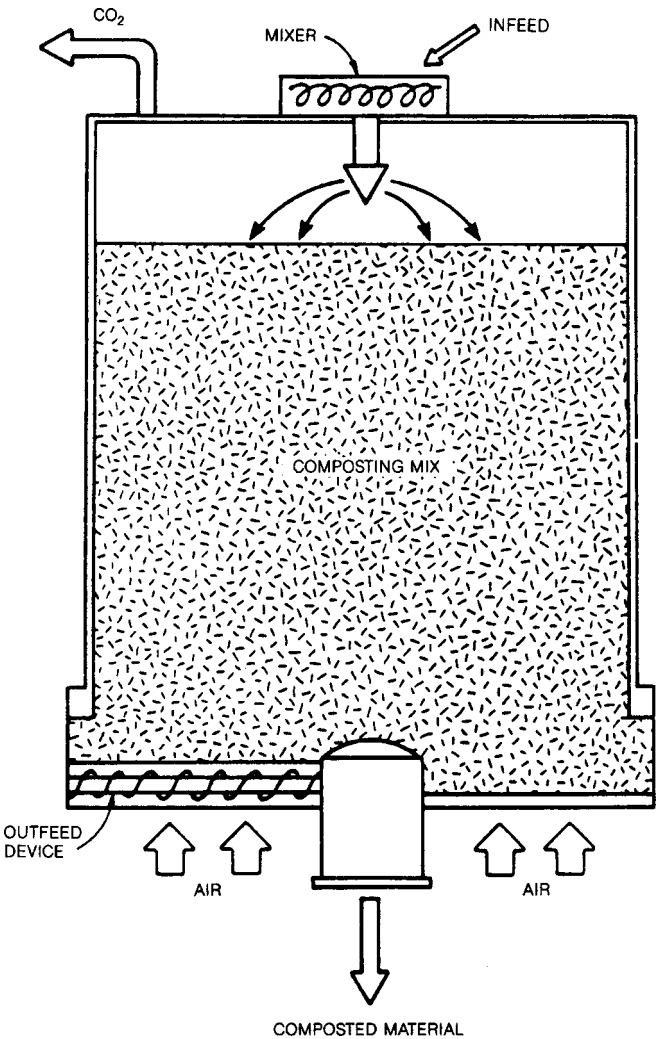


FIGURE 32.4 Silo type in-vessel composting system.

TYPICAL OPERATIONS. Although composting can be accomplished by a variety of methods, the basic process flow remains unchanged (see Figure 32.1). Even though composting systems may differ in appearance, they all include the following basic steps:

- Mixing of the sludge and bulking agent,
- Composting or microbial decomposition of the organic matter,

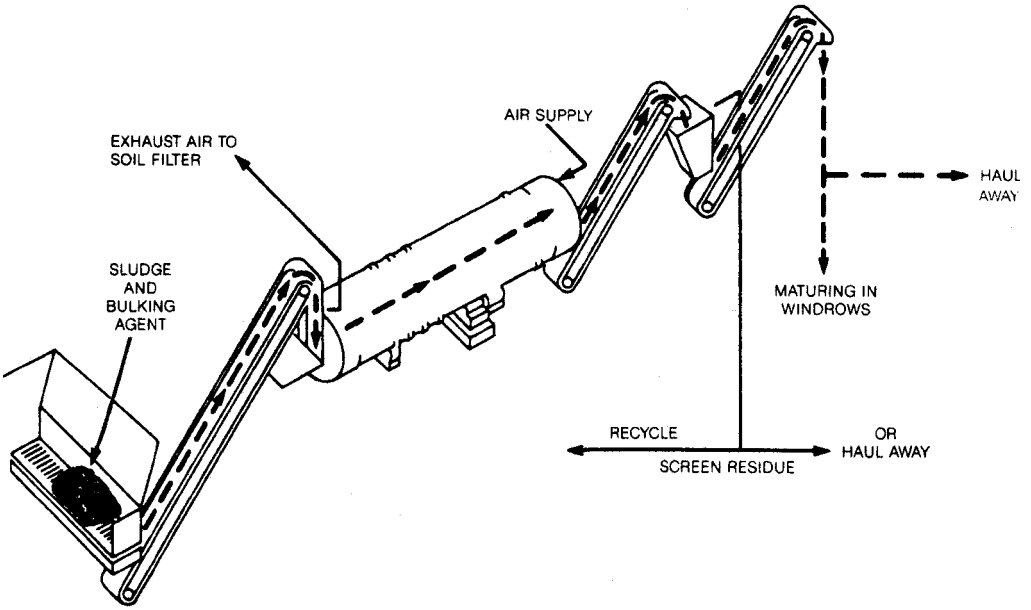


FIGURE 32.5 Rotating drum type in-vessel composting system.

- Recovery of the bulking agent or product recycling,
- Curing,
- Storage, and
- Final disposition of the composted material (which may be distributed or marketed as a humus material).

Homogeneous mixing is an extremely important aspect of composting. Partially dewatered sludge (typically 15 to 25% solids) is mixed with recycled compost or other bulking agents to provide proper porosity, initial moisture content, and nutrients. As sludge is evenly distributed within most compost systems, air flow becomes more uniform, resulting in greater microbial activity and efficiency, odor control, and ease of material handling.

Bulking agent recycle depends on the composting method used and the moisture content of the sludge. Some methods include recycling a portion of the finished compost product.

Curing is an extension of the composting process that results in further organic matter stabilization and volatile solids reduction. The length of the curing period de-

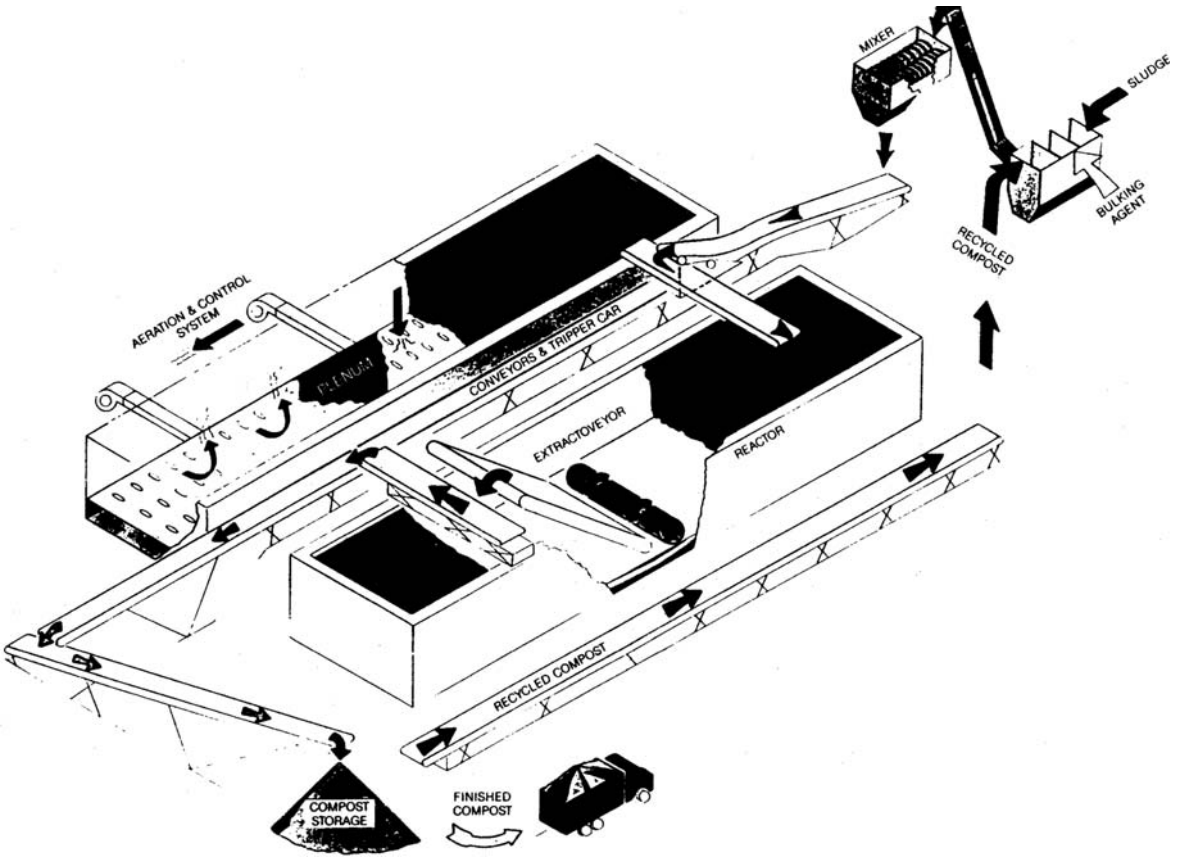


FIGURE 32.6 Horizontal bed type in-vessel composting system.

pends on the product's end use and the process efficiency in pathogen reduction, odor control, and reduction of volatile organic compounds.

Aeration Systems. Aeration systems can be either movable or fixed. Movable aeration equipment includes compost mixers (for windrow systems) or 0.5- to 2-hp blowers connected to perforated pipe over which compost piles are constructed (see Figure 32.3). Permanent systems include blowers that are connected to a pipe or plenum that is imbedded within the compost pile; or, as in a closed vessel system, the pipe or plenum feeds a reactor vessel.

The air supply to each pile or reactor (and in some cases zones within each pile or reactor) should be controlled separately. The air supply may be controlled manually,

by time clocks, or by a temperature sensor inside the pile. In some systems the carbon dioxide level in the exhaust air has been used to control the air supply. Also, the system should be able to pull or push air through the pile.

Typical temperatures for active composting range from 55 to 60 °C (131 to 140 °F). These set points may be lowered before compost removal or pile breakdown to increase moisture removal, cool the compost pile, and reduce odors. Aeration requirements for moisture removal may be more than 10 times what is needed to maintain an aerobic environment (Haug, 1980).

Mixing Systems. An effective mixing of sludge and bulking agent is essential for rapid and even composting. A uniform mix reduces the likelihood of anaerobic pockets within the compost mass, thereby decreasing the potential for odor generation.

Two typically used mixing systems are

- A stationary system (that is, a plug mill or rotary drum) using paddles or augers to stir the materials; and
- Moving equipment, such as a wheel loader or composter.

Movable equipment is best for smaller WWTPs and for interim composting operations; however, facilities processing more than 10 dry tons/day should consider a stationary mixing system.

Screening. Screening is important in the production of a uniform fine-grained product and in the recovery of the bulking agent for reuse. Screening compost is difficult because at different moisture contents compost can be sticky (which tends to clog screens) or light (which tends to skip off the screen instead of passing through). Relatively dry compost (less than 48% moisture) produces the best results. To reduce the moisture content for efficient screening, a drying step is sometimes included before screening. However, very dry compost may create a severe dust problem. To counter the problem of clogging, almost all screens use some kind of shaking action or brushing to keep the screen clean.

Trommel, harp, and vibratory screens have been used successfully; however, vibratory screens may be better able to handle wet compost (WEF, 1995). The size of the screen openings depends on the need for bulking agent recovery and the required sizing for product marketing. Typical screen sizes between 6 and 10 mm (0.2 and 0.3 in.) allow for both high bulking agent recovery and desirable product quality. For some commercial applications of compost, screen sizes of up to 25 mm (1 in.) are used. The smaller screen sizes, however, remove objectionable materials that may be present in the raw sludge such as razor blades and plastic tampon applicators.

PROCESS CONTROL. Moisture, temperature, nutrients, bulking agents, and aeration greatly affect stabilization by composting.

Moisture. Moisture affects the rate of biological activity. At less than approximately 40% moisture, activity begins to decrease. At approximately 60% moisture, the air pore space is blocked (WEF, 1995). This affects the aeration efficiency of the system and results in anaerobic zones within the compost bed. Thus, the interaction of moisture and aeration will affect the composting rate and odor production. Moisture content will also affect materials handling and, thus, processing efficiency.

Temperature. Temperature has a dramatic effect on the microbial population (see Table 32.1). Decomposition is fastest in the thermophilic range. Research indicates the optimum temperature to be between 55 and 60 °C (131 and 140 °F); at temperatures more than 60 °C (140 °F) microbial activity decreases (Feinstein et al., 1980). One method for maintaining the temperature within the optimum range is to use forced ventilation or aeration and control the blower rate so as to hold the pile exit temperature to less than 60 °C (140 °F). Maintenance of an adequate temperature of 55 to 60 °C (131 to 140 °F) for at least 3 days is required to achieve pathogen destruction (see Tables 32.1, 32.2, and 32.3). Temperature can also influence the volatilization rate of many organic compounds.

Nutrients. Carbon and nitrogen are the principal nutrients that affect composting. The carbon : nitrogen ratio (C : N) affects the microbial activity and the rate of organic

TABLE 32.1 Populations during aerobic composting (Poincelot, 1975).

	Numbers per gram of wet compost for each stage			
	Mesophilic, ambient to 40 °C	**Thermophilic, 40 to 70 °C**	**Cooling**	**Number of groups of microorganisms identified**
Bacteria				
Mesophilic	10^8	10^6	10^1	16
Thermophilic	10^4	10^9	10^7	1
Actinomycetes				
Thermophilic	10^4	10^8	10^5	14
Fungi				
Mesophilic	10^6	0	10^5	18
Thermophilic	10^3	10^7	10^6	16

TABLE 32.2 Temperature and time required for pathogen destruction in sludge—laboratory data (Stern, 1974).

	Exposure time for destruction at various temperatures, minutes				
Microorganisms	**50 °C**	**55 °C**	**60 °C**	**65 °C**	**70 °C**
Cysts of *Entamoeba histolytica*	5				
Eggs of *Ascaris lumbricoides*	60	7			
Brucella abortus		60		3	
Corynebacterium diptheriae		45			4
Salmonella typhi			30		4
Escherichia coli			60		5
Micrococcus pyogenes, var., aureus					20
Mycobacterium tuberculosis					20
Viruses					25

matter decomposition. Microorganisms require carbon for both metabolism and growth, and nitrogen for protein synthesis and cell construction.

The best approach is to maintain the C:N ratio at a level that allows for optimum microbial growth; that is, between 26 and 31 units of carbon/1 unit of nitrogen (Poincelot, 1975). Carbon values greater than 31 tend to slow the process and result in lower temperatures. In most cases, direct measurement of the compost mix to determine the C:N ratio is unnecessary because these ratios typically are obtained with sludge and wood chip mixtures.

Low C:N ratios (less than 20) typically affect the compost product rather than the process. With low C:N ratios, ammonia is released and the nitrogen content of the

TABLE 32.3 Temperature and time required for pathogen destruction in compost—field data (WEF, 1995).

	Exposure time for destruction at various temperatures, hours		
Microorganisms	**45 to 55 °C**	**60 °C**	**65 °C**
Salmonella newport	168	25	
Salmonella	168	48	
Poliovirus type 1		1	
C. albicane		72	
Ascaris lumbricoides		4	1
Mycobacterium tuberculosis			336

compost is reduced (40 *CFR* Part 503). Because one of the major goals of composting is to produce an economical and usable product, it is best to maintain the nitrogen content of the compost as high as possible.

Bulking Agents. When bulking agents are added to the sludge, they control moisture, increase the air voids for proper aeration by giving porosity, provide structural support for the compost mass, and act as an organic amendment for C:N ratio adjustment. Bulking agents can also be used for product modifications. Their addition can change the physical and chemical characteristics of the compost, thereby affecting its range of uses and marketability.

The physical texture of the compost varies depending on the characteristics of the bulking agent and whether it is completely screened out, partially screened out, or left in the final product. The bulking agent can dramatically affect the chemical characteristics of the compost. Sawdust and other slow-degrading, high-carbon materials left in the compost result in an unfavorably high C:N ratio that consumes the nitrogen in the soil and limits the amount available to support plant growth (40 *CFR* Part 503).

Important bulking agent properties include moisture content, particle size, and absorbency. Bulking agent characteristics affect materials handling, processing time, and product quality. Some bulking agents may require shredding or screening. High-carbon or high-cellulose materials that are not recovered and reused may require long curing times. Pilot testing of new bulking agents should be performed to ensure compatibility with process operations.

Aeration. Aeration is important for providing oxygen for the decomposition process, temperature control, and moisture removal. Higher temperatures are achieved under aerobic conditions than under anaerobic conditions. Underaeration may result in low temperatures because of anaerobic conditions; excessive aeration may result in cooling of the compost piles.

Studies suggest that 20 to 50 m^3/h (700 to 1 800 cu ft/hr) per dry ton of sludge results in oxygen levels from 5 to 15% throughout the pile (WEF, 1995). At oxygen levels below 5%, anaerobic conditions can occur, resulting in anaerobic zones in the sludge mass, the generation of odors, and inadequate stabilization. Oxygen levels can be analyzed with a portable oxygen monitor and should be measured simultaneously with each temperature reading. During the early stages of production, higher aeration rates may be necessary to control temperatures and increase microbial activity.

Aeration also provides a means of removing moisture and drying the compost product. Excessive moisture can adversely affect the materials handling and processing operation. If the solids content falls to less than 50%, the static pile process is affected

by a decrease in the efficiency of the screening. In turn, this means that less compost product will be produced causing a corresponding increase in the material to be recycled. In addition, excessive moisture can contribute to anaerobic conditions and odor problems during curing and storage. Moisture also increases the costs of distributing the compost product.

Moisture removal using aeration occurs when the air becomes saturated as it moves through the compost pile. As air is drawn through the pile, it is gradually heated by the elevated interior temperatures. This temperature increase is accompanied by an increase in specific humidity that allows the air to increase its water-holding capacity. It is this temperature and specific humidity relationship that allows successful air drying even in regions of high relative humidity.

ODOR CONTROL. In composting operations, odor control measures may be necessary whenever incompletely stabilized sludge or compost is exposed to the air. Processes within the composting operation that have a potential for odor generation include mixing, aeration, tearing down of the composting and curing piles, and screening. Odors during composting are best controlled by maintaining an aerobic environment.

Several methods are used to reduce odors depending on the location of the composting facility in relation to developed areas (especially residential areas). For example, certain facilities—such as mixing and screening—can be enclosed. Also, exhaust from aeration of the compost can be discharged through scrubber piles or air scrubbers.

SAFETY AND HEALTH PROTECTION. Employees working at composting operations should take precautions to reduce exposure to pathogenic organisms. Composting where temperatures reach the thermophilic range can eliminate practically all viral, bacterial, and parasitic pathogens; however, some fungi (Aspergillus fumigatus for example) are thermotolerant and survive the composting process. Large numbers of spores are released into the atmosphere during certain composting operations (compost screening, dumping and mixing of compost, and wood chip dumping). To reduce exposure to airborne pathogens, enclose the cabs of heavy equipment, ventilate all enclosed areas properly, and provide dust masks to employees working in dusty areas.

TROUBLESHOOTING. Table 32.4 presents a troubleshooting guide for forced air static pile (FASP) systems that will help the operator identify problems and develop solutions. If you operate a reactor system, refer to the troubleshooting guide in the operation and maintenance manual provided by the reactor manufacturer.

TABLE 32.4 Troubleshooting guide for composting with the forced air static pile system (U.S. EPA, 1978)

Problem	Probable cause	Solution
Compost pile does not reach 50 to 60 °C (122 to 140 °F) in a few days after construction	Poor mixing of sludge and bulking agent	If oxygen levels are above 15%, reduce operating time of blower
	Compost pile too wet	Pipe hot exhaust air from an adjacent pile into this pile to raise its temperature
	Too much aeration	Reduce aeration rate; if the pile does not come up to temperature within a couple of days after taking these steps, the pile should be torn down, remixed, and reconstructed; if the bulking agent is too wet (more than 45 to 55% moisture) it must be dried, or drier bulking agent can be found deeper within the bulking agent storage pile
Temperature does not remain above 50 to 60 °C (122 to 140 °F) for more than 1 to 2 days	Poor mixing of sludge and bulking agent	Adjust blower cycle to maintain oxygen between 5 and 15%
	Compost pile too wet	Pipe hot exhaust air from an adjacent pile into this pile to try to maintain it at temperature; this should only be done for a few days at a time because of moisture accumulation
	Overaeration	Reduce aeration rate; if temperature does not come back up, the material should be recycled or remixed, and steps should be taken to correct the problems before the next composting cycle
Odors are emitted from a composting pile	Poor air distribution in pile	Check blower for proper operation; check that aeration pipes are not plugged
	Poor mixing of sludge and bulking agent	Typically the odors develop from anaerobic conditions in the pile because of a lack of air; probably the best procedure is to increase the blower "on" cycle or run it continuously until the odors disappear, or turn the windrow more often
	Inadequate or nonuniform air distribution through the pile	Check for water accumulation in the lines and blower; review air distribution system design and layout for causes of high pressure drops
Blower does not operate	Timer failure; power failure; motor failure; fan is "frozen" from corrosion or ice and will not turn	Check each probable cause until trouble is found

LIME STABILIZATION

DESCRIPTION OF PROCESSES. Lime can be used to stabilize raw primary, waste-activated, and anaerobically digested sludges. Lime stabilization can be accomplished either before dewatering (prelime) or following a de-watering step (postlime). Prelime stabilization is more typical; however, postlime stabilization may have significant advantages including reduced lime dosages and the elimination of special constraints on conditioners and equipment used for dewatering (WEF, 1995). The lime-stabilized material may be disposed of in landfills or beneficially used.

The standard process involves adding sufficient lime to liquid sludge to raise the pH of the mixture to 12 or more and to maintain a pH of 12 for a minimum of 2 hours. This typically destroys or inhibits pathogens and the microorganisms involved in the decomposition of the sludge. Therefore, little or no decomposition occurs and few odors are produced by biological activities. The destruction of pathogenic organisms reduces bacterial hazards to a safe level.

In a typical operation, lime slurry and sludge are combined in a mixing tank equipped with either diffused air or mechanical mixing systems. After initial mixing, the treated material is transferred to a contactor vessel where mixing is continued, typically for a period of 30 minutes. If necessary, additional lime can be added in the contactor to maintain a pH of 12 or more for a minimum of 2 hours following mixing. The treated sludge is then dewatered and stored or disposed of immediately.

Differences between various designs may affect the operation at individual WWTPs. For example, in a batch process the mixing, 30-minute contact time, and the required thickening may all occur in one tank (U.S. EPA, 1978). Figure 32.7 presents a typical process flow sheet for lime stabilization.

The postlime stabilization process has several significant advantages over the prelime stabilization process. These advantages include

- The option of using either hydrated lime or quicklime (without slaking);
- The avoidance of high lime-related abrasion, corrosion, and scaling problems with mechanical dewatering equipment when a prelime stabilization process is used; and
- Pathogen destruction through use of heat generated during slaking of quicklime in the lime–sludge mixture.

Some proprietary processes are related to lime stabilization. Sludge is mixed with a setting agent, either cement kiln dust or Portland cement and silicate, thereby producing an alkaline environment in the treated sludge. Typically, the pH of the treated sludge is between 11.5 and 12.5. The chemical reaction between the sludge and the set-

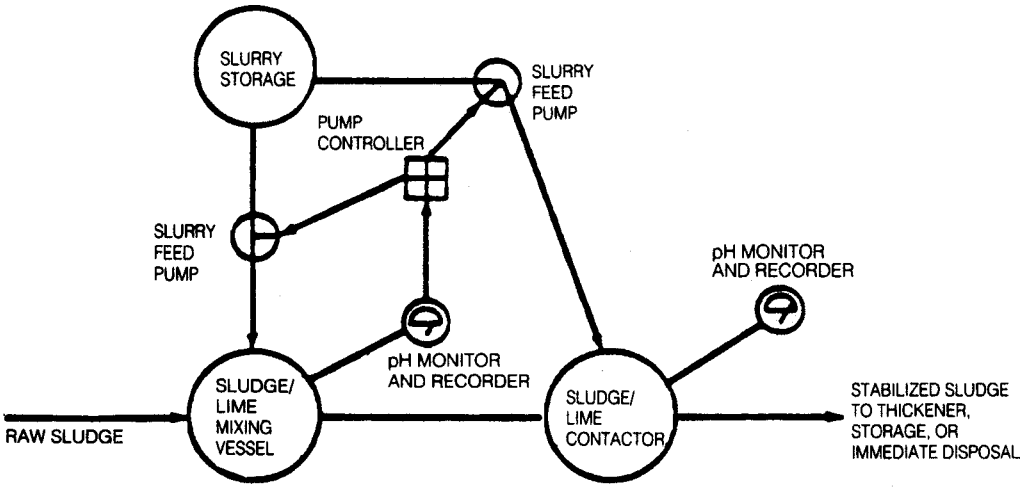


FIGURE 32.7 Lime stabilization process flow diagram.

ting agent also results in elevated temperatures. The combination of elevated temperatures and high pH destroys pathogenic organisms and drives off water. By windrowing and periodic turning of the sludge mass, the solids content of the product can be increased to more than 50% in 2 to 3 weeks. The end product may be suitable for beneficial use.

ADDITIONAL TECHNOLOGY. One proprietary process uses a mixer designed to gently mix sludge and lime together to produce proper stabilization without turning the material into a pasty-type consistency. The ability to control the consistency of the material is accomplished by adjusting the speed of the augers and the depth setting of a weir located at the discharge. Optimum operation of the mixer is accomplished by controlling the depth of the material within the mixer.

Another proprietary process elevates the solids temperature in accordance with 40 *CFR* Part 503 regulations to reduce pathogens. The process uses lime to increase the pH, to meet the vector attraction requirements. The supplemental heat system is used to reduce the amount of lime necessary to obtain proper temperatures. On a typical sludge containing 20% dry solids, the lime dosage and operating costs for the process are cut in half by the use of supplemental heat. The process includes a heat pulse step that is accomplished within the pasteurization vessel. The pasteurization vessel is a totally enclosed, heated vessel that holds the material at the pasteurization temperature for the time required. The vessel provides a continuous flow of material in and out.

PROCESS CONTROL. Process control is critical to achieve adequate lime stabilization. Proper control techniques are important because the effects of incomplete stabilization are not readily apparent and may not be seen at the WWTP.

Sensors, particularly pH electrodes, need to be properly cleaned, calibrated, and maintained. Special pH electrodes are necessary for routine measurements more than pH 10. Sensitive narrow-range pH paper is acceptable for process monitoring.

The absence of odors at the WWTP plant and acceptable dewatering characteristics are not good indicators of adequate stabilization. Only careful monitoring of the pH will ensure that an adequate pH is being maintained for a period sufficient for adequate stabilization. Microbiological examinations for indicator organisms such as fecal coliforms and fecal streptococci should be performed on a quarterly basis.

Compared to composting, the lime stabilization process is simpler to operate. Some of the principal disadvantages of lime stabilization are that the sludge can become unstable if the pH drops after treatment and a regrowth of biological organisms occurs, that the added lime increases the mass to be disposed, and that lime is expensive.

SAFETY AND HEALTH PROTECTION. Employees should take pre-cautions to reduce exposure to lime when working in a lime stabilization area. The high pH of the lime is very caustic and will damage skin, eyes, and lungs if exposed through contact or inhalation. Use of personal protective equipment should be mandatory for all employees when working in or around the lime stabilization areas, including, at a minimum, gloves, safety goggles, and a ventilator. Proper housekeeping and storage procedures as recommended by the chemical manufacturer should be followed at all times because the lime materials can be very corrosive if not handled properly.

TROUBLESHOOTING. Table 32.5 presents a troubleshooting guide for lime stabilization that will help the operator identify problems and develop solutions.

THERMAL TREATMENT

DESCRIPTION OF PROCESSES. Thermal treatment systems release water that is bound within the cell structure, thereby improving the dewatering and thickening characteristics of the sludge. Thermal treatment systems include the processes of heat treatment and wet air oxidation. Thermal processes are an attractive reduction technique because of the limited volume of the resulting product. However, volume reduction and product quality must be evaluated with regard to fuel costs, equipment expenditures, air pollution control demands, and increased concentration of metals in the end product.

TABLE 32.5 Troubleshooting guide for lime stabilization (U.S. EPA, 1978).

Problem	Probable cause	Solution
Air slaking occurring during storage of quicklime	Adsorption of moisture from atmosphere when humidity is high	Make storage facilities airtight, and do not convey pneumatically
Feed pump discharge line clogged	Chemical deposits	Provide sufficient dilution water
Grit conveyor or slaker inoperable	Foreign material in the conveyor	Check and replace shear pin if necessary; remove foreign material from grit conveyor
Paddle drive on slake is overloaded	Lime paste too thick	Adjust compression on the spring between gear reducer and water control valve to alter the consistency of the paste
	Grit or foreign matter interfering with paddle action	Remove grit or foreign materials, try to obtain lime with a lower grit content, or install grit removal facilities in slaker or slurry line
Lime deposits in lime slurry feeder	Velocity too low	Maintain continuous high velocity by use of a return line to the slurry holding tank
"Downing" or incomplete slaking of quicklime	Too much water is being added	Reduce quantity of water added to quicklime (detention slaker/water to lime ratio = 3.5:1; paste slaker ratio = 2:1)
"Burning" during quicklime slaking	Insufficient water being added, resulting in excessive reaction temperature	Add sufficient water for slaking (see ratios above)
Sludge retains definite offensive odor after addition of lime	Lime dose too low	Check pH in sludge-lime mixing tank and increase lime dose, if needed; check pH for possible malfunction

Heat Treatment Process. In the heat treatment process (see Figure 32.8), sludge is ground to a controlled particle size and pumped at a pressure of more than 2 100 kPa (300 psi) (U.S. EPA, 1986). The sludge is brought to a temperature of approximately 180 °C (350 °F) by heat exchange with treated sludge and direct steam injection. The sludge then "cooks" in the reactor at the desired temperature and pressure. Finally, the hot treated mass cools by heat exchange with the incoming sludge.

The treated material settles from the supernatant before the dewatering step. Gases released at the separation step pass through a catalytic afterburner at 340 to 400 °C (650 to 750 °F) or through a deodorizing device. In some cases, these released gases are returned to the diffused air system in the aeration basins for deodorizing.

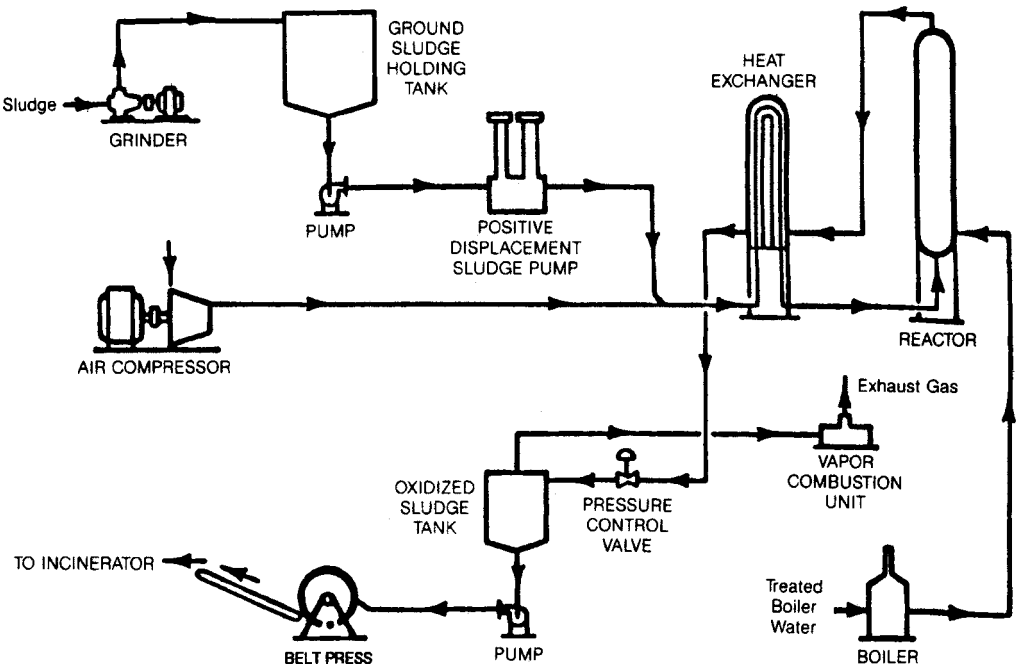


FIGURE 32.8 Heat treatment system flow diagram.

Wet Air Oxidation. The wet air oxidation process resembles heat treatment except that the former operates at higher temperatures (230 to 340 °C [450 to 640 °F]) and higher pressures (8 200 to 11 000 kPa [1 200 to 1 600 psig]) than does heat treatment (U.S. EPA, 1986). The wet air oxidation process is based on the principle that any substance capable of burning can be oxidized in the presence of water vapor at temperatures between 120 and 370 °C (250 and 700 °F). The degree of oxidation achieved varies depending on the temperature, pressure, reaction time, and air supplied to the reactor. The process is used either as a thermal conditioning process or as a relatively complete oxidation system, although the maximum achievable oxidation levels do not approach the degree of organic destruction achieved in a true incineration process. Either method of operation results in a liquid sludge with optimum dewaterability characteristics.

The feed to the wet air oxidation process does not require dewatering as does the feed to the processes involving both heat drying and incineration, discussed later in this chapter. However, the oxidized ash must be separated from the water by vacuum filtration, centrifugation, or some other solids separation technique. The water content of the feed sludge may exceed 95%. The sludge feed mixes with compressed air and passes through a heat exchanger before entering the reactor. The oxidized sludge leav-

ing the reactor supplies the heat in the heat exchanger. If high levels of oxidation are occurring and the sludge has a relatively high fuel value, oxidation in the reactor may be self-sustaining. If this is not the case, heat to the heat exchanger is supplied by injecting steam. Because the temperature in the reactor typically is approximately 260 °C (500 °F) for high levels of oxidation, high pressures (between 6 900 and 20 600 kPa [1 000 and 3 000 psig]) in the reactor may be necessary to prevent water vaporization.

Depending on the installation, either before or after passing the sludge through the heat exchanger, the gases are separated through a pressure control valve and sent to a catalytic gas purifier for odor control. The gases then may be expanded for power recovery or released to the atmosphere. If not done before separation, the oxidized material then is passed through a heat exchanger, released through a pressure control valve, and dewatered. The liquid portion, which is odorous and has a high COD, typically is returned to the WWTP. This side stream may have a significant effect on other treatment processes.

PROCESS CONTROL. Control of the heat treatment and wet air oxidation processes is discussed below.

Heat Treatment. Heat treatment converts suspended solids to dissolved or dispersed solids. These dissolved solids cause a highly polluted liquid from the dewatering process that is recycled through the WWTP for reprocessing.

Increasing the holding time in the thermal reactor increases the breakdown of the sludge cells and degrades the fibrous material. For example, in low oxidation at 180 to 200 °C (350 to 400 °F), the color units of the recycle liquor increase from 2 150 units with a reaction time of 3 minutes to 3 800 units with 15 minutes, and to 5 500 units with 30 minutes (U.S. EPA, 1978). The recycle liquor can be foul smelling, difficult to treat, and disruptive to WWTP processes. Typical recycle liquor characteristics are presented in Table 32.6.

The high concentrations in Table 32.6 illustrate the potential effect that recycle of the liquor can have on the wastewater treatment processes. Accordingly, designers and operators must recognize the significance of the recycle load in the overall WWTP operation.

If the recycled liquors adversely affect other wastewater treatment processes, two potential solutions can be considered:

- Storing the liquors and recycling them back to the WWTP during low-flow or low-BOD (nighttime) conditions, and
- Installing a separate treatment system for the liquors before they are recycled to the WWTP.

TABLE 32.6 Typical recycle liquor characteristics for heat treatment (U.S. EPA, 1978).

Substances in strong liquor[a]	Concentration range, mg/L (except as shown)
TSS	100–20 000
COD	10 000–30 000
BOD	5 000–15 000
NH_3–N	400–1 700
Phophorus	20–150
Color	1 000–6 000 units

[a]TSS = total suspended solids; COD = chemical oxygen demand; BOD = biochemical oxygen demand; and NH_3–N = ammonia-nitrogen.

An equal degree of filterability and settleability can, within limits, be accomplished by various combinations of time and temperature. For instance, high temperature and short reaction time provide results comparable to lower temperature and longer reaction time. Typically, the most economical is the longer reaction time, low-temperature treatment. Overcooking (various combinations of high temperatures and long reaction times) actually breaks down the fibrous material itself (as compared to simply releasing the cell water) and produces a material that is more difficult to dewater.

Cooling of heat-treated sludges before atmospheric exposure can reduce, but will not eliminate, odor problems. Increasing the solids content of the sludge feed to the heat treatment process decreases operating costs but increases the concentration of dissolved COD, nitrogen, and phosphorus in the recycle liquor and may reduce the dewaterability of the treated material.

Wet Air Oxidation. The wet air oxidation process may be operated intermittently or continuously. Heat for start-up is provided by steam that is injected into the heat exchanger upstream of the reactor.

Operations will vary from one facility to another depending on the degree of oxidation that is selected. Any degree of organic destruction may be accomplished and is dependent on the temperature, pressure, reaction time, and air supply. Increasing the values of these parameters typically results in increased oxidation of organics.

It has also been noted that the percentage of solids in this feed will affect operations and fuel requirements. A given installation may be able to reduce costs and increase the maximum capacity of a wet air oxidation WWTP by increasing the percentage of solids in the feed, provided there is sufficient air capacity.

The four important physical variables that control the performance of wet oxidation units are

- Temperature,
- Air supply,
- Pressure, and
- Feed solids concentration.

Controls typically are provided for regulating reactor temperature, pressure, and the air supply.

The reactor pressure, temperature, and quantity of air used determine the extent and rate of oxidation. Much higher degrees of oxidation are possible at higher pressures and temperatures. The reactor temperature and pressure affect the quality of the recycle water (liquor) and the dewaterability of the oxidized sludge. Reaction temperature is kept as low as possible, consistent with adequate conditioning. Higher temperatures cause more complete breakdown of the sludge particles, releasing more cell water, and releasing more BOD into the solution (U.S. EPA, 1978). Higher temperatures produce a treated sludge that dewaters readily but has a poorer-quality recycle liquor. This recycle reduces the capacity of the wet end process.

As with conventional incinerators, discussed later in this chapter, an external supply of oxygen (air) is required to attain nearly complete oxidation. The air requirement for the wet oxidation process is determined by the heat value of the sludge being oxidized and by the degree of oxidation desired. Thermal efficiency and fuel requirements are functions of air input; therefore, it is important that the air flow not be higher than needed. Because the input air becomes saturated with steam from contact with the liquid in the reactor, it is also important to control the air flow to prevent excessive loss of water from the reactor.

ADDITIONAL TECHNOLOGY. An additional proprietary technology uses an aerated thermophilic pretreatment phase in conjunction with conventional mesophilic anaerobic digestion to produce a Class "A" biosolid. This system is suited particularly to upgrading the solids handling capability of WWTPs with existing anaerobic digesters. This system uses the biogas production from the digesters to heat the sludge. The net fuel energy requirement for the combined system typically is no greater than the digester system without this type of process added. This process may enhance the settlability and dewaterability of the biosolids, allowing a greater solids concentration to be maintained in the digestors, and an increase in the solids concentration of cake from the dewatering equipment, thus reducing hauling costs and possibly enhancing beneficial use prospects.

SAFETY AND HEALTH PROTECTION. Typically, these types of processes are contained in enclosed vessels with minimal exposure potential for employees. However, the high temperatures at which these facilities operate could be hazardous, and basic precautions should be taken by employees working in or around the equipment, valves, boilers, reactors and heat exchanger units.

TROUBLESHOOTING. Table 32.7 presents a troubleshooting guide for thermal treatment systems that will help the operator to identify problems and develop solutions.

HEAT DRYING

DESCRIPTION OF PROCESSES. The process of heat drying sludge removes moisture from the sludge to practical limits and thus reduces the total volume, retains the fertilizing properties of wet sludge, destroys pathogenic organisms, and produces a nonodorous product.

Heat drying raises the temperature of the incoming sludge to remove moisture and reduce total volume. The temperature remains low enough to retain the nutrient properties of the sludge. The end product contains soil nutrients but no pathogenic organisms. Auxiliary fuel or waste heat is required for heat drying.

The three principal processes of the heat drying method of stabilization are low-temperature heat drying, flash drying, and rotary kiln drying.

Low-Temperature Heat Drying. Low-temperature heat drying involves raising the temperature of the incoming sludge to 100 °C (212 °F) to evaporate moisture. Either a cylindrical drum or a multiple hearth is used for this process.

Flash Drying. Flash drying produces an instantaneous removal of moisture by introducing the wet sludge into a hot gas stream. The process has the flexibility to operate as a heat dryer for the production of fertilizer or as an incinerator by returning the dry solids to the furnace as a fuel. Figure 32.9 represents a typical flash dryer system.

Before introduction to the flash dryer, the sludge undergoes thickening and dewatering. The product from the flash dryer may be sold as fertilizer; the incinerator ash is amenable to landfilling.

The incoming dewatered sludge is blended with a portion of the previously heat-treated sludge in a mixer that provides the consistency necessary for pneumatic conveying. Then, hot gases from the furnace (650 to 700 °C [1 200 to 1 300 °F]) are mixed with the blended sludge in a drying tower before introduction to the cage mill. Agitation in the cage mill dries the sludge to approximately 2 to 10% moisture and reduces the temperature to approximately 150 °C (300 °F) before conveyance to cyclone separa-

TABLE 32.7 Troubleshooting guide for thermal treatment (U.S. EPA, 1978).

Problem	Probable cause	Solution
Odors	Odors being released in decant tanks, thickeners, vacuum pump exhaust, or in dewatering	Cover units, collect air, and deodorize it before release by use of incineration, adsorption, or scrubbing
		Cover open tank surface with small floating plastic balls to reduce evaporation and odor loss
	Odors being released when recycle liquors enter treatment wastewater tanks	Preaerate liquors in covered tank and deodorize offgases
Scaling of heat exchangers	Calcium sulfate deposits	Provide acid wash in accordance with manufacturer's instructions
	Operating temperatures too high—causing baking of solids, if there is insufficient air	Operate reactor at temperatures below 199 °C (390 °F) for heat conditioning of sludge and increase air
		Use hydraulically driven cleaning bullet to clean inner tubes
Steam use is high	Sludge concentration to heat treatment unit is low	Operate thickener to maintain 6% solids if possible; 3% minimum
Solids dewater poorly	Anaerobic digestion before heat treatment	Discontinue anaerobic digestion of sludge to be heat treated
	Temperatures not maintained high enough	Temperature should be at least 177 °C (350 °F)
High system pressure	Blockage in reactor	Remove blockage
		Check pressures and temperatures to note any discrepancies from normal
	Pressure controller set too high	Reduce set point on pressure controller
	Block valve closed	Check system for proper valving
	Improper temperature control setting	Adjust setting
	Heat exchanger scaling	Acid wash heat exchangers
Feed pumps not pumping adequate flow	Improper control setting	Adjust control setting
	Leakage or plugging in product check valves	Repair or replace check valves
	Air trapped in pump cylinders	Bleed off air
System pressure is dropping	Pressure controller set too low	Set pressure controller at proper level
	Pressure control valve trim is eroded	Replace valve

TABLE 32.7 Troubleshooting guide for thermal treatment (U.S. EPA, 1978) (*continued*).

Problem	Probable cause	Solution
Oxidation temperature is rising	Inlet temperature too high	Reduce temperature by diluting incoming sludge with water
	Sludge feed rate is too slow	Increase sludge feed rate
	Improper control setting	Appropriately adjust control setting
	Pump stopped or slowed	Start pump or increase rate
	Volatile matter such as gas or oil being pumped through the system	Switch from sludge to water and stop the process air compressor
	Pneumatic steam valve not functioning properly	Repair malfunctioning valve
Oxidation temperature is falling	Heat exchanger fouled	
	Reactor inlet temperature is too low because of low-density sludge	Reduce dilution of incoming sludge
	High flow rate being pumped through system	Reduce flow rate at high-pressure pump
	Pneumatic steam valve not functioning properly	Repair malfunctioning valve
	No signal air to the temperature control valve	Check instrument air supply
	Boiler not functioning properly	Consult boiler manufacturer's instruction manual for corrective action
Filter cake difficult to feed into incinerator	Filter cake too dry for pumping	Reduce temperature (and pressure) of the treatment system or adjust dewatering process
Low system pressure	High-pressure pump, process air compressor, or boiler stopped	Restart pump or air compressor
	Intake filter clogged	Clean or replace filter
	Pressure controller set too low	Increase set point on pressure controller
	Any of the blowdown valves may be partially opened	Check compressor valving
	Leaking interstage trap	Check trap for proper operation
	Slipping drive belts	Adjust belt tension
High air temperature	Inadequate water flow	Adjust water flow
	Cake too dry	Adjust dewatering
	Leaking cylinder valves	Repair, clean, or replace
	Intercooler or jackets plugged	Clean intercooler or replace

TABLE 32.7 Troubleshooting guide for thermal treatment (U.S. EPA, 1978) (*continued*).

Problem	Probable cause	Solution
	No flow from the force-feed lubricators	Add oil
		Repair lubricator
		Tighten loose belt, or replace if worn
Air compressor safety valve relieving	Pressure controller set too high	Reduce set point on controller
	No signal air pressure to pressure control valves	Check instrument air supply
	One or more block valves in the system are closed	Check system for proper valving
	Plugged pressure control valve	Switch to standby pressure control valve and clean plugged valve

tion of the solids from the gases. At this point the solids may be sent either to storage or to a furnace for incineration.

The gases from the cyclone separators are conveyed by the vapor fan to the deodorization preheater in the furnace where the temperature is raised to approximately 650 to 760 °C (1 200 to 1 400 °F). The deodorized gases release a portion of the heat to the incoming gases and release more heat in the combustion air preheater. The temperature is reduced to approximately 260 °C (500 °F) before the gas is scrubbed for particulate removal and discharged.

If the dried solids are not used in the furnace as a fuel, auxiliary fuel such as gas, oil, or coal is then necessary. The combustion air fan introduces preheated air into the furnace. If sludge incineration is practiced, ash may be sluiced from the bottom of the furnace.

Rotary Kiln Dryers. The kiln is a cylindrical steel shell mounted with its axis at a slight slope from the horizontal (see Figure 32.10). When used for sludge drying, refractory lining typically is unnecessary.

The feed to the unit requires previous dewatering and is introduced into the breech or upper end. A portion of the dried sludge is mixed with the feed cake, thereby reducing its moisture and dispersing the cake. The unit is directly fired at the upper end by a long-flame burner mounted in the hood. Gases are removed at the lower end, providing countercurrent movement of the sludge and the gases. Axial ledges that are provided along the interior wall of the dryer pick up the material, then spill it off in the form of a thin sheet of falling particles as the dryer rotates. This motion is intended to provide contact between the sludge and gases to promote rapid drying.

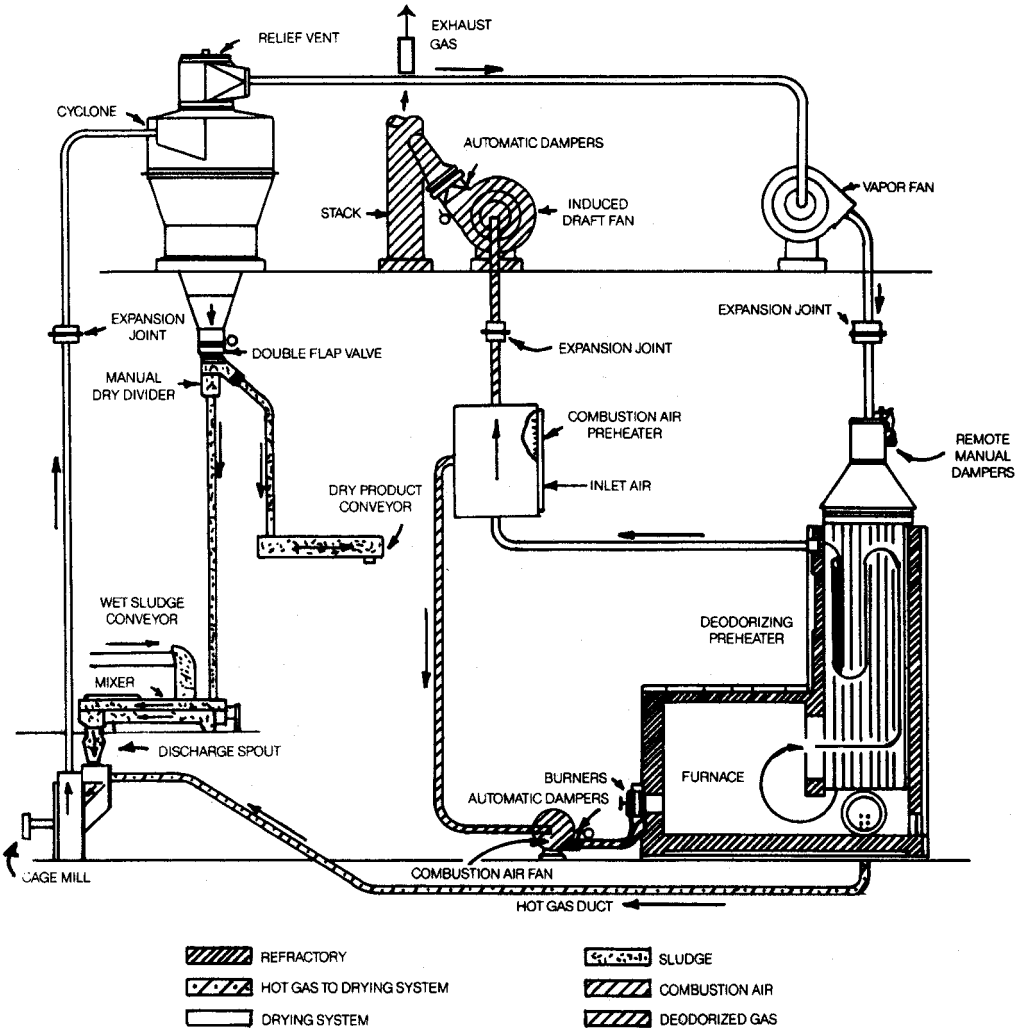


FIGURE 32.9 Flash dryer process schematic.

The dried material may consist of varied particle sizes that require grinding before use as a fertilizer. The internal temperature of a rotary kiln dryer typically is maintained at approximately 370 °C (700 °F). Deodorization of the exhaust gases by after burning at approximately 650 to 760 °C (1 200 to 1 400 °F) is necessary if odors are to be avoided. Also, scrubbers must be used to remove particulates from the exhaust gases.

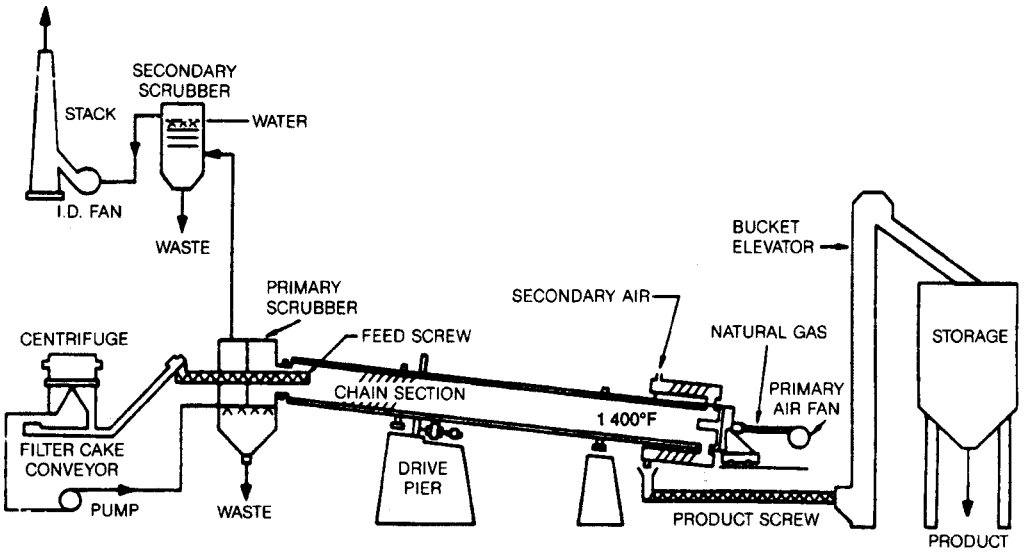


FIGURE 32.10 Rotary kiln dryer schematic.

PROCESS CONTROL. Efficient and consistent operation of heat drying equipment depends on frequent monitoring, both sensory and analytical. By periodically inspecting the drying equipment during the shift, any irregularities in the operating temperatures can be detected, such as pressures and flow rates. After gaining some operating experience, it is possible to recognize any strange sounds or changes in pitch that may indicate a problem.

The four major variables that affect the operation of the heat drying equipment are

- Percent solids in the wet sludge feed,
- Ratio of dried sludge:wet sludge,
- Quantity of hot combustion gases used for drying, and
- System temperatures.

Controlling the dewatering process that precedes the heat drying equipment results in a product of the desired moisture content range of between 2 and 10%. Efficient operation depends on a consistent solids concentration in the sludge feed. The percent solids in the feed is also critical to the economy of operation of heat dryers. The higher the moisture content of the incoming sludge, the more fuel is burned to evaporate the added moisture.

As presented in Figures 32.9 and 32.10, the incoming sludge is mixed with previously dried sludge to create the proper consistency for pneumatic conveying equipment.

A significant change in the incoming percent solids concentration changes the ratio required for proper operation. This ratio varies depending on the sludge used and the incoming percent solids and is determined through trial and error.

For efficient operation, the quantity of hot combustion gases used for drying is just enough to dry the cake to the desired percent solids. This depends on the ratio of the dried to wet sludge and the sludge flow rate, and is determined through operational experience.

Refer to the manufacturer's manuals for their suggestions on system operating temperature maintenance. Operating temperatures that are too low will not properly dry the sludge mixture, while high operating temperatures are inefficient and costly.

Flash Dryers. Smaller facilities may operate on an intermittent basis, typically 8 hours per day for 5 or fewer days per week. Intermittent operation typically requires a warmup period of one hour before drying. Extra fuel is consumed during this period as compared with continuous operation.

Controlling the dewatering process can result in a product at the desired moisture content of approximately 2 to 10%. Control consists of varying the amount of dried sludge mixed with the wet cake and varying the quantity of hot combustion gases for drying. To ensure optimum operation, closely monitor and control the temperature conditions throughout the system.

The exhaust gases are afterburned to eliminate odorous materials and scrubbed to remove particulates. Temperature controls on the afterburner indicate typical operation at approximately 650 to 760 °C (1 200 to 1 400 °F). Analysis of particulates both before and after the scrubber or monitoring of the pressure differential across the scrubber will indicate deviations in scrubber operations.

Rotary Kiln Dryers. The following typical operating conditions of the flash dryer also apply to the rotary dryer.

- The facility may operate continuously or intermittently.
- The product typically compares with that from flash drying except that grinding is necessary.
- A portion of the dried product is mixed with the dewatered cake before it enters the dryer.
- The stack gases are controlled. In contrast to the flash dryer, the rotary kiln dryer is direct fired; the temperature around the cake is controlled at approximately 370 °C (700 °F); and the dryer rotates at approximately 4 to 8 rpm to ensure mixing as opposed to the rapid mixing provided in the cage mill of a flash dryer.

ADDITIONAL TECHNOLOGY. Additional technologies being used for drying sludge are a multipass sludge dryer and a paddle dryer/processor. The multipass dryer uses a combination of both direct and indirect heat transfer to continuously process and thermally dewater sludge cake. The resulting weight and volume reduction significantly reduces hauling and disposal costs. As the sludge is conveyed through the dryer on stainless steel belts, it is not tumbled or suspended, thereby holding particulate emissions to a minimum. Recirculation of the hot exhaust air and water vapor within the dryer before discharge also reduces odors.

The paddle dryer/processor uses hollow wedge-shaped blades mounted on a hollow shaft with the heat transfer medium flowing through them. This method provides a high ratio of heat transfer surface area to process volume, using heat transfer media ranging in temperature from −40 ° to 650 °F.

SAFETY AND HEALTH PROTECTION. The equipment used for these processes is similar to other equipment in the solids-handling area, including pumps, valves, centrifuges, conveyors, fans, and exhaust systems. Use of personal protective equipment, good housekeeping and storage procedures, proper labeling of containers to include detailed information on handling and first aid, posting of warning signs to alert employees to hazardous conditions and special precautions, posting of emergency procedures and instructions at critical operations, and training should all be a part of the employee's operating procedures for these facilities.

These processes use high temperatures. The equipment, valves, and fans should be protected from casual contact by the use of guardrails, covers, and signs to prevent possible burn injuries.

INCINERATION

DESCRIPTION OF PROCESSES. Incineration involves heat from combustibles in the sludge and from auxiliary fuel. Incineration removes all moisture from the sludge, thereby reducing the total volume. It destroys all organic matter by complete combustion; destroys pathogenic organisms; and produces a nonodorous product (WPCF, 1988).

Air emissions from incinerators should be monitored on a specific frequency to determine that no toxic or objectionable substances escape destruction. The U.S. EPA regulations for sludge disposal (40 *CFR* Part 503) limit the pollutant limits in the feed sludge, as well as in any air emissions from burning sludge for disposal. Specific pollutants limited by the 40 *CFR* Part 503 regulations include lead, cadmium, chromium, and nickel in the feed sludge, and beryllium, mercury, and hydrocarbons in the air emissions from burned sludge. The firing of sludge in an incinerator cannot violate the

requirements of the National Emissions Standards for these pollutants, outlined in 40 *CFR* Part 61, Subparts C and E.

Multiple-hearth furnaces and fluidized bed incinerators are the most typical types used for sludge combustion in the U.S.

Multiple-Hearth Incinerators. As in the case of rotary kiln and flash dryers, the sludge feed to the multiple-hearth incinerator unit is dewatered and fed in as a cake. The furnace consists of a cylindrical steel shell surrounding a number of solid refractory hearths, and a central rotation shaft to which rabble arms are attached. Upper hearths typically have four rabble arms and more teeth than lower hearths (U.S. EPA, 1986).

Because the operating temperature in the fuel-burning hearths may reach 1 100 °C (2 000 °F), the central shaft and rabble arms are cooled with compressed air fed from the bottom (see Figure 32.11). A portion of the cooling air is drawn from the top of the furnace and returned to the bottom of the furnace to act as hot combustion air.

The multiple-hearth incinerator basically consists of three zones—the top hearths that comprise the drying zone; the middle hearths that comprise the combustion zone; and the bottom hearths that comprise the cooling zone. If auxiliary fuel is required, gas or oil burners are provided in the middle or combustion hearths. The countercurrent flow of combustion air to the sludge and the constant mixing of the sludge by the rabble arms provide maximum contact between the sludge particles and the hot gases.

Scrubbing the exhaust gases from the top hearth removes particulates. Deodorization may or may not be required, depending on the governing codes and standards and the operation of the incinerator. Deodorization may be accomplished in the incinerator itself, provided the cake does not dry too quickly on the lower-temperature hearths near the top of the incinerator.

Fluidized-Bed Incinerators. Fluid bed incineration sets graded silica sand particles in fluid motion in an enclosed space by passing combustion air through the bed zone so that all particles are in homogeneous boiling motion (U.S. EPA, 1986) (see Figure 32.12).

The reactor is a closed cylindrical vessel with refractory walls. Fluidizing and combustion air enters the unit and is dispersed upward through the orifice plate and grid that support the sand. Sufficient air is used to keep the sand in suspension but not enough to carry it out of the reactor.

The dewatered sludge cake is injected into the fluidized sand bed. The boiling action of the bed results in a rapid dispersion of the sludge solids and optimum contact with the combustion air. The sand bed retains the organic particles until they are reduced to ash. The rapid boiling action comminutes the ash to prevent clinker buildup.

Auxiliary fuel is injected into the bed as required to maintain the combustion temperature. Gas, fuel oil, or other fuel sources are used as auxiliary fuels.

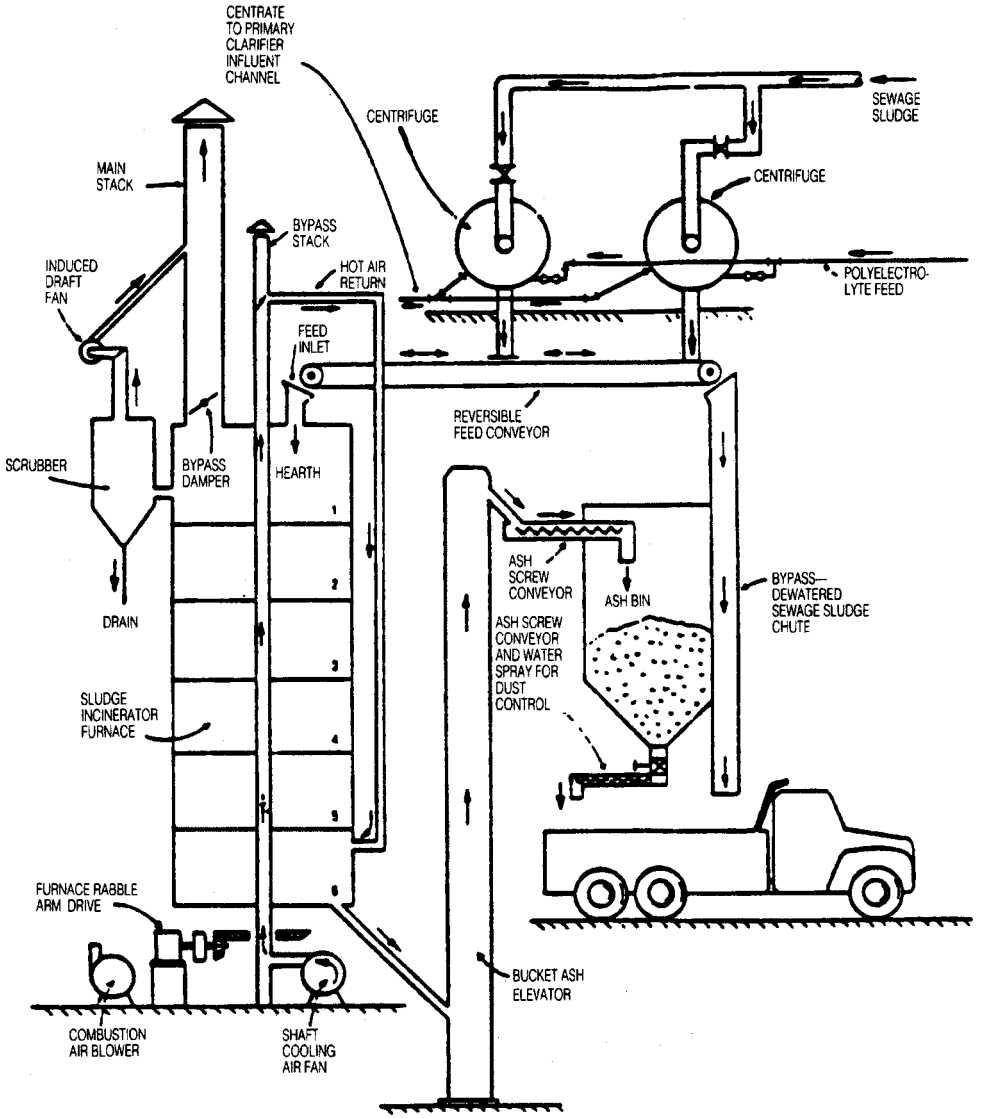


FIGURE 32.11 Multiple-hearth incinerator schematic.

The combustion and fluidizing air quantities supplied are determined by the requirements to

- Fluidize the bed to the proper density without blowing sand and incomplete combustion products out of the bed;

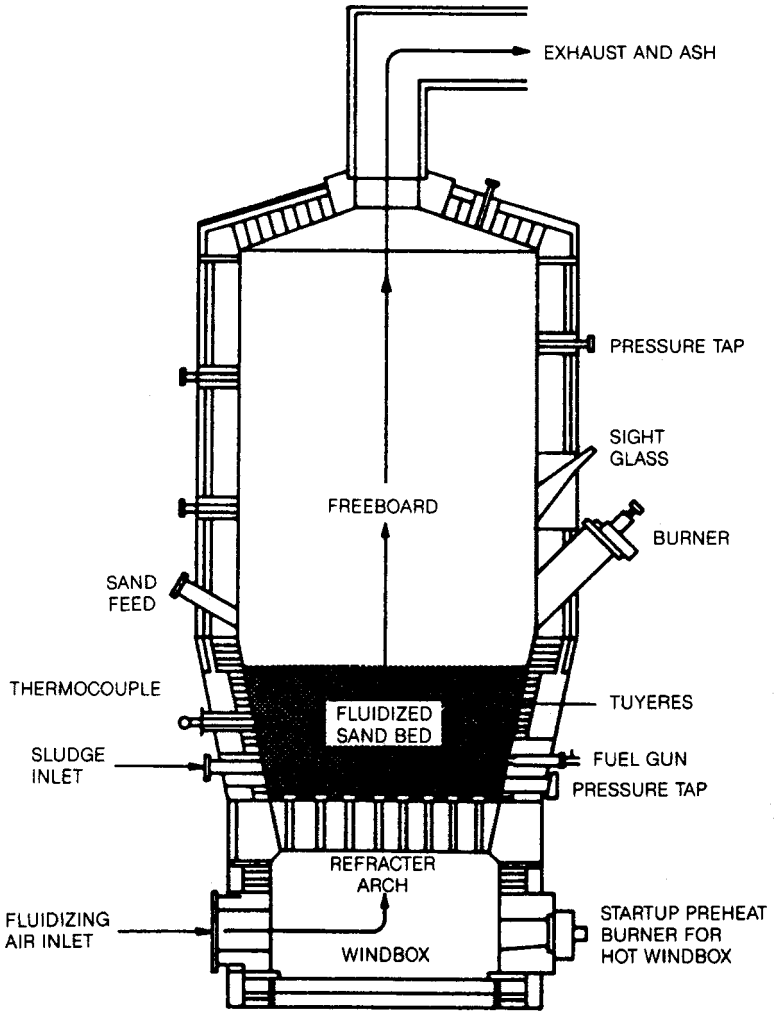


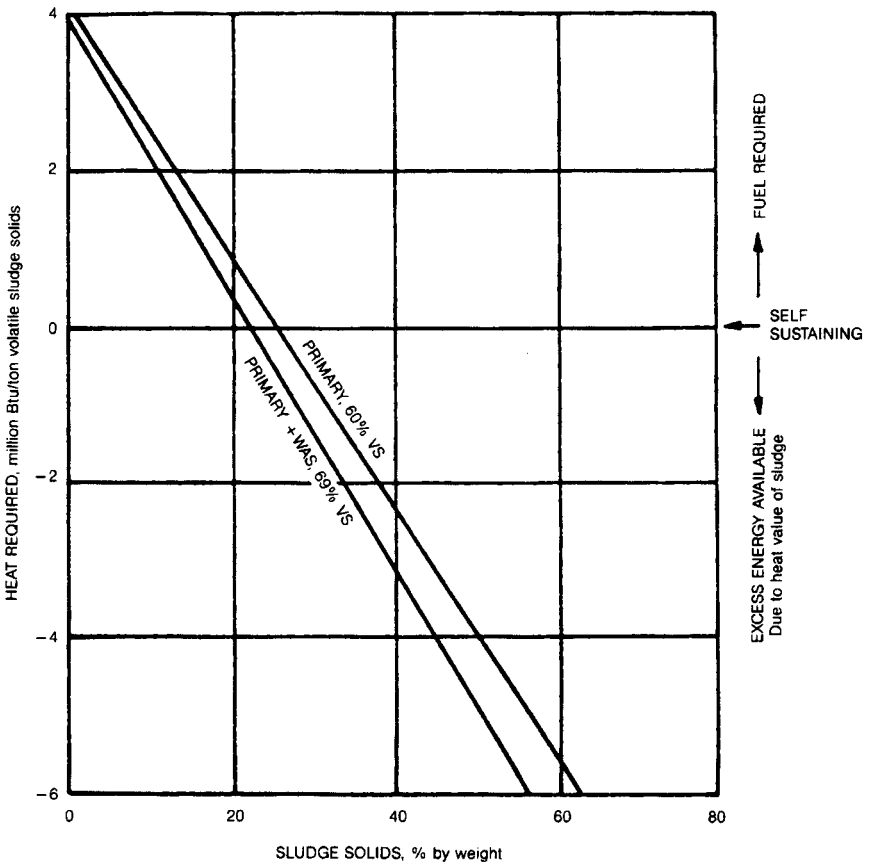
FIGURE 32.12 Fluidized-bed incinerator schematic.

- Provide minimum oxygen requirements for complete combustion of all volatiles in the sludge; and
- Provide temperature control to ensure complete deodorization and protection of the refractory, heat exchanger, and flue piping.

Because of scouring in the bed, periodic replenishment of the sand is necessary. A port is provided on the side of the reactor into which sand is added as needed.

PROCESS CONTROL. For effective and efficient process control, the following components of the incineration process need to be considered.

Dewatering. Optimization of the dewatering process before drying or incineration to conserve fuel is an important consideration. As the percentage of the volatile solids (VS) in the cake increases for a given sludge, the cost of auxiliary fuel per ton of solids decreases (U.S. EPA, 1986). If the cake VS are high enough, autogenous combustion will result and no additional fuel is necessary. Figure 32.13 presents the relationship between auxiliary fuel required and feed sludge solids concentration.



—Assumed heat value of sludge: 10 000 Btu/lb of volatile solids
—Curve assumes that afterburner is not used.

FIGURE 32.13 Auxiliary heat required for incineration.

Heat Recovery. Heat may be recovered by recycling process gases to preheat combustion air. For a given percentage of cake solids, only enough heat is available in the sludge to raise the temperature of the moisture and combustion products to some maximum temperature. With heat recovery, however, the temperature may be raised to a higher temperature, which may provide deodorization.

Air Requirements. The air requirements for combustion include the stoichiometric amount of excess air that is necessary to ensure complete combustion. The amount of excess air will vary with the type of incineration, the type of sludge, and the disposition of stack gases. Because excess air requires fuel to heat it, excess air is provided in the minimum amount that will ensure complete combustion and deodorization. Too little air will result in incomplete combustion and deodorization.

Sludge Fuel Value. The fuel value in the sludge is important in reducing auxiliary fuel consumption. The combustible elements in sludge are carbon, sulfur, and hydrogen. They primarily exist in organic sludges as grease, carbohydrates, and protein. These materials combine with oxygen to release heat and form carbon dioxide, sulfur dioxide, and water. Typical heat values for various sludges and their constituents are presented in Tables 32.8 and 32.9. The percentage of volatiles in the sludge is reduced by previous digestion, which can greatly reduce the heat value of the sludge. As the percentage of volatiles increases, the auxiliary fuel consumption decreases. The volatile content of a sludge is maximized by removing inorganics such as grit; by avoiding the use of inorganic chemicals such as ferric chloride and lime in dewatering processes; and by avoiding biological processes such as digestion before incineration.

Multiple-Hearth Incinerators. As in the drying processes, multiple hearths may be operated continuously or intermittently. When not in operation, however, auxiliary fuel is fed to the multiple hearth to maintain temperatures to protect refractory materials (U.S. EPA, 1986).

TABLE 32.8 Effects of prior processes on fuel value (U.S. EPA, 1986).

Type of sludge	Heating value, Btu/lb (dry solids)[a]
Raw primary	10 000–12 500
Activated	8 500–10 000
Anaerobically digested primary	5 500
Raw (chemically precipitated) primary	7 000
Biological filter	8 500–10 000

[a]Btu/lb × 2.326 = kJ/kg.

TABLE 32.9 Representative heating values of some solids (U.S. EPA, 1986).

Material (dry solids)	Combustibles, %	Heating value, Btu/lb[a]
Grease and scum	88	16 700
Raw wastewater solids	74	10 300
Fine screenings	86	9 000
Ground garbage	85	8 200
Digested sludge	60	5 300
Chemically precipitated solids	57	7 500
High organic grit	30	4 000

[a]Btu/lb × 2.326 = kJ/kg.

While the temperatures vary in different facilities, the temperature on any given hearth is kept constant to ensure uniform operations. Temperatures typically are interlocked either with the sludge feed and air feed or the auxiliary fuel feed and air feed systems. If the temperature drops, more sludge or fuel and air are added, and vice versa.

In typical operation, a multiple-hearth furnace provides three distinct combustion zones:

- Two or more upper hearths on which most of the free moisture is evaporated,
- Two or more intermediate hearths on which sludge volatiles burn at temperatures exceeding 820 °C (1 500 °F), and
- A bottom hearth that serves as an ash cooling zone by giving up heat to the cooler incoming air.

During evaporation of moisture in the first zone, the sludge temperature is not raised to more than approximately 60 °C (140 °F). At this temperature no significant quantity of volatile matter is driven off and no obnoxious odors are produced. Distillation of volatiles from sludge containing 75% moisture does not occur until 80 to 90% of the water has been driven off. By this time, the sludge has traveled far enough into the incinerator to encounter gases hot enough to burn the volatiles that cause odors. Typically, when fuel is required to maintain combustion in a multiple-hearth furnace, a gas outlet temperature of more than 480 °C (900 °F) indicates that too much fuel is being burned.

An analysis of stack conditions is used to determine typical operations. Oxygen, carbon dioxide, and carbon monoxide are monitored automatically in the stack and compared with preset values. An increase of the carbon monoxide level indicates that incomplete combustion is occurring. If, during the same period, the oxygen level compares well with the preset value, then either the mixing of sludge and air combus-

tion is inefficient or the temperature has been reduced by the addition of cake that is wetter than normal. When introducing air above the hot (combustion) zone, false high readings can occur. In any event, an analysis of stack gases may be used to determine normal operation and indicate problems. Appropriate steps can then be taken to correct the problem and return to normal operation (see Table 32.10).

Fluidized-Bed Incinerators. The basic principles that apply to the operation of multiple-hearth incinerators also apply to the operation of the fluidized bed incinerators (U.S. EPA, 1986). The fluidized bed does have the advantage of operating intermittently without auxiliary fuel wastage because the sand bed acts as an enormous heat reservoir that holds the heat in the furnace longer. Also, temperature control is simpler in the fluidized bed.

The quantity of fluidizing air injected into the reactor is an important variable. An excessive quantity of air would blow sand and incomplete products of combustion into the flue gases, and would then result in needless fuel consumption. Insufficient air results in unburned combustibles in the exhaust gases. Fluidized-bed systems typically are operated with 20 to 40% excess air. In practice, this rate is controlled by measuring the oxygen in the reactor exhaust gases and adjusting the air rate to maintain 4 to 6% oxygen.

Because the theoretical amount of air is never enough for complete fuel combustion, excess air is added. The extra air is expressed as a percentage of the theoretical air requirement. For example, if a fuel requires 1 000 standard cubic feet of air per minute (SCFM) based on theoretical air requirements, and the actual air rate is 1 200 SCFM, the percent excess air is

$$\frac{(\text{Actual air rate} - \text{Theoretical}) \times 100}{\text{Theoretical air rate}} = \frac{(1\,200 - 1\,000) \times 100}{1\,000} = 20\%\ \text{Excess air} \qquad (32.1)$$

During start-up, auxiliary fuel is used to raise the temperature of the sand bed to approximately 650 °C (1 200 °F). As soon as sludge feed to the furnace begins, the auxiliary fuel rate is adjusted downward to achieve the maximum heat release from the sludge to avoid wasting fuel. This is done by gradually reducing the fuel feed rate to the minimum needed to maintain bed temperatures in the range of 680 to 700 °C (1 250 to 1 300 °F).

During typical operations, the fluidized bed without an air preheater requires more fuel than a multiple-hearth unit; however, if deodorization is required on the multiple-hearth unit, both will use approximately the same amount of fuel.

SAFETY AND HEALTH PROTECTION. Typically, these types of processes are contained in enclosed vessels with minimal exposure potential for employees. How-

TABLE 32.10 Troubleshooting guide for incineration (U.S. EPA, 1978).

Problem	Probable cause	Solution
Multiple-hearth incineration		
Furnace temperature too high	Excessive fuel feed rate	Decrease fuel feed rate
	Greasy solids	If fuel is off and temperature is rising, this may be the cause; raise air feed rate or reduce sludge feed rate
	Thermocouple burned out	If temperature indicator is off scale, this is the likely cause; replace thermocouple
Furnace temperature too low	Moisture content of sludge has increased	Increase fuel feed rate until dewatering system operation is improved
	Fuel system malfunction	Check fuel system; establish proper fuel feed rate
	Excessive air feed rate	If oxygen content of stack gas is high, this is likely the cause; reduce air feed rate or increase feed rate
Oxygen content of stack gas is too high	Sludge feed rate too low	Remove any blockages and establish proper feed rate
	Air feed rate too high	Decrease air feed rate
	Air feed excessive above burn zone	Check doors and peepholes above burn zone; close as necessary
Oxygen content of stack gas is too low	Volatile or grease content of sludge has increased	Increase air feed rate or decrease sludge feed rate
	Air feed rate too low	Check for malfunction of air supply and increase air feed rate, if necessary
Furnace refractories have deteriorated	Furnace has been started up and shut down too quickly	Replace refractories and observe proper heating and cooling procedures in the future
Unusually high cooling effect from one hearth to another	Air leak	Check hearth doors, discharge pipe, center shaft seal, air butterfly valves in inactive burners, and stop leak
Short hearth life	Uneven firing	Check all burners in hearth; fire hearths equally on both sides
Center shaft drive shear pin fails	Rabble arm is dragging on hearth or foreign object is caught beneath arm	Correct cause of problem and replace shear pin
Furnace scrubber temperature too high	Low water flow to scrubber	Establish adequate scrubber water flow
Stack gas temperatures too low (260 to 320 °C [500 to 600 °F]); odors noted	Inadequate fuel feed rate or excessive sludge feed rate	Increase fuel or decrease sludge feed rates

TABLE 32.10 Troubleshooting guide for incineration (U.S. EPA, 1978) (*continued*).

Problem	Probable cause	Solution
Stack gas temperatures too high (650 to 870 °C [1 200 to 1 600 °F])	Excess heat value in sludge or excessive sludge feed rate	Add more excess air or decrease fuel rate
Furnace burners slagging up	Burner design	Consult manufacturer and replace burners with newer designs that minimize slagging
	Air-fuel mixture is off	Consult manufacturer
Rabble arms are drooping	Excessive hearth temperatures or loss of cooling air	Maintain temperatures in proper range and maintain backup systems for cooling air in working condition; discontinue scum injection into hearth
Fluidized bed incineration		
Bed temperature is falling	Inadequate fuel supply	Increase fuel feed rate or repair any fuel system malfunctions
	Excessive rate of sludge feed	Decrease sludge feed rate
	Excessive sludge moisture	Improve dewatering system operation
	Excessive air flow	Reduce air rate if oxygen content of exhaust gas exceeds 6%
Low (<4%) oxygen in exhaust gas	Low air flow	Increase air blower rate
Excessive (>6%) oxygen in exhaust gas	Fuel rate too high	Decrease fuel rate
	Sludge feed rate too low	Increase sludge feed rate and adjust fuel rate to maintain steady bed temperature
Erratic bed depth readings on control panel	Bed pressure taps plugged with solids	Tap a metal rod into the pressure tap pipe when reactor is not in operation
		Apply compressed air to pressure tap while the reactor is in operation after reviewing manufacturer's safety instructions
Preheat burner fails and alarm sounds	Pilot flame not receiving fuel	Open appropriate valves and establish fuel supply
	Pilot flame not receiving spark	Remove spark plug and check for spark; check transformer, replace defective part
	Pressure regulators defective	Disassemble and thoroughly clean regulators
	Pilot flame ignites but flame scanner malfunctions	Clean sight glass on scanner, replace defective scanner
Bed temperatures too high	Fuel feed rate too high through bed guns	Decrease fuel flow rate through bed guns

TABLE 32.10 Troubleshooting guide for incineration (U.S. EPA, 1978) (*continued*).

Problem	Probable cause	Solution
	Bed guns have been turned off but temperature still too high because of greasy solids or increased heat value of sludge	Raise air flow rate or decrease sludge feed rate
Bed temperature reads off scale	Thermocouple burned out or controller malfunction	Check the entire control system; repair as necessary
High scrubber temperature	No water flowing in scrubber	Open valves
	Spray nozzles plugged	Clean nozzles and strainers
	Water not recirculating	Return pump to service or remove scrubber blockage
Reactor sludge feed pump fails	Bed temperature interlocks may have shut down the pump	Check bed temperature
	Pump is blocked	Dilute feed sludge with water if sludge is too concentrated
Poor bed fluidization	During shutdowns, sand has leaked through support plate	Once per month, clean windbox

ever, the high temperatures at which these facilities operate could be hazardous, and basic precautions should be taken by employees working in or around the equipment, valves, fans, blowers, reactors, and heat exchanger units. The equipment, valves, fans, and blowers should be protected from casual contact by the use of guardrails, covers, and signs to prevent possible burn injuries.

TROUBLESHOOTING. Table 32.10 presents a troubleshooting guide for incineration that will help the operator identify problems and develop solutions.

COMPARISON OF SLUDGE STABILIZATION PROCESSES

Table 32.11 lists the advantages and disadvantages of the five sludge stabilization methods discussed in this chapter.

TABLE 32.11 Comparison of sludge stabilization processes (WEF, 1995).

Process	Advantages	Disadvantages
Composting	High-quality, potentially saleable product suitable for agricultural use	Requires 40 to 60% solids
		Requires bulking agent or carbon source
	Can be combined with other processes	Requires either forced air or turning (labor)
		Potential for pathogen spread through dust
	Low initial cost (static pile and windrow)	High operational cost; can be power and labor intensive
		May require significant land area
		Potential for odors
Lime stabilization	Low capital cost	Increases volume of sludge for disposal
	Easy operation	Land application may not be appropriate where soils are alkaline
	Good as interim or emergency stabilization method	Chemical intensive
		Overall cost site specific
		pH drop after treatment can lead to odors and biological regrowth
Thermal treatment	More readily dewaterable sludge	Ruptures cell walls of biological organisms releasing water and bound organic material
	Effective disinfection of the sludge	Treatment of this high-strength organic waste may require special consideration
Heat drying or incineration	Major reduction in sludge volume for disposal	Complex mechanical and control equipment
		Requires auxiliary fuel source
	Total destruction of pathogens	Requires time to raise the operating temperature
		Requires relatively uniform dewatered sludge feed
		May generate odors

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Dewatering

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INTRODUCTION

Each of the dewatering methods described in this chapter has advantages and disadvantages. Economics should drive the selection process. It is often helpful to list the specifics of the situation in terms of needs and wants. Needs are things that must be the design. Wants are things that would be good to have, but are negotiable. For example, if space is a severe limitation, then a disposal method is needed that does not require much space; a dewatering method that requires very little operator attention might be a good choice. The rational buyer should speculate on what changes might be made in the ultimate disposal method in the next 5 to 10 years. If, for example, development is rapidly heading for the plant, dewatering methods that require a lot of land and might

cause odor are not a long-term solution. Likewise, for a small plant that will dewater 1 or 2 days a week and haul the biosolids to a nearby land application, high-performance dewatering equipment is probably not cost-effective. Ideally, the selection of major equipment is a cost-effective life-cycle evaluation—the present worth sum of the cost of equipment, maintenance, operation, and disposal. It is tempting to make an exhaustive list of costs, but, typically, the top three (capital, operating, and disposal costs) drive the decision. The Water Environment Federation® (WEF) (Alexandria, Virginia) publication *Engineered Equipment Procurement Options to Ensure Project Quality* (WEF, 1995) can help guide equipment selection.

The process and equipment descriptions given here are necessarily general and are not intended to describe any particular design or manufacturer. Changes to the recommended maintenance procedures and operation of equipment should be made with the advice of the manufacturer. It is important to read the manuals that came with the equipment. If the manuals are missing or incomplete, replacements are available from the manufacturer.

WHAT MAKES BIOSOLIDS DIFFICULT TO DEWATER?

Unfortunately, management's eye is generally on the wet end of the plant because the purpose of the plant is to receive wastewater and produce clean water. The dewatering operations are often treated as an unfortunate consequence of producing a satisfactory plant effluent. There is a tendency to feel that, if only the people in the dry end would do their job, there would not be any problem. Unfortunately, for this point-of-view, the quality of the biosolids sent to dewatering and the equipment available largely determine the cost to dewater. To minimize the overall cost of treatment, the wet end needs to be operated with an eye toward the consequences in the dry end.

DIFFICULTY IN DEWATERING BIOSOLIDS. Biosolids vary greatly regarding the ease with which they can be dewatered. In a paper that speculated about how the various ways that water could be held in the biosolids could affect its dewaterability, Vesilind (1994) realized that sludge is very complex, but sought an analogy or model that would provide insight to cause and effect. Vesilind pointed out that there are several ways that water could be held by biosolids, and this logic can be used to understand the way biosolids are generated and show which treatment alternatives result in more difficult-to-dewater biosolids. It should be noted that more recent research suggests that sludge is much more complicated than Vesilind's model; however, for the purposes of understanding why some sludges are more difficult to dewater than others, Vesilind's model is convenient to use.

Free Water. Free water is not connected in any way with biosolids. This water is the easiest of all to remove. Typically, the free water is removed in clarifiers and therefore does not reach dewatering. The exception is a plant where no attention is paid to a process, such as a clarifier skimmer pumping clear water to dewatering.

Bound Water. Bound water is water held in the particle either by chemical bonds or within a membrane. An example of this might be aluminum hydroxide, which precipitates as a hexihydrate. Each molecule of aluminum has 6 molecules of water attached to it. The City of Windsor (Ontario, Canada) uses ferric and/or aluminum hydroxide to remove phosphorus from wastewater. When the plant switched from ferric hydroxide to alum, the dewatered cake solids dropped 3 percentage points. Some time later, when the plant switched back from alum to ferric hydroxide, the cake dryness increased 3 percentage points (Macray, 2000).

Likewise, bacteria consists of a membrane encasing mostly fluid. Mechanical dewatering cannot break the membrane to release the fluid. Primary solids can be dewatered to 35 to 40% solids, whereas the amount of activated biosolids in the same plant rarely exceeds 25 to 18% solids. From this, it can be concluded that anything that increases the percentage of bacteria in the biosolids will result in wetter biosolids. Likewise, the practice of eliminating the primary clarifiers—while it does save capital costs and simplify the flow diagram—greatly increases the difficulty of dewatering the resultant biosolids. In effect, easy-to-dewater primary solids are broken down by the bacteria and thus increase the volume of bacteria going to dewatering. By anecdotal observation, eliminating the primary clarifier results in 5 percentage points wetter cake, with all other conditions being equal.

Minneapolis Wastewater Treatment Plant (Minnesota) has published data to show that the polymer dose increases and cake dryness decreases as the ratio of primary to secondary biosolids goes from 50:50 to 30:70 (MWWTP, 1999).

Vicinal Water. Vesilind (1994) postulated that water in the vicinity of the surface of a solid particle is attached to the particle by electrostatic and Van der Waals forces. As a result of these forces, this water is very difficult or impossible to remove by mechanical means. From this, it can be concluded that the greater the surface area per kilogram (pound) of solids, the more vicinal water will remain in the dewatered cake. Under a microscope, it can be observed that waste activated biosolids have a lot of surface area—remarkably more than primary biosolids. This profusion of surface area is another reason why secondary biosolids are harder to dewater than primary biosolids.

If a stone is broken into pieces, the weight of stone is unchanged, but the surface area clearly increases. In general, larger particles have less surface area per kilogram

(pound) than smaller particles and thus have less vicinal water associated with them. Therefore, it is not good practice to make little particles from big particles, which is what happens when the primary clarifier is absent or not operating properly.

Interstitial Water. Interstitial water is water trapped in the spaces between the biosolids particles. There are several mechanisms to explain the reduction in the amount of interstitial water. Anyone filling a canister with flour or cereal has observed that shaking the canister causes the contents to move closer together and displace some of the interstitial air from between the cereal flakes. In this example, cereal does not change shape, and the packing density increases somewhat to reach a terminal packing density. If the cereal was flexible, then applying pressure to it would press the flakes closer together, causing them to conform to one another, and press the interstitial air out. In wastewater treatment, as the biosolids form a blanket in the clarifiers, the weight of one particle upon another squeezes the biosolids particles together, and squeezes water out. As the biosolids blanket becomes deeper, the cumulative weight of the particles on the lowest layer becomes greater, progressively more water is removed, and the biosolids blanket becomes thicker. Following the biosolids to dewatering, filters or centrifuges apply a great deal more pressure to press the solids further together, expressing even more water from the biosolids. It is interesting that in dewatering biosolids in dry solids centrifuges, various techniques are used to make the cake layer in the centrifuge as deep as possible. This increases the pressure of the solids, one upon the other. It is also true that to obtain dryer cakes requires an increase in the polymer dosage. Simply adding more polymer without increasing the cake depth does not make much difference in cake dryness.

Capillary Water. Capillary water is water held in crevices within the biosolids and is contained by capillary attraction. Generally, mechanical means cannot remove this water, although perhaps if the biosolids particles are not too rigid, squeezing the particles may crush the capillaries and extrude the water, much like squeezing toothpaste from a tube. Certainly, adding sufficient pressure to nonrigid particles could express capillary water out of the biosolids.

Some water is easier to remove than other water, and considering this allows one to profitably speculate on ways to make the biosolids easier to dewater. Unfortunately, efforts to quantify the amount of water held in these various states have not been immediately useful, but the concept itself is quite helpful. For example, in observing that dewatering biosolids from 98% water to a cake containing 72% water, the dewatering process has failed to remove the great majority of the water in the biosolids. By expressing cake solids as a percent, it is implicitly suggested that 100% dryness is possible. Vesilind (1994) has pointed out that it is not possible to mechanically remove

100% of the water, or 50% of the water, or perhaps even as little as 33% of the water in the biosolids. As with nearly everything, as the efficiency improves, further improvements are progressively harder to achieve.

IMPROVING THE QUALITY OF BIOSOLIDS. There are a number of practices that have been shown to improve dewatering, including the following:

- Increasing the capture of suspended solids in the primary clarifiers. Primary biosolids are easier to dewater than secondary biosolids; thus, reducing the amount of solids undergoing aeration will reduce the amount of biological biosolids produced. If the plant does not have primary clarifiers, one could consider adding them in the next plant redesign.
- Avoiding holding or storing biosolids in the plant. Dewaterability changes if biosolids become septic. Gravity thickeners are often a problem, as are tanks that store biosolids for days. The exception is anaerobic digesters, where longer residence times typically reduce the polymer dosage.
- Not allowing uncontrolled bacteria growths. If the temperature in anaerobic digestion is allowed to drift, it causes major changes in the bacteria population, resulting in difficult-to-dewater biosolids. In aerobic digestion, excessive aeration may reduce the volume of biosolids, but often the biosolids that remain are more difficult to dewater.
- Recent work suggests that, while short anaerobic digestion times may be sufficient for volatile reduction, longer digestion times result in lower polymer doses.
- Changing to two-stage digestion, starting with thermophilic anaerobic digestion, followed by mesophilic digestion. Research shows reduced biosolids volume and reduced polymer dosage.
- Avoiding the use of alum in the plant. Ferric salts result in dryer cakes. Mixing alum water treatment biosolids with wastewater biosolids should be avoided. The alum water treatment biosolids contain a high proportion of inorganics, often a high proportion of alum, and sometimes substantial amounts of grit.

TRACKING DOWN THE CAUSE OF A CHANGE. No dewatering operation responds well to change. If the feed biosolids varies, then the operators must determine how it has varied and respond to the change. Some changes can be predicted in advance. If one digester is just coming online, then biosolids from that digester will behave differently in dewatering. Other changes are more difficult. Many plants ob-

serve that the biosolids properties change from summer to winter. Process problems upstream are also a problem. It is important to look for changes in the following:

- Feed total solids, total volatile solids, pH, and temperature;
- Alkalinity;
- Conductivity;
- Polymer type, delivery, reaction, and concentration;
- Plant load;
- Customer loadings;
- Biosolids ratio;
- Weather;
- Plant bypass;
- Mixed liquor;
- Sludge volume index; and
- Biosolids age.

It is also important to look for changes in digestion properties, including the following:

- Residence time,
- Volatile acids,
- Alkalinity,
- pH,
- Temperature variation , and
- Feed variation.

THINKING AHEAD: INORGANIC CHEMICAL ADDITION TO ACHIEVE CLASS A BIOSOLIDS. The need to achieve a Class A biosolids through lime addition is more common in recent years, and the previous information provides a good basis to consider how to add lime and other alkaline agents, such as fly ash and kiln dust. There are two general ways to admix the lime.

The wet method is the simplest, where the pulverized lime (calcium oxide) is mixed with water, and the lime slurry is pumped into the biosolids feed line ahead of dewatering. This is a neat, trouble-free, low-maintenance system.

Alternately, the pulverized lime is conveyed by screw conveyor or air to a paddle mixer, where it is blended directly into the dewatered biosolids. This releases large amounts of ammonia, dust, and sulfides. Operators cannot work in this atmosphere, which mandates an odor control system.

From both an operating and an equipment point-of-view, the wet method is a much less expensive option than mixing powdered lime directly into the dewatered cake.

Liming Before Dewatering.

1. When the lime (calcium oxide) reacts with biosolids, it absorbs one molecule of water to form calcium hydroxide. This water is taken from the feed and is water that otherwise would leave the dewatering system in the filtrate, but now moves to the cake and must be hauled away as biosolids.
2. The lime has surface area and therefore will carry surface moisture with it through dewatering.
3. Relatively few polymers react well with high-pH biosolids and, when they do, the polymer dosages are higher. This alone will complicate polymer selection and increase the polymer costs.
4. The addition of lime before dewatering will increase the amount of lime needed, because it must also increase the pH of the filtrate/centrate that recycles back into the plant.

Liming After Dewatering.

1. When the lime (calcium oxide) reacts with biosolids, it absorbs one molecule of water to form calcium hydroxide. This water comes from the dewatered biosolids and is water that would have had to be hauled away.
2. Biosolids to dewatering are unchanged, so there is no problem with polymer selection and use.
3. Only the pH of the dewatered biosolids is raised; no lime is wasted on the filtrate/centrate

In filtration devices, the addition of lime reduces the specific resistance to filtration, which, in turn, would improve performance, so there is an additional benefit not present for centrifuges. In water and wastewater centrifuges, filtration is not a separation mechanism; therefore, there is no such mitigation. In both cases, the amount of material to be hauled is greater with preliming—in part, because the lime must be hauled away, but also because all of the surface area of the biosolids is covered with vicinal or surface water. Adding lime increases the amount of surface area and therefore adds to the surface water that moves to the biosolids.

Cost should be the major factor driving this decision. It is expensive to buy special equipment to place chemicals in the sludge, which increases the volume and weight of

the sludge, only to throw the sludge away. The obvious up-front costs need to be balanced by the disposal costs. Regardless of how the lime is added, the product is of value to most agriculture reuse. In addition, limed sludge can be stored for a long time without odor problems. This is a great benefit when the recycle of biosolids to farmland is not possible during the winter or when crops are in the field.

SAFETY. All of the alkaline agents used are irritants to the skin, eyes, and lungs. Calcium oxide is more aggressive than calcium hydroxide. It is important to follow the precautions on the Material Safety Data Sheet.

OBTAINING HELP. It is often difficult to find the cause of problems because there are so many problems. Plants are operated in a certain way, and it takes time to change from what has worked in the past. Also, most operators have relatively little experience at other plants and so have little to compare with their own operation. Thus, from time to time, help is needed. All help comes with a bias. The manufacturer's solution will tend to involve new equipment and/or upgrades. The engineer's solution will tend to involve design work, and so on. This is why visits to other plants are invaluable. It is helpful to join the state chapter of water and wastewater operators and visit the host plant, but perhaps more important is get to know the operators of local plants. Local plant operators have probably encountered many, if not all, of the problems one may have, and they are an invaluable resource of knowledge and experience; the only thing they are likely selling is their self image of competence. Best of all, the only cost is reciprocation.

KNOWLEDGEABLE EXPERTS. The equipment manufacturer has staff who know wastewater treatment and dewatering. They can often provide considerable help over the phone, at no charge. Likewise, there are outside experts available who are specialists in various equipment and processes. The annual Water Environment Federation Technical Exposition and Conference (WEFTEC) and the WEF Residuals and Biosolids Conference have extensive technical programs. Presenters are another source for names of experts. Again, phone calls are typically free; however, not all problems are solved over the phone. The cost to bring an expert to the plant is typically modest in proportion to the cost of living with the problem. Some experts are better than others. One can get some idea of the depth of a person's knowledge by talking the problem over with them. Do not be afraid to ask for references, then call them and talk to them. Most people are reluctant to be frank about anything negative, especially to a stranger. However, they will rarely fail to answer a direct question candidly, so ask such questions. If it seems, from the preceding, that the person is experienced and helpful, pay

that person to come out to the plant—and not someone on the person's staff. If there must be a switch, interview the person planning to come out and, if there is no great confidence in that person, demand someone else. It is hard to reject someone, but better to do that than to pay someone who cannot fix the problem.

SUPPLIERS. The people one interacts with regularly can often be of very good help. For example, the polymer salesman sees countless plants and can often point to problem areas within a plant. Often, representatives of firms that do not have a particular plant's business are more willing to point out obvious problems to impress that plant's operators with their knowledge; wishing to diminish the competitor's business volume is also a motive. Equipment representatives often have in-depth experience with a plant's specific equipment and processes and can be a good source of information and suggestions regarding who in the industry can help. If nothing else, they can put one in touch with other plants that have had similar problems.

WATER ENVIRONMENT FEDERATION. One resource often overlooked is WEF. One can search their database for articles and papers on almost every topic. There are numerous publications, such as this book, that will help. Especially useful are the discussion groups at the WEF website, where people can post problems and questions and discuss them with other members of WEF.

U.S. ENVIRONMENTAL PROTECTION AGENCY. The U.S. Environmental Protection Agency (U.S. EPA) (Washington, D.C.) has a series of fact sheets that are useful summaries on various topics (http://www.epa.gov/owm/mtb/biosolids/index.htm). Website organization changes, so it may be necessary to search the U.S. EPA website (http://www.epa.gov).

OPERATING PRINCIPLES FOR DEWATERING

Current management information systems are typically more focused on receiving information than on disseminating it. Each Supervisory Control and Data Acquisition (SCADA) screen focuses on a small section of the process, and there is not enough thought given to what to display and where to display it.

MANAGEMENT OF INFORMATION. Most plants have not taken advantage of modern information-transfer capabilities. Operating information, laboratory analyses, and economic information typically moves up the chain-of-command, when it is at least as important that it move horizontally and downward. The goals of the plant

include compliance with regulations and, at the least, cost. Dewatering operators cannot operate at the least cost when they do not know what the costs are. Most SCADA systems are a series of descriptive screens that convey a small amount of sometimes useful information to the operator amidst a clutter of worthless information. The screens look nice, and because once they are designed every such system can use the same screen, they become a generic standard. Unfortunately, they are designed by people who have little experience actually running a dewatering operation. Operating personnel should consider what information is available, both upstream and downstream of their plant, consider what would be useful to them, and find a way to display this information on their screen. If this means that the pretty illustration on the screen needs to go, it will not be missed. It is important to consider the importance of wet-end information to the downstream dewatering operation.

No dewatering operation works well if the dewatering characteristics of the biosolids change without warning. To some extent, variations are unavoidable; after all, the production rate of primary biosolids varies during the day, and therefore the resulting ratio of primary to secondary biosolids blend varies also. Nevertheless, wet-end operators should make an effort to minimize the magnitude of such changes and tell the dry end of the plant when a change is coming. For example, if it is decided that the mixed liquor suspended solids are too high, an unthinking supervisor may make a dramatic change in the wasting rate and bring the mixed liquor down to the target in 2 hours. The resulting large and sudden change from a typical 50:50 blend to perhaps a 30:70 primary to secondary blend will cause a major upset in dewatering. In a few hours, the operators will get the dewatering process under control, and when the wasting rate suddenly returns to normal and the biosolids are once more a 50:50 ratio, there will be yet another upset. This sort of operation demoralizes the dewatering operators—in part, because it is unnecessary and, in part, because the biosolids seem to be unpredictable. Better management of the information would have given the operator changing the wasting rate a "pop-up" telling him that such a large change would upset the dry-end operation, and suggesting that the wasting rate be increased moderately and the mixed liquor be brought down to the target over 24 hours. If there is no overwhelming reason for a sudden change, presumably the operator will be persuaded to opt for a more gradual change in wasting rate. Whatever the decision, when a change was made in the wasting rate, ideally a pop-up on the dewatering operator's screen would show the coming change in biosolids quality; in 45 minutes, the ratio of primary to secondary biosolids will change from 50:50 to 47:53. Some small adjustment could be made to the dewatering devices, and the process would not have gone out of control. If the wasting rate had been increased moderately and the mixed liquor brought down to the target over 24 hours, the operation

would have gone much more smoothly. This is an example in which the SCADA system needs to communicate horizontally.

Of course, the operator may be able to call up the wet-end screens, do a trend line on the secondary wasting, and discover that the wasting rate changed; however, realistically, no one has the idle time to do this, especially just at the moment the rate was changed. Also, no one should have to, when the need for the information is clear, and the SCADA system can handle it automatically, if only it was programmed properly.

It may well be worthwhile for a plant to redo the SCADA screens to reflect what is important for the operators to know, and to relegate the less important data to a secondary screen.

CHANGING VALUES. The wastewater plant is a dynamic system, and often it is the changes that are of interest, and not so much the actual value of some parameter at the moment. No one can use all of the data collected all of the time, so some sort of reduction of information needs to be done. Much of what is seen is useful only if the viewer possesses an additional piece of information that is not displayed. For example, knowing that the conveyor torque is 15 Nm is not helpful unless it is also known that the torque trip point is 17 Nm, indicating that the device is about to go down on high torque. The torque reading would have been much more user-friendly if the display read 88% load. Similarly, one's response if the torque is rising is quite different than the response if the torque is falling. The absolute number is often not as useful as information that the reading is steadily changing. A trend line is forensic analysis; after the crash, one looks to see what led up to it. The SCADA system could automatically look for trends and display a summary on the main screen of only those trends that are unusual. This would help spot trouble before it arrived.

Undoubtedly, everyone benefits from prompt feedback. The samples sent to the laboratory are analyzed and entered into the SCADA system, but rarely do they pop up on the screen in dewatering, where the information can be used. Likewise, the dewatering operators often grab samples and analyze them, and then write the results down on a piece of scrap paper. If they entered this data into the computer, then the computer could calculate the percent recovery, polymer dose, and even dewatering cost. The computer could generate a trend line of dewatering cost by shift. It would store the data, which would help other operators on subsequent shifts and easily be retrieved even in 6 to 12 months. Instead, operators rely on logbooks, data sheets, and the like, which disappear into storage every few months, never to be seen again. It would seem, in the age of searchable databases, that operators should write their logs into the computer database.

In summary, plant controls need to be tailored by the operator, for the operator. One-size-fits-all generic displays are not good enough. In the future, it would be very beneficial if operators could click, drag, and paste on the screens and customize the screens to suit themselves.

INORGANIC CHEMICAL ADDITION

FERRIC CHLORIDE AND ALUM. Ferric and aluminum salts are often added in the wet end of the plant because both react with the phosphate in the water to form an insoluble precipitate. The use of these chemicals in the wet end will have a noticeable effect on dewatering; the use of ferric chloride will improve the dewatering process, whereas aluminum will have either no change or result in more difficult-to-dewater biosolids. The effect on dewatering will be proportional to the amount added; therefore, the dewatering operation needs to be advised of any changes in the dosing rate. Likewise, when comparing the cost of ferric chloride and alum, the effect on dewatering also needs to be considered. When ferric chloride is diluted with water, it hydrolyzes, forming positively charged soluble iron complexes that neutralize the negatively charged biosolids particles, causing them to aggregate. Unlike polymers, alum and ferric chloride do not require aging time, and special mixing devices are not used. Ferric chloride also reacts with the bicarbonate alkalinity in the biosolids to form hydroxides that also act as flocculants.

STRUVITE CONTROL. Some anaerobic digesters have a problem with struvite, which is a crystal comprised of calcium ammonium phosphate. Struvite can precipitate out in the digester anywhere carbon dioxide can flash off or where there is a lot of turbulence. The crystals sometimes are a serious problem in the centrate/filtrate lines, where they can block a pipeline in 1 week or so. In theory, struvite can be controlled by altering the amounts of the component ingredients or, to bind up phosphate, one of the key ingredients of struvite. Ferric chloride is commonly added because it ultimately reacts with phosphates and coincidentally lowers the pH of the sludge. Ferric chloride does improve dewatering; the bad news is that it is expensive and adds to the weight of material hauled away.

Another approach to struvite control is to acidify the feed to dewatering, lowering the pH to the point where struvite will not form. Any acid will do (sulfuric, hydrochloric, and nitric). Sometimes spent acid can be found at a good price—even free—but it is important to check it to see if it contains anything such as heavy metals that might be a problem to the plant. In general, adding acid to the biosolids gives little benefit to

dewatering. As an acid, ferric chloride is more expensive than the more common acids, so the value of the other benefits must be weighed against its higher cost. Ferric chloride generally improves dewatering, whether added in the primaries or just ahead of the dewatering device. At current prices, it rarely pays to add it solely to improve the dewaterability of the biosolids; the justification is the sum of its benefits.

ODOR CONTROL CHEMICALS. Odor control chemicals are sometimes needed. There are several types—oxidants, such as ozone, hydrogen peroxide, chlorine dioxide, permanganate, hypochlorite, and chlorine (Lambert and McGrath, 2000). These chemicals provide oxygen, which, in turn, reacts with hydrogen sulfide and other odor constituents to convert them to compounds with a higher odor threshold. The various oxidants have different levels of effectiveness, and some may be better than others in dealing with a specific odor problem, so it is worthwhile to experiment. There is some evidence (Rudolph, 1994) that potassium permanganate has a side benefit of reducing the polymer dosage, but reduction of the polymer cost is not the reason it is used. The oxidant feed point should be located upstream of the polymer addition point, to provide a contact time of 1 minute or more before polymer addition. Odor neutralizers are oils and surfactants that bind the odor-causing chemicals to themselves and thus reduce the unpleasant odor. These are commonly sprayed into the air in areas where odors emerge. Some of these chemicals have their own pronounced odor, so they need to be tried out. Nutrients, such as ferric salts, precipitate sulfides, and nitric acid adds oxygen to the sludge, which allows organisms to oxidize fatty acids. Bacterial dosing and enzymes are also reported in the literature.

BUYING CHEMICALS. The chemicals mentioned above are bulk commodities. When buying small amounts, it makes sense to buy through a distributor. In return, for applying a markup, a distributor supplies chemicals in the form and volume needed, may provide technical support, and is cooperative with the purchasing system. If these services are not of value to the operator, it may be possible to save money by buying directly from the manufacturer. In any event, it is worth doing an internet search and finding out the bulk price of the chemicals being purchased and compare it to what is being paid. If the chemical cost can be cut by 25% by accepting 2 large shipments a year, rather than 12 small ones, then it may be worthwhile to increase the storage capacity.

ORGANIC FLOCCULANTS

BACKGROUND. Organic flocculants are widely used in many industries and processes involving the separation of solids from liquids. These liquid–solid separation

applications may involve processes related to the recovery of finished products, clarification or purification of liquids, and volume reduction of waste materials. Several major applications are identified in Figure 33.1, which also indicates the relative electronic charge and molecular weight of organic flocculants typically used in the respective application.

The use of organic polyelectrolytes, frequently called *organic flocculants* or *polymers*, in municipal wastewater plants began during the 1960s and increased rapidly as wastewater facilities expanded to include secondary treatment. The use of these products is widespread in the estimated 16 000 publicly owned wastewater treatment works, which process approximately 130 tril. L (34 tril. gal) of household and industrial wastewater each day in the United States, while generating some 6.2 mil. Mg (6.9 mil. dry tons) of wastewater residuals, sludge, or biosolids each year. Figure 33.2 shows the various application points for organic flocculants within the typical municipal wastewater treatment operation.

Initially, ferric chloride and lime were commonly used to condition wastewater residuals before thickening and dewatering. However, in today's sophisticated municipal dewatering operations, these products are rarely used, with the exception of any remaining vacuum filtration and recessed-plate filtration processes.

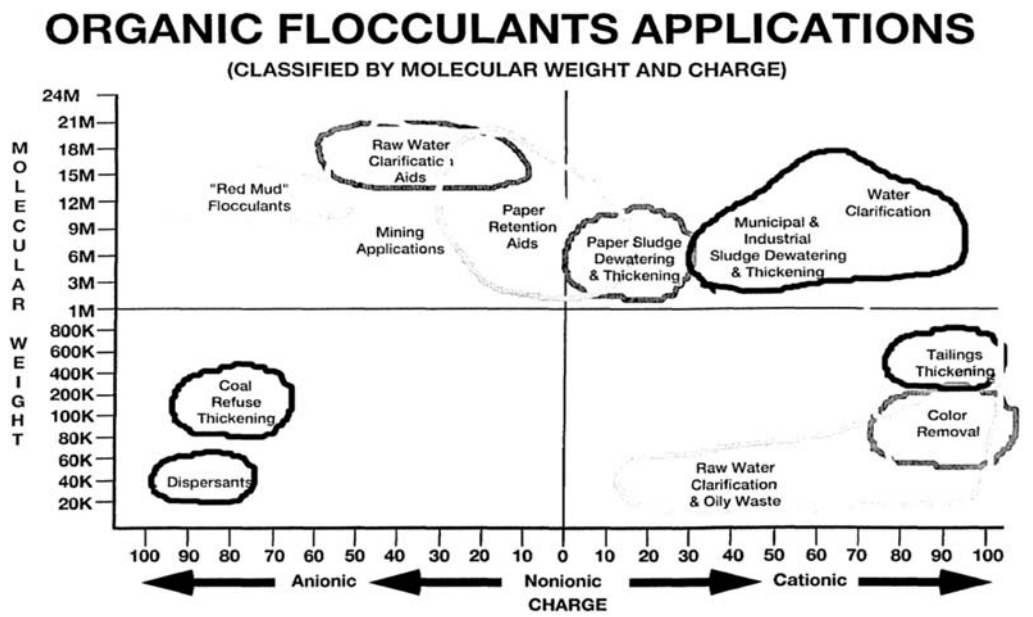


FIGURE 33.1 Typical points of addition of organic flocculants in wastewater treatment.

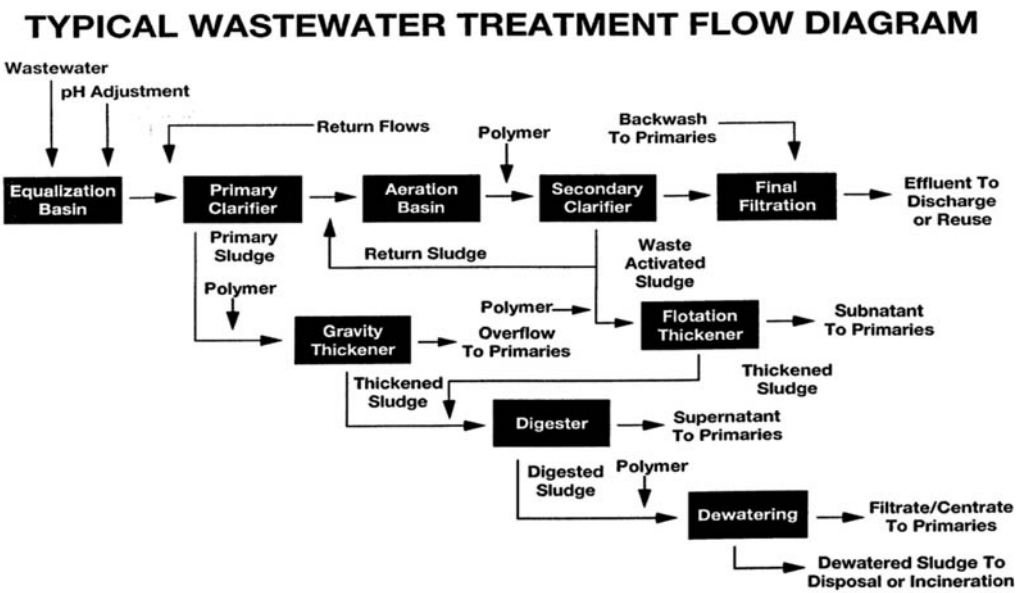


FIGURE 33.2 Typical wastewater treatment flow diagram.

While organic polyelectrolytes are commonly used in applications involving liquid–solid separation, the processes of wastewater sludge thickening and dewatering are completely dependent on their use. These municipal processes consumed approximately $188 million worth of complex, proprietary, cationic polyacrylamide (PAM) flocculants in North America in 2002, specifically for sludge conditioning.

Several factors have contributed to the widespread use of PAM flocculants as conditioners for sludge dewatering, including the following:

- Development of more sophisticated dewatering equipment, such as belt filter presses (BFPs) and centrifuges;
- Technological advances in polymer chemistries to provide more convenient, user-friendly, and high-performance products;
- Development of convenient and effective polymer make-down units; and
- Increased emphasis on the costs of solids processing and disposal.

Because of the complex and proprietary nature of these PAM flocculants and their varying levels of performance or effectiveness with different sludges, each manufacturer offers a full range of products based on product characteristics and forms. The remainder of this discussion will focus on cationic PAMs, as they represent virtually 95

to 100% of the organic flocculants for conditioning wastewater sludge residuals before dewatering.

POLYMER CHARACTERISTICS. The product characteristics of these complex and proprietary PAM flocculants may vary according to the following:

- Electronic charge (anionic, nonionic, or cationic);
- Charge density;
- Molecular weight (standard viscosity); and
- Molecular structure.

As shown in Figure 33.3, the "families" or types of organic flocculants are depicted according to molecular weight and electronic charge and charge density. It is useful to review Figure 33.3 in conjunction with Figure 33.1 to identify the family or type of organic flocculants, which are frequently used in each respective application.

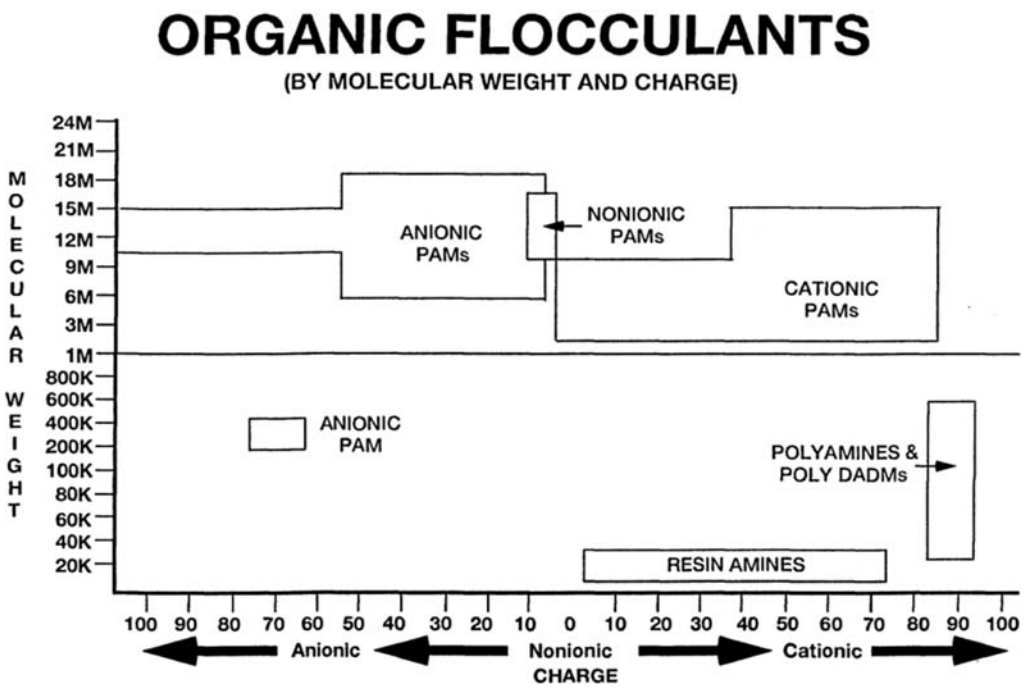


FIGURE 33.3 Types of organic flocculants according to electronic charge density and molecular weight.

Electronic Charge (Type). A variety of organic flocculants are manufactured with three distinct types of available electronic charge—anionic (negative), cationic (positive), and nonionic (no charge)—each suitable for specific liquid–solid separation applications. For conditioning wastewater residuals before dewatering, virtually all of the organic flocculants used are cationic PAMs, carrying a positive charge. There is almost an unlimited number of cationic PAM flocculants that may be produced. A variety of cationic monomers may be co-polymerized with acrylamide in varied molar ratios relative to acrylamide to produce flocculants with a wide range of charge density.

Cationic PAMs are formed either by co-polymerizing the acrylamide monomer with a positively charged monomer to create the cationic polymer or by modifying the acrylamide monomer itself following polymerization. This latter method of cationizing the acrylamide monomer is performed by reacting formaldehyde and dimethylamine with acrylamide, which yields aminomethylated PAM, the traditional Mannich solution PAM named after the inventor of the chemical reaction.

A variety of cationic monomers may be incorporated to the PAM backbone at various molar ratios, thereby giving rise to various degrees of cationic charge or charge density. Typical molar ratios of acrylamide monomer to the cationic monomer are 80:20, 60:40, and 45:55. The weight ratios differ substantially from the molar ratios as a result of the higher molecular weights of cationic monomers to that of the uncharged acrylamide. The names and chemical structures of these cationic monomers may be found in the Water Environment Research Foundation (WERF) (Alexandria, Virginia) publication *Guidance Manual for Polymer Selection in Wastewater Treatment Plants* (WERF, 1993).

Charge Density. Manufacturers of organic flocculants refer to charge density in relative terms. While there is no standardized representation for charge density, the information presented in Table 33.1 may be used as a typical convention for relative charge density.

The charge density of cationic flocculants used for dewatering municipal sludges generally fall into the broad range 10 to 80%. The majority of polymers, which perform effectively to condition most municipal sludges comprised of blends of digested pri-

TABLE 33.1 Charge density.

Relative charge density	Charge density (mole %)
Very high	>70 to 100
High	>40 to 70
Medium	>10 to 40
Low	<10

mary and waste activated sludge (WAS) for dewatering in centrifuges or on BFPs, fall into the category of medium-to-high charge—typically 20 to 60%.

While there is no substitute for laboratory testing and full-scale machine evaluations to determine effective products, the following comments may be considered as general guidance:

- Higher concentrations of primary sludge will require lower-charge products;
- Higher concentrations of biological solids or WAS will require higher charge;
- Sludge with smaller particle size will typically require higher polymer dose and possibly higher charge; and
- Older, septic sludge will require higher charge and higher polymer dose.

Molecular Weight. Similar to that for charge density, most manufacturers of organic flocculants refer to molecular weight in relative terms. While there is no standardized representation for molecular weight, the information presented in Table 33.2 may be used as a typical convention for relative molecular weight.

Variations in the chain length of the polymer may result in products with an extremely wide range of molecular weight, which is typically indicated by standard viscosity data. Further, these polymers may be chemically modified for improved performance by cross-linking the polymer chain or incorporating branching to the polymer backbone.

The molecular weight data can only be estimated. As an indicator of molecular weight, many manufacturers provide standard viscosity data. Unfortunately, standard viscosity measurements are not comparable across different product chemistries. As a side note, viscosity is not a measure or an indicator of polymer content.

In general, lower-molecular-weight products tend to be more soluble and less viscous. The majority of polymers, which perform effectively to condition most municipal sludges comprised of blends of digested primary sludge and WAS for dewatering in centrifuges or on BFPs, fall into the category of medium-to-high molecular weight, ranging from an estimated 0.8 to 6.0 million units and represented by standard viscosities ranging from 0.0025 to 0.0035 Pa (2.5 to 3.5 cP).

TABLE 33.2 Molecular weight.

Relative molecular weight	Molecular weight
Very high	>6M to 18M
High	>1M to 6M
Medium	>200K to 1M
Low	<200K

POLYMER FORMS AND STORAGE AND HANDLING. There are three physical forms of cationic PAMs, which are typically used in conditioning municipal sludge for thickening and dewatering applications.

- Dry PAMs (DPAM),
- Emulsion PAMs (EPAM), and
- Solution PAMs (SPAM), sometimes called *liquid PAMs*.

There is a fourth form, the gel log, which is rarely used in wastewater treatment.

Factors that may affect the determination of which form is most suitable for an operation include the following:

- Cost-effectiveness,
- Storage and handling of neat product,
- Polymer make-down and aging equipment and solution feeding capability, and
- Personnel safety considerations.

Dry Polyacrylamide. Dry PAM may be provided in granular (pellet), flake, or bead (pearl) forms. These may affect storage and handling considerations, as each has different moisture adsorption (caking), flowability, and wetting for polymer make-down characteristics. Dry PAMs generally remain effective for more than 1 year, provided that they remain free of moisture. Most manufacturers suggest a maximum shelf life of 1 year.

Dry PAMs are not 100% active polymer, as is frequently reported. Dry PAMs generally contain 88 to 96% active polymer, with the balance being residual moisture and inert salts. Dry PAMs, therefore, are advantageous for having the lowest shipping cost per unit weight of active ingredient. In many cases, additional salts are added to enhance product life or flowability. Accordingly, a simple solids determination probably does not accurately reflect the active polymer content.

The effective make-down of dry polymers is critical for efficient product use. Each polymer particle must be wetted to ensure complete dissolution into the polymer solution and to avoid product agglomeration and gels. Any gels or "fish eyes" that do not properly dissolve into the polymer solution are not useable and therefore are wasted.

Storage and handling of DPAMs must be carefully considered. Dehumidified areas are recommended for product storage and make-down, as excessive humidity or moisture may cause caking and handling problems in the storage and conveying equipment. Conversely, dust must also be controlled, and personnel may be required to wear protective respiratory equipment. Some DPAM products have a tendency to cause more dust than others.

Spills of DPAM must be contained and promptly swept or vacuumed away for proper disposal. Moisture and water cause the polymer to become a hazardous, gelatinous, and slippery goo and should be strictly avoided.

Consult the polymer manufacturer for storage and handling, humidity and moisture control, dust control, product make-down and solution concentration, and cleanup recommendations.

Emulsion Polyacrylamide. Emulsion PAMs (emulsion or dispersion) appear as a milky liquid, although some emulsions or dispersions, with much smaller particle size, may appear somewhat clearer or cloudy. The emulsion product provides for a higher concentration of active polymer in a convenient, easy-to-handle, liquid form. The EPAMs typically contain 25 to 60% of active polymer.

Most emulsion products have a recommended shelf life of 6 months when stored under normal conditions. Samples stored in a refrigerator have considerably longer shelf lives. Emulsions consist of two distinct phases—oil and water; there is the potential for phase separation or layering. Users should consider slow mixing or recirculation of the polymer storage tank to maintain uniformity of the neat polymer. Similarly, drum or semibulk containers of emulsion polymers should be checked for uniformity and mixed, if necessary, before use. The manufacturers have mixing recommendations for maintaining neat polymer homogeneity and can supply mixers for drums and the semibulk containers.

In an emulsion, the organic polymer is actually contained in a mineral oil phase of droplets, which are stabilized in an aqueous media by emulsifiers or surfactants. These additives also assist in the inversion of the polymer during make-down. However, there is an additional cost associated with the oils and surfactants used to make the convenient product package.

Emulsion PAMs are generally shipped and stored in bulk tanks or semibulk, returnable containers (totebins). The EPAMs may also be available in 208-L (55-gal) steel or fiber drums. Handling takes place within pipes and hoses, which are a closed system. The make-down of emulsion polymers is generally convenient and reliable, using any of several readily available, packaged systems offered by numerous manufacturers. The bulk viscosity of EPAMs may vary considerably, thereby affecting pumping capability and calibration. This means that the equipment must be recalibrated when polymers are changed.

When lines, hoses, or other equipment containing EPAM must be disassembled, they should be flushed with lightweight machine oil, such as SAE 10 to 30, to remove residual polymer. If water is used to flush the neat emulsion lines, the polymer will gel into a sticky mass.

Similarly, spills should be quickly contained and adsorbed in any one of a number of clay-based adsorbents. A number of commercial cleaners are available for cleaning spills and belt washing. Any polymer supplier can recommend specific types. Avoid using water during the cleanup of spills outside of a contained and properly drained area, as it will result in a slippery, gelatinous mass.

Consult the polymer manufacturer for specific recommendations regarding product uniformity and mixing, storage conditions and product stability, neat product viscosity and pumping, product make-down and solution concentration, and cleanup.

Solution Polyacrylamide. As the name implies, SPAM is a true solution of polymer in water, appearing as a clear to cloudy liquid, highly viscous syrup that is almost gel-like. These products are also referred to as *liquid PAMs* or *Mannichs*, named after the inventor of the chemical process. Solution PAMs have a very high molecular weight and range from approximately 3 to 8% active polymer content. The neat SPAM product may also contain inert salts or diluents, so that a simple solids determination may not accurately reflect active polymer content.

These products are very dilute, so they are typically sold in bulk tanker loads. The user will need storage tanks to hold the large volume inventory. The storage time should be limited to 1 month or less, even though some manufacturers suggest a shelf life of 3 months or more. The SPAM products are more susceptible to biological and chemical degradation than the other forms of polymers. The SPAM products may continue to react in storage, increasing viscosity even to the extent of gelling. At the least, this causes pumping and product make-down difficulties; at worst, the tank has to be cleaned out and the product discarded.

Bulk storage and handling are convenient and are generally conducted in closed systems, although the pump that is used for emulsion probably will not be large enough to deliver the volume of SPAM that is needed. Because the polymer exists in an aqueous solution, traditional make-down, such as that required for the dry and emulsion forms, is not necessary. Simple dilution of the neat product with water to a recommended concentration for use, followed by adequate mixing, should be adequate.

The active polymer concentration is very low—typically 5% or less—which results in very high transportation costs. The SPAM products are generally not cost-effective beyond a 400-km (250-mi) radius of the manufacturing plant.

Spills of SPAM should be readily contained and adsorbed in appropriate media for disposal. A number of commercial cleaners are available for cleaning spills and belt washing. Avoid water during cleanup of spills outside of a contained and properly drained area, as it will result in a larger amount of slippery, gelatinous mass.

Consult the polymer manufacturer for specific recommendations regarding neat polymer storage conditions and product stability, neat product viscosity and pumping, product make-down and solution concentration, and cleanup.

GENERAL SAFETY. Review the manufacturer's product literature and Material Safety Data Sheet for each polymer for detailed handling and safety precautions. In general, polymers used in sludge dewatering are not particularly toxic, but it is prudent to avoid contact. Safety problems are primarily related to slip hazards and dusting. Of course, personnel should take appropriate precautions to avoid getting dust into their eyes, ears, nose, and mouth. Any dust that attaches to a moist body part will become sticky and slippery and will be difficult to wash off. Accordingly, use protective equipment and disposable clothing when working in dusty polymer conditions.

Dust from dry polymers is extremely hazardous when wetted. Simply walking in a minor amount of polymer dust with wet shoes can cause a fall. Similarly, dust tracked or carried by drafts into an unexpected area can await the unwary for months. Polymer dust should be carefully contained and thoroughly swept or vacuumed and discarded before it can result in a hazardous, slippery condition.

Similar slippery conditions may result from leakage or spillage of liquid solution or emulsion polymer or from tracking liquid polymer into an unexpected area. When a liquid polymer dries, it is relatively harmless. However, once rewetted, it quickly becomes a slippery hazard. Cleanup of liquid polymer is difficult, and it must be thorough. Adsorbents may be used, and steam cleaning can be effective. The addition of rock salt or bleach (sodium hypochlorite) may help to break the polymer chain before washing with water. A number of commercial cleaners are available for cleaning spills and belt washing. Any residual polymer will result in the same hazardous, slippery condition when contacted again with water.

The best precaution is to avoid polymer leaks, spills, and dusting. Prevention is much easier than containment and cleanup.

POLYMER SPECIFICATIONS AND QUALITY CONTROL. Along with the product identification and type and form of product, the following standard product specifications should be obtained to determine storage conditions, pumping requirements, and potential hazards:

- Total solids (percent),
- Specific gravity,
- Bulk viscosity,

- Flash point,
- Freezing point, and
- Shelf life.

The product specifications should also include the related quality control limitations or variability of the manufacturer, each of which is critical to the usage and performance of the product in the dewatering process.

- Active polymer content (percent),
- Charge density (mole percent), and
- Standard viscosity (hertz [cycles per second]).

Active Polymer Content. Active polymer content (percent) should be obtained by the end-user with total solids. In addition, the end-user should receive, from the manufacturer, the quality control capability, in the form of the minimum and maximum active polymer (percent), to be contained in any individual shipment.

Active polymer content is the specific measure of the real product that is responsible for dewatering performance. This measurement of active polymer eliminates inert solids, which are included in total solids, but do not contribute to dewatering performance. The procedure for determining active polymer involves solvent extraction and is quite involved. Unfortunately, there is no industry-wide standardized procedure. It is prudent to ask for a copy of the manufacturer's procedure and consider spot-checking the deliveries.

Charge Density. Similarly, cationic charge density should be obtained by the end-user for each product. The charge density should be a quantitative assessment expressed as the mole percent of cationic charge, rather than a relative reference, such as low, medium, or high. Also, the end-user should receive from the manufacturer the quality control capability, in the form of the minimum and maximum cationic charge density (mole percent), to be contained in any individual shipment. Charge density is an indicator of the ratio of positive charges relative to the polymer backbone. For any given application or sludge type, if the charge density falls below a certain level, it will be necessary to use more polymer to achieve the same performance. Therefore, it is important to identify the minimum charge density that will be provided by the manufacturer for a selected optimum product, which has been identified through full-scale field evaluations, and the actual charge density of the products tested to obtain the bid information.

Standard Viscosity. Standard viscosity is also important to the end-user with the manufacturer's relative classification of molecular weight. Standard viscosity may be used as an alternative, quantitative comparison for molecular weight.

Standard viscosity is different than bulk viscosity or the viscosity of the neat product. Bulk viscosity is determined on the neat product and is useful for determining pumping and flow and related equipment requirements. Standard viscosity is determined at various make-down concentrations of the neat polymer product and is useful as an indicator of molecular weight. For standard viscosity, there are no industry-wide standardized procedures, so ask the manufacturer for copies of the analytical procedures they use.

PRODUCT MAKE-DOWN. A wide variety of very effective, packaged polymer make-down systems for handling emulsion or dry polymers are available from any number of independent equipment manufacturers and from the polymer producers. Unfortunately, most facilities are set up to effectively handle one form of polymer and are not readily able to convert to another product form without a lot of re-engineering. Flexibility in a polymer make-down system and related polymer handling equipment is very desirable. It is impossible to predict what form of polymer will be the most cost-effective in the future. A number of make-down systems are available that provide universal make-down capability for dry, emulsion, and solution polymer.

To be truly effective, a universal make-down system must include the appropriate ancillary equipment, such as metering pumps and storage tanks, capable of handling varied polymer concentrations and the related volumes and flowrates. As such, universal product make-down systems are not always practical and are a lot more expensive. Installation of equipment to handle the dry and emulsion products is a good compromise between price and value. Sometimes the form of product currently being used dictates the make-down system used, and the built-in capabilities of ancillary equipment preclude the easy conversion from one product form to another.

Accordingly, thorough consideration should be given to a variety of issues, including the following:

- Neat product storage and handling,
- Personnel and safety,
- Make-down capability and space limitations,
- Convenience,
- Dewatering performance and economic criteria,
- Changes in the polymer market and competitive landscape,

- Potential for sludge changes, and
- Anticipation of future developments.

All of these factors should be considered before any final decisions are made relative to the form of polymer and type of make-down unit to be used.

At a minimum, every system should include the make-down device and a separate agitated storage (day) tank for feeding the diluted polymer solution to the dewatering operation. The day tank should be sized to hold the equivalent volume of polymer to satisfy the maximum demand for at least 1 hour, thereby providing effective aging time with gentle mixing of 30 minutes minimum. Tanks should be fitted with clear and calibrated sight tubes for monitoring polymer solution draw-down.

Low-head centrifugal pumps are acceptable for one-time transfer of the polymer solution from the make-down unit to the day tank. Rotary gear pumps and progressive cavity pumps are better for metering the dilute polymer solution to the dewatering process. Inline flow meters are important for each polymer solution feed pump, and each metering pump should be outfitted with an appropriately sized calibration cylinder for confirmation of the feed rate. Sufficient water pressure (minimum of 280 kPa [40 psig]) and flow are required to overcome system head pressure and to operate an atmospheric eductor for aspirating dry polymer.

Dry Polyacrylamide. For dry polymers, care must be taken to ensure that the neat polymer remains dry and free from humidity. The polymer make-down system or dispersing unit must meter the dry polymer at a controlled rate and effectively wet the individual dry polymer particles, to produce a uniform dilute polymer solution without polymer agglomeration, gels, or fish eyes.

Generally, cationic dry polymers are made-down to a concentration ranging from 0.1 to 0.5%, with a target of 0.2% of polymer as supplied by the vendor. The dilute solution should be mixed with a low-speed mixer (400 to 500 r/min) for at least 30 minutes for proper aging and uncoiling of the polymer structure before feeding to the dewatering process. Higher concentrations of polymer and colder makeup water will probably need longer mixing time for proper aging of the polymer.

Emulsion Polyacrylamide. Recall that emulsion polymers may separate or layer over time. Products in storage or containers should be checked for uniformity and mixed, if required, before make-down.

Emulsion polymers must be activated before they can be effectively used. The first step is called *inversion* and occurs relatively quickly. During inversion, the make-down system imparts significant energy, in the form of turbulence or shear, into the emulsion and water mixture to invert the polymer from the oil droplet phase into the aqueous

phase. The second step, termed *aging*, occurs over a period of up to 30 minutes, during which quiescent mixing allows the polymer structure to thoroughly uncoil to become completely effective.

There are some emulsion products that may be fully effective without aging, and some equipment manufacturers claim that their make-down units are so effective that aging is not required. Nonetheless, adequate aging capability is strongly recommended in every system to provide the flexibility to use many products.

Cationic emulsion polymers are typically made-down to a concentration of 0.5 to 2.0% of polymer as supplied by the vendor, which typically amounts to approximately 0.2% on an active basis. As with the dry products, the storage (day) tank should be sized for dilute polymer solution to hold the polymer solution for a minimum of 1 hour before refilling.

Polymer Degradation. Intense mixing, pumping, and shearing of the dilute polymer solution will reduce the molecular weight and increase the dosage. Temperatures higher than 50 °C (120 °F) are also to be avoided. The quality of water used for polymer make-down is important. Suspended and dissolved solids found in nonpotable water result in increased polymer demand. It is also important to check the pH of the water to ensure that it is close to 7.0.

Cationic flocculants perform effectively over the typical range of pH (6.5 to 7.5) found in municipal sludge dewatering; however, as pH increases above this level, polymer effectiveness generally decreases. In the case of Mannich SPAM, a pH of 7.5 and higher may result in decomposition of the polymer itself, thereby releasing odor-causing amines. Other substances that may interfere with the performance or cause higher-than-normal doses of cationic PAMs include sulfides, hydrosulfides, phenolics, and chlorides. For a more detailed discussion of make-down systems, including materials of constructions, schematics, and pump-and-valve specifications, the reader may consult *Design of Municipal Wastewater Treatment Plants* (WEF, 1998), the polymer suppliers, and the respective manufacturers of specific make-down systems.

SOLIDS CONDITIONING. It cannot be emphasized enough that polymer conditioning evaluations should be conducted on the actual sludge or sludges that are found in the full-scale operations. A BFP or centrifuge will not perform effectively unless the biological sludge to be dewatered has been effectively conditioned with organic flocculants.

The polymer must contact each sludge particle to capture those particles in a floc. Interfacing of polymer with sludge particles is affected by three mixing factors—the sequence of chemical addition, intensity of mixing, and duration of mixing. The major

objective is to get a viscous polymer solution thoroughly dispersed with what may also be a viscous sludge to affect polymer interaction with sludge particles.

This sludge-conditioning process is a two-stage activity. The first, charge neutralization or stabilization, occurs very quickly and eliminates the negative electrostatic charge on the sludge particle. The second stage, flocculation or bridging, occurs within a few seconds thereafter and creates a sludge floc or agglomeration of sludge particles, with many individual sludge particles held together by coiled strands of organic polymer.

Consequently, short-duration, high-intensity mixing is required for dispersing the polymer solution effectively into the sludge, with longer-duration (few seconds), low-shear mixing to flocculate the particles into larger agglomerates. Conversely, as soon as flocs of polymer–sludge particles are formed, excessive shear or mixing should be avoided.

There are a number of mechanisms that assist this sludge–polymer interfacing. The first is simply to add dilution water to the polymer solution to reduce its viscosity and provide more efficient mixing and contact of the polymer with the sludge. Dilution of made-down polymer solution is not an alternative to the proper design of appropriately sized polymer tanks and feed pumps. Rota meters are generally suitable for controlling the flow of dilution water. Dilution water pressure and volume must remain constant to prevent the polymer dosage from fluctuating and to overcome pressure drops in the system. There should be adequate inline mixing of the polymer solution and dilution water before the diluted polymer solution contacts the sludge stream.

One of the more common recommendations that dewatering equipment manufacturers make is to have three or more alternative feed points for adding the polymer to the sludge stream. In the case of centrifuges, the last feed point is typically at the sludge injection tube already inside of the feed end of the centrifuge. Other feed points may be as far back as 9.1 to 15 m (30 to 50 ft) in the sludge line, thereby providing for more mixing at elbows and additional time for sludge–polymer reaction.

Belt filter presses use a mechanical device to accomplish the same effect. They recommend a polymer injection ring, followed by a manually adjusted butterfly mix valve. This is a convenient, trouble-free system that is frequently found in sludge feed systems to BFPs, but, on centrifuges, it is rarely used. Why this is the case is the cause of speculation, but it is certainly not because it has not been tried.

Static mixers are commonly used to mix the polymer with sludge. Dynamic, motorized mixers that provide variable mixing energy sludge–polymer streams are also commercially available; however, their limited use suggests that they may not be cost-effective.

PERFORMANCE OPTIMIZATION (DEWATERING). The economics of dewatering performance is the bottom line. In sludge dewatering, there are typically four economic factors that comprise overall dewatering performance. These are

- Polymer cost (polymer dose times unit price),
- Cost of sludge disposal or downstream processing (dependent on cake solids percent),
- Cost of recycle (function of capture percent), and
- Throughput (feed rate).

It is very important that operating personnel have an understanding of these cost factors and have the ability to calculate these costs with real-time operating data. If operations personnel do not have real-time analytical data for feed solids (percent), cake solids (percent), capture (percent), and polymer dosage, they cannot maintain optimum performance. Laboratory results for cake solids, sludge feed solids concentration, and suspended solids in recycle, which may be available 24 hours later, do not provide the information necessary to make immediate operational adjustments.

Similarly, it is important that sample points for collecting feed sludge, recycle (filtrate/centrate), and dewatered sludge cake are convenient for operators. It should not be necessary to walk down two flights of stairs into the basement to collect a sample of sludge feed or to collect dewatered cake on a different level than recycle (centrate). Ideally, the operator can see the centrate/filtrate running into a drain while walking along a well-traveled route.

Cost of Polymer. Simply stated, polymer cost is polymer dose in weight as supplied by the vendor per weight of solid processed times the unit price of the polymer (price per weight delivered). Polymer dose is typically determined from formal polymer evaluations under standardized conditions. This is discussed in further detail in the section entitled "Outline for Conducting Effective Polymer Evaluations and Product Selection."

Cost of Solids Disposal or Downstream Processing. The cost of sludge disposal or downstream processing is a function of the cake solids (percent) achieved in dewatering times the unit cost of disposal, such as incineration or transportation and landfilling. In the case of further solids processing for reuse, such as composting or lime stabilization, it would include these processing costs plus the cost for transportation and land application. More broadly, the basic disposal cost is the sum of the polymer cost plus the disposal cost. If the plant SCADA system does not calculate and display

these costs, then the operators have no way of determining if they are operating at the minimum cost per Mg (ton).

Cost of Recycle (Capture). There is a quantifiable cost of solids recycled to the front end of the treatment operation. Unfortunately, most facilities do not identify this cost. A simple gross method would be to assign to recycled solids the same cost assessed to industrial sewer customers who have excess suspended solids. Alternately, the plant budget could be divided by the amount of suspended solids and biochemical oxygen demand (BOD) processed. The result is a fair representation of the cost to treat the recycle solids. Most plants treat recycle simply on a pass or fail basis and arbitrarily assign a capture requirement of ±95%. They use this assigned value as an operating standard and make operational adjustments accordingly.

Throughput (Feed Rate). Throughput or feed rate is often overlooked as an operational parameter related to overall economics in running the dewatering unit. Most of the reference books treat this parameter as an equipment design factor. Dewatering equipment is specified with sludge throughput parameters based on hydraulic loading (volume) or on solids loading mass of dry solids per hour or per meter per hour for BFPs. For effective process control, operators should know the throughput on a mass basis, generally in dry tons of solids per hour. Accordingly, operators must have access to accurate real-time data for hydraulic loading (flow) and solids concentration (%) in the feed sludge. Throughput varies significantly with the type of sludge being dewatered. Specific data related to throughput rates for various sludges are referenced in standard wastewater engineering manuals and WEF publications. In general, primary sludges yield the highest throughput, with digested WAS yielding the lowest. Blends of raw or digested primary sludge with WAS or digested WAS generally yield maximum throughputs between the two extremes. Unfortunately, the equipment capability is limited by the following:

- The intrinsic design of the equipment,
- The way the equipment is set up and operated,
- The type and quality of the sludge, and
- The strength of the reaction between the polymer and the sludge.

From an operational perspective, it is intuitive that the best economics are achieved when the equipment is used to its maximum throughput, while still achieving the desired performance for cake solids and solids capture. Similarly, it is intuitive that this approach would provide for optimum economics relative to power consumption, labor, and maintenance costs. Unfortunately, intuition is not a good substitute for carefully obtained process data, evaluated with good cost numbers.

Nevertheless, many plants established their dewatering throughput on the basis of the quantity of sludge required for downstream processing rates or to satisfy hauling conditions at some time in the distant past. Another factor often used to determine the throughput rate is the hours necessary to fulfill the personnel schedule. On occasion, multiple units are all being operated, at less than maximum throughput, even when the total volume could be readily handled by fewer machines running at a higher throughput, thereby saving power and equipment wear.

There are a number of factors to be considered when determining the optimum throughput at a particular facility. Operations personnel should spend some serious time and effort determining the optimum performance. Once the optimum performance is established, the operators need training so that they know how to keep operations at the optimum throughput rate and achieve desired performance, while minimizing the costs associated with electricity, equipment wear, labor, and maintenance.

AUTOMATION. There has been much technological development on a variety of automated process sensors, controllers, and related software for managing dewatering operations for optimum performance and polymer usage. These systems are coming into their own in sludge dewatering. The best success occurs when the instrument, installation parameters, and application are considered together. Automation is not a sensor in a box. Operator attention will always be necessary for routine maintenance, such as probe cleaning and recalibration, but, on the whole, not a lot of time is required. In exchange, automation promises to smooth out the variation in unit operations throughout the plant.

The WERF and STOWA, a European wastewater association, are contributing to the research effort, and wastewater plants themselves, often in conjunction with automation engineering consultants, are applying an increasing number of instruments in the field. There are several publications that may provide more detailed information about the state of automation for dewatering operations (e.g., Gillette and Scott, 2001; Pramanik et al., 2002; WERF, 1995, 2001).

POLYMER SELECTION. Selecting the most cost-effective polymer for use in dewatering wastewater residuals is one of the most demanding, frustrating, and time-consuming experiences for many operations personnel and process engineers in the field of municipal wastewater treatment. It seems that every experienced operator and engineer has an individual horror story related to polymer evaluations and they often extend bad contracts rather than face the polymer trials. This section will provide some suggestions for conducting more effective evaluations and eliminating some of the frustrating experiences.

Traditionally, municipalities have used a two-step approach, incorporating product evaluations and competitive bidding to the product selection process. This selection process is intended to differentiate the cost performance of each product under standardized conditions. Unfortunately, the conclusions of these evaluations often result in inappropriate product selection or unrealistic performance expectations. As much as 30% (representing $56 million per year) of the polymers used in municipal sludge conditioning applications results from overuse or improper product selection.

To make matters worse, it is not uncommon for traditional product evaluations to be conducted over an extended period of time, often 4 to 6 weeks or longer. The internal cost for all of the in-house personnel involved in a complete series of evaluations is very significant—estimated to be $6,000 to 10,000. The argument that the plant gets free polymer for the trials is misguided; the cost is folded into the price for the selected polymer.

These evaluations typically contain extensive deficiencies and, more often than not, conclude with the selection of a particular product, influenced primarily by ancillary factors rather than the product's actual performance. These factors are

- Trial conditions and
- Trial management.

The purpose of the two-step selection process is to differentiate the cost performance of each product under standardized conditions. The emphasis is that standardized conditions are absolutely critical to effective product evaluations. Standardized trial conditions mean that the sludge consistency must be maintained throughout the course of the entire product evaluation period. As such, it is virtually impossible to conduct effective trials over a 4- to 6-week period or longer. Formal product evaluations conducted under the old notion that "the sludge is the sludge" are totally inappropriate for effective trials. The sludge processed on Monday, February 17, will most likely vary significantly from that processed on Friday, March 7—a short 3 weeks apart. Nevertheless, it is quite common for formal product evaluations to be conducted by municipalities over extended periods of time, with one product being tested during 1 week and another product tested some 3 weeks or even 5 weeks later. Some municipalities test the polymers on the sludge at one plant, and use the polymer selected at several plants. It is difficult to justify such practices.

Trial conditions, including sludge consistency and equipment modifications, are manageable by the operations personnel. While there are many additional details associated with standardized trial conditions, all are quite manageable, and the most

significant factor relates to shortened trial duration. Competitive products can be evaluated in less than 8 hours; five products can be effectively tested in less than 1 week.

With respect to trial management, there are a lot of factors that influence performance results other than the actual product itself. These ancillary factors must be eliminated. Traditionally, municipalities involve vendors, who have a vested interest in the results of the performance evaluations, to participate in the formal evaluations of their respective products. At a minimum, this results in trial techniques that differentiate individual companies or support personnel, rather than the products themselves. And, in worst cases, participation of vendors may result in distorted samples or analyses and polymer concentration and dosage.

Another trial management issue is the trial design or protocol. In particular, performance based on averages over time are most subject to influence by trial personnel. Averages of results do not demonstrate optimum or maximum product performance, but are simply a reflection of the vendor personnel or municipal staff making adjustments and managing the trial. An even worse situation involves product dosages, which are determined by totalizer readings over a specific increment of time. These types of trial design are particularly subject to manipulation by trial participants, thereby resulting in distorted performance results, which are not reproducible under normal operating conditions, and frequently improper product selection.

The purpose of the evaluation is not to identify the company or individual that can conduct or manage the best trial, but solely to differentiate product performance. Vendor participation in formal product evaluations represents a natural conflict of interest. The vendor wants to achieve the best performance to differentiate his or her product, while the municipality wants standardized conditions to allow each product to demonstrate its own respective performance. The WERF *Guidance Manual for Polymer Selection in Wastewater Treatment Plants* (WERF, 1993) acknowledges this natural conflict of objectives when it states that the "primary role of a sales representative is advising customers with the obvious goal of increasing product sales."

Outline for Conducting Effective Polymer Evaluations and Product Selection. There are many details that must be considered to conduct effective polymer evaluations for municipal sludge dewatering. A few principal suggestions to lead one to more efficient and effective polymer evaluations are as follows:

1. Identify proper performance criteria.

   Define economic values.

2. Minimize the time period to complete all product evaluations.

   Allow sufficient time for vendors to conduct informal laboratory testing and possibly informal full-scale testing to recommend their best product.

   Reduce the entire formal, full-scale trial period from 4 to 6 weeks to 1 week.

3. Standardize the sludge conditions.

   Do not operate under the premise that "sludge is sludge." The sludge on Monday, February 17, will not be comparable to that on Friday, March 7.

   Ensure that all variations affecting sludge characteristics are thoroughly understood and controlled throughout the evaluation period.

4. Eliminate the participation of all unnecessary personnel from the formal trial activity.

   Conduct all formal product evaluations solely with in-house staff, supplemented with independent consultants, as necessary.

   Minimize the number of staff personnel involved in the product trials and provide thorough training and written procedures—especially for the polymer make-up calibrations—to ensure consistency.

   Prevent vendor personnel from coming on-site during the formal product trials.

5. Standardize sampling and analytical activities and generate real-time performance data.

   Real-time analysis and data for feed solids, cake solids, and capture is imperative to making appropriate operational adjustments to identify the product's optimum performance and operating range. If the plant does not have a microwave oven, buy or borrow one.

6. Analyze performance data in a manner that assesses actual product performance rather than trial conditions.

   Determine optimum performance based on a dose–response curve, such as cake dryness versus polymer dose.

   Do not average individual data points to determine performance.

   Do not determine polymer dosage based on total polymer usage over the trial period for the respective product. Do not use totalizer readings.

By following these suggestions for more effective polymer trials, operations personnel and process engineers will be better equipped to select the most cost-effective polymer based on overall product performance and related economics, established with criteria determined by the municipality. Also, the product performance will be reproducible under normal day-to-day operating conditions.

CASE HISTORIES. Following are several case histories that demonstrate the types of conditions that often lead to ineffective product evaluations or, even worse, to improper product selection.

Trial Conditions (Sludge and Equipment Management). Some dewatering facilities receive large bulk (barge) transfers of sludge from other wastewater facilities. At other plants, sludge transfers may be made on a periodic basis from digesters or secondary treatment trains to a wet well or sludge holding basin before dewatering. These types of transfers should be monitored and controlled to maintain the consistency of sludge during formal polymer evaluations. More frequent transfers of smaller volumes are less likely to skew the results.

Barge Transfers of Sludge. A barge transfer of wastewater sludge containing a significant quantity of water treatment residuals, such as alum or ferric chloride sludge, produces a significant influence on the charge demand and polymer dosage, relative to that determined from 100% organic or WAS. This is the type of condition that must be managed during the course of a formal polymer evaluation.

Managing In-Plant Sludge Transfers. The periodic transfer of WAS from individual treatment trains to a sludge wet well is frequently conducted in massive slugs to accommodate pumping schedules and personnel convenience. At a particular wastewater treatment facility, the wet-well capacity is 379 000 L (100 000 gal) and the transfer pump was routinely run for 1 hour at the beginning of each shift to transfer 265 000 L (70 000 gal) of sludge from a single treatment train. This slug transfer of sludge repeated itself on each successive shift for each of three treatment trains, resulting in significant differences in sludge consistency each time a new transfer was made. A more effective sludge management protocol during formal product trials was to operate the transfer pump for 20 minutes on each of three treatment trains during each shift, while maintaining the sludge level in the wet well at a high level. This approach transferred the same volume and ensured a uniform mixture and consistency of sludge in the wet well, which was being fed to the dewatering unit.

Managing Sludge Transfers from Digesters. Transfers of sludge from digesters to the wet well represent significant potential for sludge inconsistencies. At one facility, these

transfers were made blindly on the basis of volume, without regard for the sludge consistency, solids content, and volatiles. In a particular extreme situation, the transfer of sludge from a digester resulted in a reduction in feed solids to the dewatering unit, from an average of 2.5% to less than 0.5%.

Upon further investigation, sludge mixing in the digester was inadequate, and sample ports and decant lines along the wall of the digester were inoperable. This type of situation is not nearly as uncommon as might be imagined, and it represents an intolerable condition for effective product evaluations. Furthermore, this type of condition also represents extremely inefficient day-to-day operating results and should be promptly corrected.

Equipment and Design Limitations. At one facility, the agitated day tank of the make-down system was adequately sized. However, the upper and lower level controls were set such that only one-third of the tank was used, causing polymer to be batched more frequently, while providing for reduced aging time. This was not a limitation with the house product; however, it did provide limitations for alternative products, which required lower make-down concentrations. In addition, at the same facility, the capacity of the polymer feed pumps was limited such that they were not able to handle lower polymer concentrations. Thus, the system design and equipment limitations severely limited the ability of the facility to effectively evaluate or handle alternative products.

Equipment Limitations. During the competitive bidding and product selection process, polymer vendors frequently suggest that a facility evaluate different product forms than the facility is designed to accommodate. For convenience, polymer vendors may offer to provide their own equipment to facilitate the use of such products during formal trials. Unfortunately, this approach adds another dimension and lack of control over standardized procedures for the product evaluation activity. Such evaluations are valuable, but formal polymer trials are not the time to evaluate alternative product forms that the facility is not functionally capable of handling. Most facilities have an open-door policy and are happy to accommodate vendors' suggestions and informal product tests, but such testing needs to be done at a time when the plant operators can focus on the hardware testing.

Trial Management. Trial design or protocol frequently includes the use of averages or volumes from totalizer readings to determine dosage or performance. These types of designs are most subject to manipulation by trial participants. Trials evaluated in this fashion do not effectively determine the performance of the specific product, but instead represent the results of the personnel most adept at managing the trial.

A dose–response curve is more effective for analyzing performance than is the average of data points. A dose–response curve provides an indicator of the optimum product performance and is much more accurate.

Real-Time Analyses and Data. To effectively determine the optimum product performance, the operator must make adjustments based on real-time performance data. Laboratory data, which may be provided 24 hours later, is useless for determining whether the polymer rate should be increased or decreased. Virtually all vendors provide their own solids analyzers, if none are available at the facility, when conducting formal product evaluations.

Manipulation of Trial Design. Following is an example of a trial that was based on the averages of data points, with the polymer dosage determined from totalizer readings. As is typical, vendors participated in the evaluations of their respective products and were permitted to manage the polymer feed adjustments throughout the trials. This particular trial demonstrates the manipulation of trial design, which resulted in the selection of this product for a long-term award. Unfortunately, the product was never able to reproduce comparable trial performance, which resulted in extensive cost overruns, relative to the costs predicted from the trial throughout the term of the contract.

As is readily evident from the table of data shown in Table 33.3, the specific data points collected at the 10:45 sampling (highlighted) show the lowest feed solids and an extremely low polymer dose—less than 50% of the average of all test dosages. Yet, this same reading shows a polymer feed pump setting at the same level as all of the other

TABLE 33.3 Data from polymer evaluation demonstrating manipulation of trial design.

Time	Feed solids (%)	Sludge flow (gpm[a])	Poly flow (gpm)	Poly pump (%)	Poly dose (lb/dry ton[b])	Cake solids (%)	Capture (%)
8:30	1.95	392	13	50	20.61	28.77	94.72
9:15	1.87	484	10[c]	50	13.16[c]	26.44[c]	94.01
10:00	1.88	366	17	50	29.46	27.93	94.02
10:45	1.85	364	6[c]	50	9.85[c]	28.79[c]	93.39
11:30	1.87	562	27	50	31.06	26.71	94.01
12:15	1.93	615	18	50	17.63	27.83	94.67
Average	1.89	464	15	50	20.29[c]	27.75	94.14
Average dosage without the 10:45 run					24.69		
					22%[c]		

[a]gpm × 5.451 = m^3/d.
[b]ton × 907.2 = kg.
[c]Readings based on polymer totalizer.

readings. Obviously, the polymer feed pump settings could not remain the same throughout the trial, while yielding such wide extremes in polymer flows and dosages, as shown in the data. Ironically, the cake solids corresponding to this lowest polymer dose were shown to be the highest of the entire evaluation, which is extremely inconsistent with typical polymer performance.

It should also be noted that the dewatering unit would not even operate at the two lowest polymer dosages (5 and 6.6 g/kg [9.9 and 13.2 lb/dry ton]), as shown in this trial. This is an example of manipulation of the trial design based on averages and the use of totalizer readings to determine polymer dosage.

Figure 33.4 represents a dose–response curve of the same set of trial data from the preceding table. This dose–response analysis demonstrates the inconsistency of polymer performance in this trial. This is a scatter chart of data points connected by a smooth, solid, thin line. Note that the specific data points indicate a very erratic dewatering performance, as indicated by cake solids, for this particular polymer. The hatched line represents a logarithmic regression analysis (trend line) of the same data points. It is important to note that this trend line is inverted, suggesting that higher dose will yield

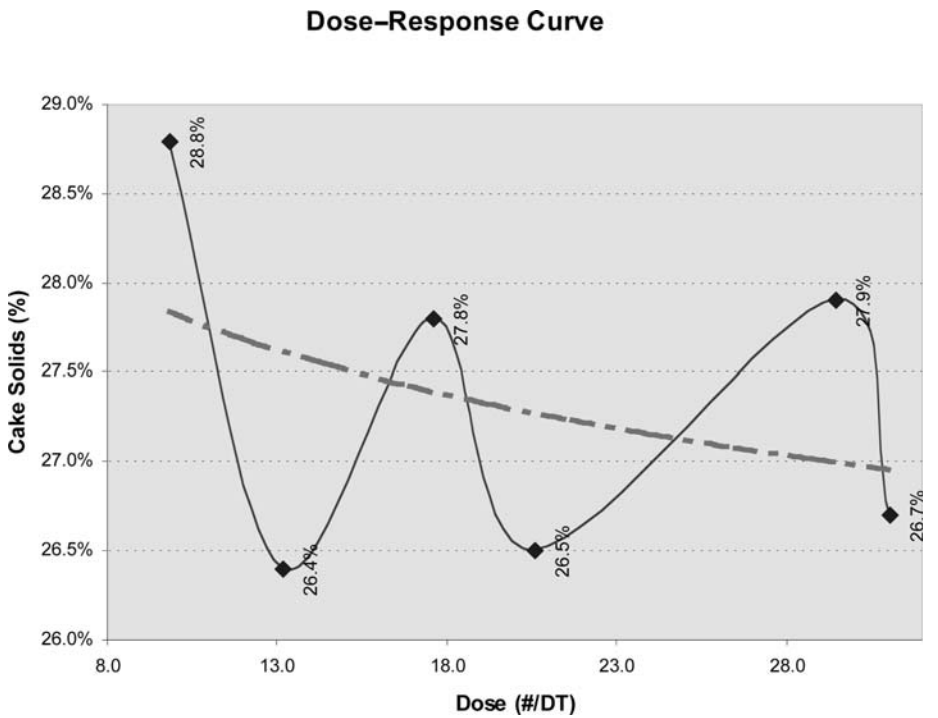


FIGURE 33.4 Dose–response curve of manipulated trial data.

lower cake solids. This trend line is contrary to the normal bell-shaped curve depicting polymer performance, whereby higher doses generally yield increasing cake solids. This depiction of the trial data demonstrates that the results represented by the trial data are reflective of something other than the product performance itself.

Figure 33.5 shows two graphs that represent the dose–response relationship of typical polymer performance. As in Figure 33.4, each of these figures represents a

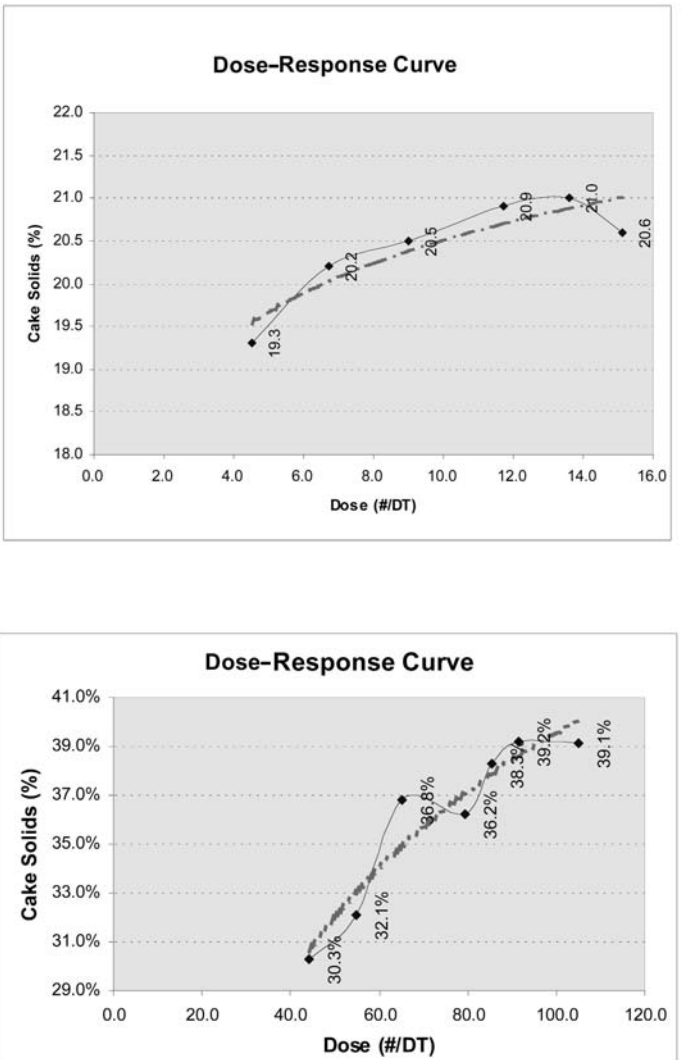


FIGURE 33.5 Typical dose–response curves.

scatter chart of data points connected by a solid, thin line. Note that these data points indicate an increasing performance (cake solids) with higher dose. Similarly, the hatched line represents a logarithmic regression analysis (trend line) of the same data points and shows the traditional bell-shaped appearance. Similarly, the hatched line in each graph represents a logarithmic regression analysis (trend line) of the same data points. The trend lines in each of these graphs shows the typical bell-shaped curve representative of increasing polymer performance (as indicated by cake solids) corresponding to increases in polymer dose up to a maximum level. After that maximum level, performance generally levels off and sometimes declines as polymer dose continues to increase.

Trial Management (Sludge Manipulation). One particular facility was designed to feed sludge directly from digesters or a lagoon via a manually controlled valve at a splitter box. The lagoon served as a buffer to absorb fluctuations in sludge generation and sludge dewatering. During formal product evaluations, the trials were conducted with the mindset that "sludge is sludge." All of the products were to be evaluated on sludge from the lagoon, as there was a significant excess of sludge in storage. None of the prospective vendors were aware of this protocol and conducted their evaluations on the sludge as provided by the facility. Only the incumbent supplier was aware of the sludge control valve and was able to use freshly digested sludge during the evaluation of his product.

The results of the final performance evaluation of all products demonstrated this difference, showing the polymer dosages of the new prospective suppliers to be almost double that of the incumbent product when all dosages were compared on an active polymer basis. Upon further investigation, the polymer dose of the incumbent product used to process lagoon sludge before and after the formal trial was found to be comparable with that of the prospective new suppliers as determined during the trial.

Trial Management (Sampling and Analysis). On a thickening trial at a major facility, sludge from a gravity thickener was sampled on an hourly basis to determine polymer performance over an extended 24-hour period. These samples were collected by laboratory personnel, in conjunction with the vendor's staff of the respective product being evaluated. Separate from the trial activities, operators also pulled sludge samples on each shift for routine operating records, while correspondingly recording sludge blanket depths and comments related to sludge on the continuous circular charts for the underflow sludge pumps.

The overall performance results showed one particular product to have exceedingly high solids in the thickened sludge. In fact, the solids were so high as to raise

speculation. Upon further investigation, it was found that several of the sludge samples from the trial, which were collected during the night for this particular product, contained exceptionally high solids. The solids content reported for these samples far exceeded the maximum design capability of the underflow pumps. Ironically, corresponding to the time of these samples, the operator logs and pump charts indicated that the sludge blanket depths were so low that there were virtually no solids in the basin, and the underflow pumps had, in fact, been turned off.

Trial Management (Sampling). At a trial at another major facility, centrate/filtrate recycle water samples were routinely collected by operators from the dewatering device. The operators instinctively knew that it was not desirable to have excessive solids in the recycled stream. Accordingly, one particular operator would collect his sample of recycle, pause for a moment to allow the solids to float to the surface, then tip the sample container to pour off the solids on the surface before capping the sample container and sending it to the laboratory for analysis.

CONCLUSION. These case histories and suggestions in the previous section demonstrate the capability to conduct effective polymer evaluations and make better product selections. By following these recommendations, operations personnel and process engineers are better equipped to select the most cost-effective polymer based on overall product performance and related economics established with criteria determined by the municipality. Also, the product performance will be reproducible under normal day-to-day operating conditions.

The opportunities are readily available to each individual facility to improve dewatering performance and reduce polymer costs.

AIR-DRYING BIOSOLIDS

Air-drying refers to dewatering methods that remove moisture by natural expiration, evaporation, or induced drainage. Biosolids to be air-dried are first stabilized by aerobic or anaerobic digestion. Air-drying processes are less complex, easier to operate, and may be more energy-efficient than mechanical systems. On the other hand, air-drying systems require large amounts of land, and some require much more labor for cake removal. Furthermore, winter weather and rainfall heavily influence the efficiency of air-drying systems. Air-drying is considered for rural wastewater treatment plants (WWTPs) with design flows less than 7500 m^3/d (2 mgd), which are located in warm, dry-weather areas. In cold or wet climates, air-drying systems are less efficient and should be covered or the plant will need to have an alternate disposal method avail-

able. Air-drying systems are intrusive to the public eye and the public nose. When they cause odors, there is no doubt where they are coming from. The following are characteristics of air-drying systems:

- The simplest beds are paved with asphalt or concrete;
- The sand bed consists of an impermeable liner and underdrains embedded in gravel, with graded sand above;
- Some beds are filled with reeds, which remove water by expiration;
- Most systems flocculate the biosolids with polymer to speed water break out (reed beds are an exception);
- Some have a provision for decanting the surface water;
- Some systems use wedge wires or plastic blocks in place of sand and gravel;
- Some use a vacuum to speed the separation;
- Some use a plastic or glass greenhouse to reduce odors and insulate from the weather; and
- Some have heating pipes to speed evaporation.

Attempts to get around the inefficiencies of air-drying are successful, but add considerable cost. Glass houses keep off the rain, but they also reduce the natural breeze so that the bed is more efficient in rainy weather but less efficient at other times. The underdrains allow some water to drain from the sludge, increasing efficiency, but they are subject to damage by heavy equipment and make solids removal more costly. Adding a grid strong enough to support light equipment helps with sludge removal, but the grid is a considerable expense and needs to be cleaned each time the bed is emptied. Polymer results in a free-draining sludge, which increases the loading, but polymer adds to the cost and complexity.

Air-drying systems are either reed beds or evaporative/drainage drying beds. All such beds must have a membrane lining to prevent contamination of groundwater; drainage into groundwater is not allowed.

Some also have an underdrain system and a sand layer above to allow removal of the sludge without damage to the membrane liner. The liquid that reaches the underdrain contains biosolids, so it needs to be recycled to the plant influent. The beds have to operate with some freeboard between the surface and the containment wall so that they will not overflow in wet weather (Figure 33.6).

PRINCIPLES OF OPERATION. This section describes the basic principles of operating the typical dewatering processes—reed beds, sand beds, vacuum-assisted beds, wedge-wire beds, and paved beds. All such systems will be out-of-service for substantial periods of time for cleaning or other maintenance, so several small systems

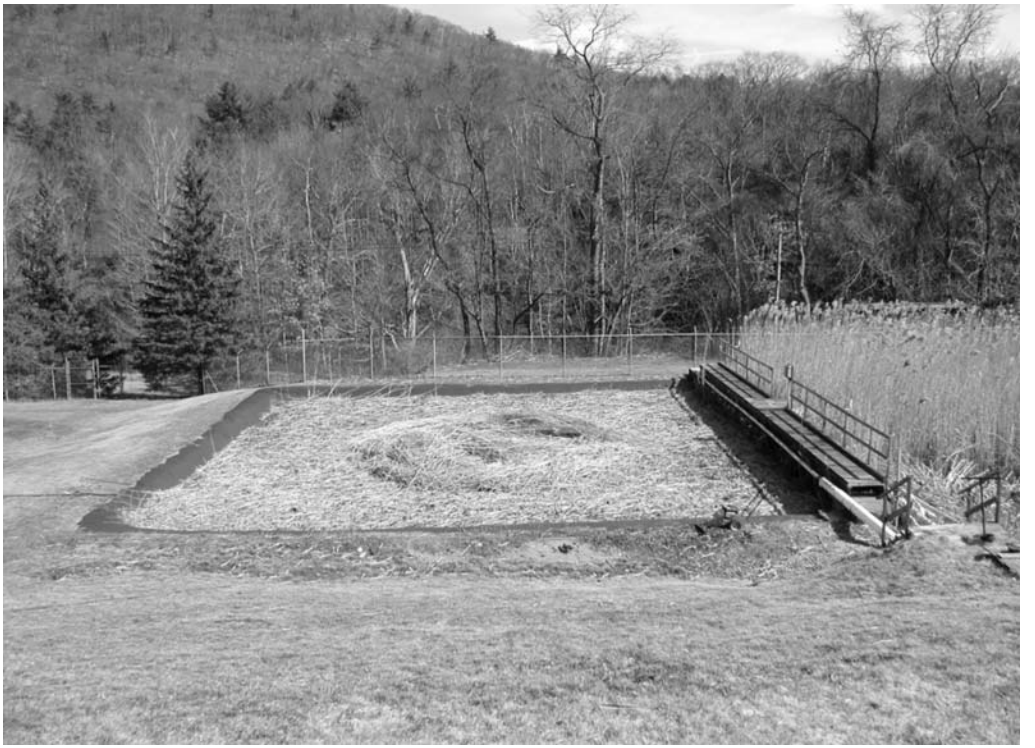


FIGURE 33.6 Reed harvesting in the spring.

are better than one large one. Depending on the local weather conditions, the capacity of the beds can be very low at times. Either substantial biosolids storage facilities or alternate methods of biosolids disposal must be available.

Reed Beds. Reed drying beds attempt to replicate natural systems, in which reeds stabilize biosolids, and also provide an environment for worms and bacteria to further break down the biosolids (Garvey, 2002). The reeds absorb water through their roots and release it to the air through expiration. To the casual observer, reed beds look like a marsh and thus a natural area. Reed beds are lined with a flexible membrane, followed by an underdrain system set in sand and gravel. The reeds used are typically phragmites comminus reeds, which can be purchased commercially or are available for the digging at other WWTPs. Figure 33.6 shows the reeds growing in biosolids. Biosolids stabilized by aerobic or anaerobic digestion are periodically pumped into the bed, approximately 0.07-m (3-in.) deep. Some water drains through the sand into the underdrains, some water evaporates, and some is taken up by the reeds. Reeds grow

best if the roots are wet. A good underdrain design allows water to pond in the bottom of the bed where the roots can reach it rather than draining or pumping the underdrains dry. The presence of other plants in the red bed suggests that the reeds are stressed and not getting a continuous supply of water. During a dry period, it may be necessary to pump plant effluent to water the beds. The transpiration of water by the reeds is one of the many advantages of this process; another is that the biosolids stay in the beds for 6 to 10 years, resulting in less volume to discard. Water that reaches the underdrains is returned to the plant as influent, but the drainage from reed beds is of better quality than the drainage from the other systems and will therefore have less effect on the plant. Biosolids are fed batchwise to the beds to a depth of 7 to 15 cm (3 to 5 in.) every 1 to 3 weeks. The reeds are harvested at the end of the growing season, as seen in Figure 33.6. They can be raked away from the edges and burned, in places where such practices are allowed, or removed, chopped, and composted or landfilled. Unfortunately, reporting requirements for reuse makes recycle of the harvested reeds an unattractive option. After several years, when the beds are 1-m (40-in.) deep, the top 78 to 80% is removed, and the process is begun again. The harvested material is typically land-applied. The reeds are not competitive with other plants outside of a wet marshy area, so reed growth in agriculture reuse has not been a problem. Some operators screen the reeds out, which results in a higher-grade product. Reed bed construction is very nearly a do-it-yourself dewatering operation. Reed beds typically require less capital, less land, and have much lower operating costs than the alternatives discussed below.

Sand Beds. Sand beds have been used since wastewater treatment became a recognized technology in the early 1900s. Dewatering on the sand bed occurs through decanting, gravity drainage of free water, and by evaporation until the desired solids concentration is reached. Figure 33.7 illustrates a typical sand bed. Generally, only stabilized biosolids are considered for air-drying. Sand bed construction is very similar to reed bed construction, except that the biosolids layer is generally no deeper than 150 to 300 mm (6 to 12 in.) and the bed is designed so that heavy equipment can operate on it.

Dewatering on sand beds is achieved by drainage by evaporation and by decanting. Initially, water drains from the biosolids through the sand and gravel to the underdrains. Biosolids from modern secondary plants do not drain very well without polymer, so beds that are intended to dewater by drainage need to use generous amounts of polymer. The drainage step requires several days, ending when the sand clogs with fine particles or all the free water is removed through the underdrains. If a supernatant layer forms, either from free water rising to the surface or from rain, it is typically decanted and returned to the plant influent. Decanting will likely be neces-

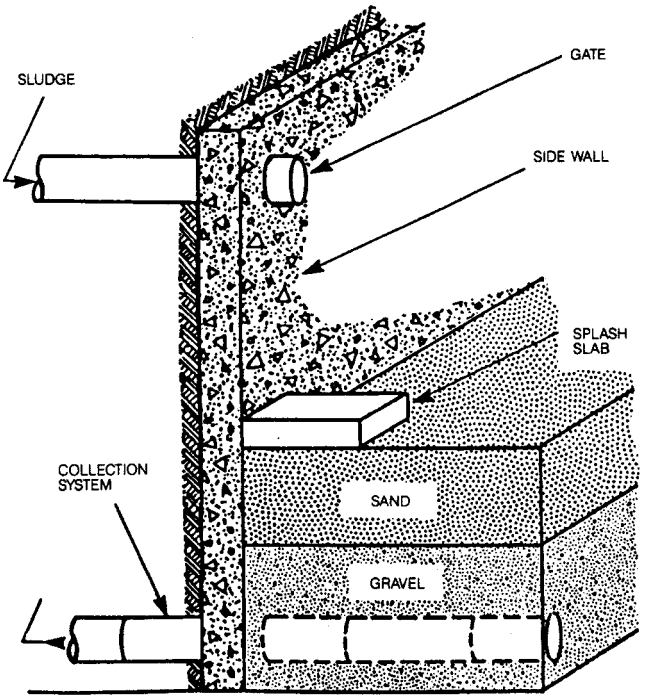


FIGURE 33.7 Sand bed details.

sary to remove the free water released by polymers added to the biosolids. Evaporation removes the water remaining after initial drainage and decanting. It is generally necessary to use tractor-mounted mixing devices to provide regular mixing and aeration. The mixing and aeration breaks up the surface crust that inhibits evaporation, allowing more rapid dewatering. When ready for harvest, front-end loaders go onto the beds and scoop up the dried biosolids, typically removing a small amount of sand. With the removal of the biosolids, more sand is spread, and the process repeats.

Vacuum-Assisted Drainage Beds. An Internet search for vacuum-assisted drainage beds resulted in very few hits, suggesting that this design is mostly of historical interest. The high capital costs to build these beds preclude them from standing for weeks, allowing the biosolids to air-dry. They resemble air-drying beds, but actually operate by drainage. With this technology, heavily polymer-treated biosolids are flooded onto a surface of rigid, porous media plates to a depth of 900 mm (36 in.). A weak vacuum draws free water through the plates, until one section opens and allows air to break the vacuum. Figure 33.8 shows a plan view of a typical single-bed system. Quite a lot of

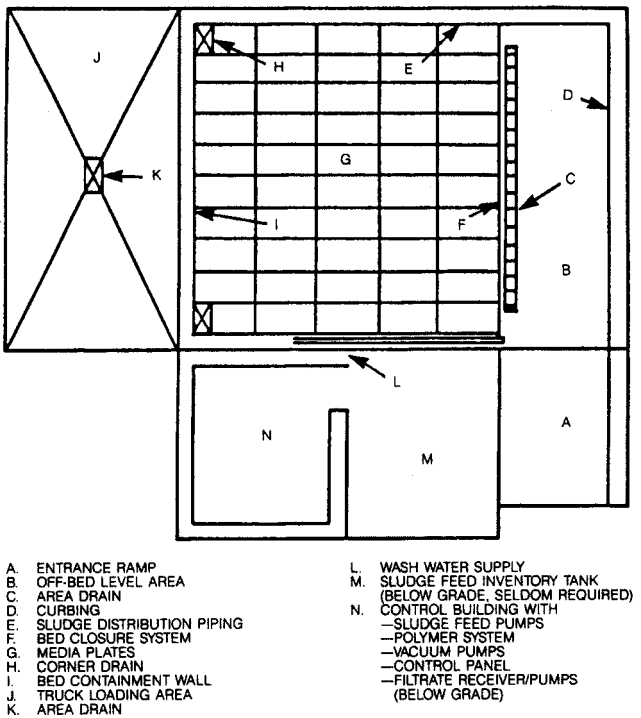


FIGURE 33.8 Plant view of a vacuum-assisted drying bed system.

solids are recycled back to the plant. The filtration media requires cleaning, and the underdrains must be hosed down after each cycle.

Wedge-Wire Beds. The wedge-wire process is physically similar to the vacuum-assisted drying beds. The media consists of a filtration surface, called a *septum*, with wedge-shaped slots approximately 2.25-mm (0.01-in.) wide in place of the porous plates in vacuum-assisted beds. Alternate designs use porous plastic blocks. The septum supports the polymer flocculated cake and allows drainage through the slots (Figure 33.9). A controlled drainage process exerts a small hydrostatic suction on the bed to remove water from the biosolids. The synthetic media (plastic and wedge-wire) filtration drying beds require less land than the simpler air-drying systems, but they require more capital to build and maintain, more labor to operate, and about as much polymer as a BFP or centrifuge would require to dewater the biosolids to a truckable state.

Paved Beds. Paved beds are the simplest drying beds. They consist of a membrane liner, topped with concrete or asphalt, surrounded by a containment wall. Sludge is

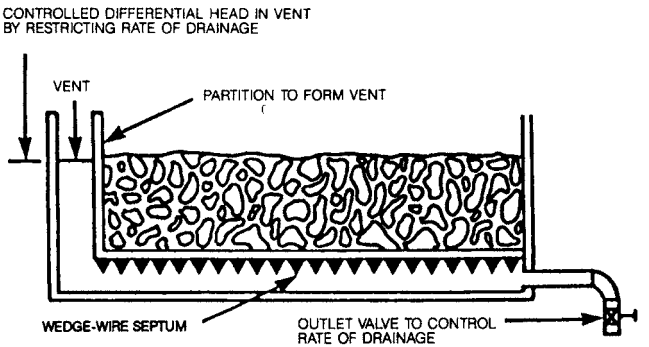


FIGURE 33.9 Cross-section of a wedge-wire drying bed.

added 150- to 300-mm (6- to 12-in.) deep. Occasionally, they benefit from polymer, but typically not. As the sludge crusts over, a tractor with a harrow breaks the crust, exposing wet sludge to the air. Operators who do this keep the mud flaps on the tractor in good repair. This is done several times, until the biosolids area is satisfactorily dry. Front-end loaders remove the cake and load it into trucks. Paved beds are the least efficient of the air-drying systems and require large amounts of land. They work well in desert conditions, and not so well elsewhere.

In an effort to improve efficiency and obtain some benefit from drainage, unpaved areas, constructed as sand drains, are placed around the perimeter or along the center of the bed to collect and convey drainage water under the bed, where it can be pumped back to the plant. The main advantage of paved beds is that heavy equipment can be used for dewatered cake removal, and the difficulties with sand and the underdrains is eliminated. On the negative side, pavement blocks drainage, requiring an increase in the total bed area to achieve the same results, and polymers may be needed to get most sludges to drain well. Figure 33.10 shows paved drying beds.

PROCESS VARIABLES. Similar process variables apply to all of the air-drying methods of dewatering. The performance of drying beds is affected by weather conditions, feed solids characteristics, system design, chemical conditioning, and the length of time before cake removal.

High temperatures, minimal rain, low humidity, and high wind velocities obviously improve drying. Conversely, cold, rain, high humidity, and little wind hinder drying. As a result of this weather dependency, either excess capacity must be built or the drying beds must be used to augment other disposal methods.

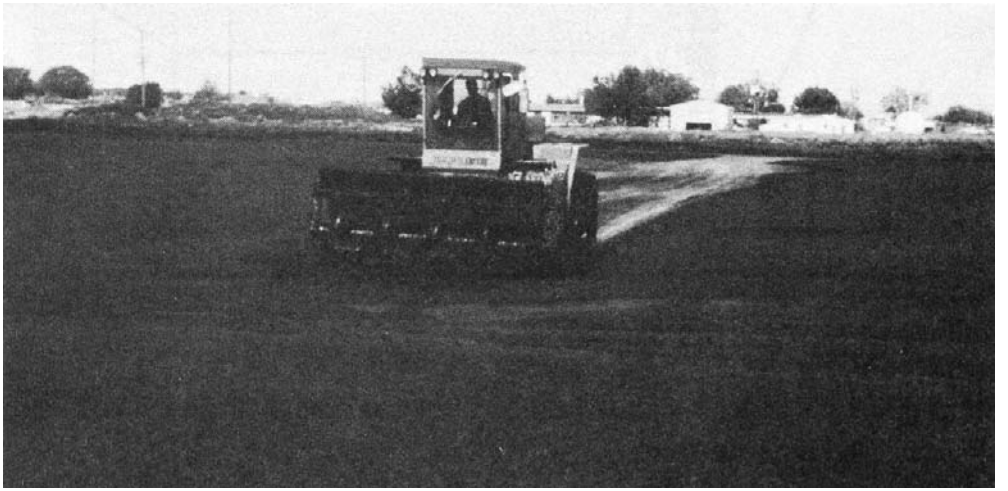


FIGURE 33.10 Paved beds.

FEED SOLIDS TYPE AND QUALITY. As with the mechanical dewatering process, the higher the proportion of secondary biosolids, the more difficult the biosolids will be to dry and the higher the chemical consumption will be. The process is broadly limited by the volume of water in the biosolids; the higher the solids concentration, the shorter the drainage and evaporation time to reach a given moisture level. Biosolids applied to drying systems are generally stabilized to class B solids to minimize odors.

SYSTEM DESIGN. The type of media, distribution of piping and drains, feed distribution system, and vacuum and pumping equipment can all affect the operation and maintenance of an air-drying system. The extent to which the system is isolated from the weather is also important.

CHEMICAL CONDITIONING. Polymer addition increases the drainage rate and volume, thus increasing the capacity of the beds and shortening the drying time. Other than reed beds and paved beds, most air-drying systems use at least some polymer. Polymer is always necessary for any filtration system.

PROCESS CONTROL—REED BEDS. A typical operating procedure (Fleurial, 2003) for reed beds is hugely simpler than other systems. Little is done from month to month. Once a year, the reeds are harvested, and, after 6 to 10 years of accumulation,

approximately 0.6 to 0.9 m (2 to 3 ft) of accumulated biosolids are removed with an excavator. Polymers are typically not used. The following are characteristics of reed beds:

- A new reed bed must be planted with rhizomes and kept wet until they sprout. Biosolids can be used to a depth of 25 mm (1 in.). When the reeds sprout, the beds can then be flooded with biosolids to a depth of 75 to 100 mm (3 to 4 in.). The shoots must not be submerged.
- Biosolids are reapplied every 2 to 3 weeks, depending on the weather.
- The beds simulate wetlands, and the plant roots must be kept wet by drainage from the biosolids or by adding plant effluent. The presence of weeds is an indication that the reeds are stressed.
- Red worms, among other types, are helpful in reducing the organic material.
- The reeds are typically harvested once per year in the late winter. A cycle bar mower is excellent, but, if the bed is too soft to support the machinery, a weed whacker fitted with a blade (rather than string) is used.
- The reeds should be removed from the bed, either by raking back from the edges and burning, where allowed, or by physically removing them.

The beds' ability to accept biosolids is much reduced during cold weather and during wet weather. After several years, the solids level in the bed will have risen, and the beds must be emptied. The full bed should lie fallow for 4 to 6 months. The biosolids do not typically support heavy equipment, unless it is frozen. If heavy equipment bogs down, it can damage the underdrain system and the liner; an excavator on the edge of the reed bed can easily dig the sludge, purposely leaving the lowest 15 cm (6 in.). Typically, sufficient plant material remains so that the reeds sprout and grow without the need for further planting.

The residual biosolids can be screened for a high-quality soil amendment or spread on agricultural land. Reeds are a marsh-dwelling plant and do not grow when spread on farm land. Reed beds require less capital cost, less land area, and are much less labor-intensive than other evaporative systems. In addition to such budget-friendly attributes, they blend in with the natural landscape. As for capital cost, everything that is needed is available as generic items, typically available locally. As a result of all of these features, reed beds are becoming much more common.

TROUBLESHOOTING. ***Sand Beds and Paved Beds.*** The operation of a sand or paved drying bed depends on the condition of the sand bed and underdrain, feed solids concentration, depth to which the feed is applied, loss of water through the underdrain system, degree and type of digestion provided, evaporation rate, type of

removal method used, and disposal method used. All these considerations determine the optimum loading for a given bed. The operator must be thoroughly familiar with the limitations of sand beds caused by the quality of the feed solids applied, conditioning effects on dewatering, and best methods of dealing with environmental conditions. Beds that use filtration as a mechanism are especially sensitive to the condition of the filtration media.

Table 33.4 presents a troubleshooting guide for sand beds that will enable the operator to identify problems and determine their solutions.

Sand Beds. The following are instructions for the use of sand beds:

- Remove weeds and debris;
- Add more sand if the beds are low;
- Rake and spread the sand evenly;
- Mix up polymer solution if used, and flood the bed to a depth of 150 to 300 mm (6 to 12 in.);
- Harrow the bed, if possible, to speed the drying;
- Allow to dry as desired, typically several weeks; and
- Carefully remove the dry sludge load into a truck.

Vacuum-Assisted Drying Beds. A typical operating cycle for a vacuum-assisted/wedge-wire drying bed is similar to that above, except for the following:

- At the start of the cycle, the vacuum pumps are off, the bed closure system is in place, the filtrate pumps are set for automatic operation, sufficient polymer is mixed or otherwise available, and drains in the bed are covered and sealed.
- The bed is flooded with water to a depth of 2.5 cm (1 in.) to assist in distributing the sludge evenly.
- The biosolids and polymer pumps are started, and the polymer addition is adjusted to give a robust floc. Biosolids depth varies, but is typically 900 mm (36 in.).
- Gravity drainage is allowed to continue until the operator decides that the rate of filtrate collection is too slow. Gravity drainage time may range from 30 minutes to several hours after the end of the application.
- The operator starts the vacuum cycle at the end of the gravity drainage. The vacuum sequence typically proceeds in discrete steps. The highest vacuum level continues until the cake has dried sufficiently to crack, with the resultant loss of system vacuum.

TABLE 33.4 Troubleshooting guide for sand beds.

Indications/ observations	Probable cause	Check or monitor	Solutions
Excessive dewatering time	Applied sludge depth is too great	Typically, 8 in.[a] of applied sludge is satisfactory	When bed has dried, remove sludge and clean; apply a smaller depth of sludge and measure the drawdown over a 3-day period; next application, apply twice the 3-day drawdown
	Sludge applied to improperly cleaned bed	Note condition of any empty beds	After sludge has dried, remove sludge; completely clean and rake surface of bed and replace with 0.5-1 in.[a] of clean sand, if necessary.
	Underdrain system has plugged or lines are broken		Backflush beds slowly by hooking clean water source to underdrain piping; check sand bed and replace media as needed; drain underdrain lines during cold weather to keep them from freezing
	Beds undersized	Effects of adding polymer	Typically 5–30 lb/ton[b] of dry solids of cationic polymer provides improved dewatering rates
	Weather conditions	Temperature, precipitation	Cover or enclose bed to protect from weather
Sludge feed lines are plugged	Accumulation of grit and solids in lines		Open valves fully at start of sludge application to clean lines; flush lines with water if necessary
Thin sludge being drawn from digester	Coning occuring in digester with water being pulled out and sludge left being		Reduce rate of withdrawal from digester
Flies breeding in sludge beds			Break sludge crust and use larvicides such as borax or calcium borate or kill adult flies with suitable insecticide
Odors when sludge is applied	Inadequate digestion of sludge	Operation of digestion process	Establish correct operation of digestion process
Sludge is dusty and crumbles	Excessive drying	Moisture content	Remove sludge from bed when it dries to 40–60% moisture content

[a]in. × 25.4 = mm.
[b]lb × 0.453 6 = kg; ton × 0.907 2 = Mg.

- An optional evaporation phase may be necessary to produce a liftable cake, typically requiring a minimum solids concentration of 10 to 12%. The time required for evaporation varies on a site-specific basis.
- A small tractor equipped with turf tires and front-loading bucket removes most of the cake. The front-end loader cannot completely remove all the cake. The small amount left on the bed requires manual removal with a shovel or scoop. Thorough removal is essential to prepare the media plates for final cleaning.
- Manual rinsing with a hose and nozzle begins at the end of the bed farthest from the drains and progresses toward the drains, recycling any remaining biosolids. Tile plates will have to be removed every so often to hose out the filtrate channels.
- A cycle without air-drying takes 8 hours and fully occupies one operator.

Two sources of problems are improper conditioning and improper plate cleaning. The wrong type of polymer, ineffective mixing of the polymer and biosolids, and incorrect dosage result in poor performance of the bed. Overdosing of polymer may lead to progressive plate clogging and the need for special cleaning procedures to regain plate permeability. Plate cleaning is critically important. If not performed regularly and properly, the media plates are certain to clog, and the beds will not perform as expected. Special cleaning measures, which are costly and time-consuming, are then required.

MECHANICAL DEWATERING EQUIPMENT

GENERAL. Before the development of organic coagulant polymers, vacuum and pressure filters were the only useful mechanical dewatering systems. They used large amounts of ferric chloride, lime, and other inorganic filter aids to condition the biosolids and improve their filterability. While a few advances have been made on such filtrations systems over the years, vacuum and pressure filters are only considered for peculiar plant requirements. They have largely been supplanted by BFPs and centrifuges. The end of dumps and the development of landfills raises the disposal cost to the point where it dominates the equipment selection. Better organic polymers have supported these changes. Generally speaking, as the polymer dosage increases, the cake dryness increases. Thus, the savings achieved by drier cake are partially offset by higher polymer costs. Likewise, higher feed rates result in wetter cake, so that higher capital costs are balanced by the benefits of drier cake. Nearly all dewatering systems are purchased based on a present-worth analysis, which seeks to find the lowest cost dewatering system for the planned design life.

DEWATERING CAPABILITY OF DEWATERING EQUIPMENT. Former editions of this book listed the performance claimed by various manufacturers for their dewatering equipment. Because the equipment varies so much and the biosolids were so ill-defined, the resulting numbers were misleading, at best. Operators interested in the capabilities of their present or future equipment are advised to request references from the various manufacturers. Check these references assiduously. Do not assume the engineer will do it. Be charitable if the phone numbers that are given are not current; area codes and telephone systems are constantly changing. Make a checklist of questions to ask each reference. Confirm who is being spoken to, and who their employer is. If possible, visit the actual plants. Unfortunately, the endorsement the plant operators tell a casual inquirer over the phone may be different from what is told to another operator one-on-one. Ask about the precise model of the equipment and especially about the biosolids process. If the equipment of interest is not what the reference has, it is a problem. If the biosolids and plant operation are not the same as your plant, then the references are different from the specific case and are suspect. It is much easier to avoid buying a poor performing piece of equipment than it is to get rid of a poor performing piece of equipment once it is installed in the plant.

INSTALLATION CONSIDERATIONS. Mechanical dewatering installations have a number of general requirements, which tend to be more important as the scale of the installation increases; for example, traveling bridges with electric hoists are very common on large installations and less often on small ones. Other features are universal. Following is an installations checklist:

- It is important that operators and maintenance people be able to safely move around the equipment. This requires a minimum of 0.9 to 1.2 m (3 to 4 ft), and, if the equipment is elevated, then catwalks on all sides are in order.
- A sink with handwashing facilities should be centrally located on each operating floor.
- Process sample points are important. A feed sample before polymer addition, a cake sample, an effluent sample, and a polymer solution sample are all necessary. It is very useful for the operator to be able to see the effluent conveniently. Sample lines that run continuously are better than those that do not. Long runs of sample piping will clog, and a flush system should be hard-piped. Avoid flat runs, and try to make the sample lines self-draining.
- The clarified effluent from the centrifuge (and sometimes filters) can contain large amounts of foam. Therefore, the lines must be oversized and designed to avoid traps.

- Centrifuges must be vented to work properly. Poor venting can cause solids buildup in the casing, catch fire, and/or erode the bowl shell. The centrifuge is automatically vented if the centrate and the cake chutes are open to atmospheric pressure. If one or both are enclosed, then both must be vented to the same pressure with a negative draft.
- Centrifuges typically vibrate excessively when they need service. A vibration meter is essential to monitor the vibration. It is much more useful than a vibration switch that only shuts the centrifuge down.
- Flow meters are very useful, on both the feed line and the polymer line. The flow meter cannot give an accurate reading unless it is upstream of the polymer-addition points. Each dewatering device should have its own flow meters.
- Most manufacturers recommend several polymer-addition points. The system should be set up so that the operator can close the valve to one addition point with one hand while opening the valve to another addition point with the other hand.
- From time to time, biosolids will spill on the floor and be hosed to the floor drains. With a bit of thought, the drains can be placed where it will be easy to direct the biosolids. The drains need to be of sufficient size (15 to 20 cm [6 to 8 in.]), so they will not plug readily.
- Centrifuges often spill liquid biosolids out of the solids end upon startup. The installation should use a knife gate or a reversing screw conveyor to contain the wet material.
- The best feed pumps for the feed biosolids and polymer are positive-displacement pumps. It is important to minimize the shear to both the polymer and the biosolids. Very large installations sometimes use a variable-speed centrifugal pump to charge a manifold with feed biosolids, with flow-control valves for each dewatering device. This works well as long as the pump speed is at a minimum and all of the flow control valves are 60 to 80% open. Pulsations in flow are not good and should be minimized.
- The control room for centrifuges does not need to be on the same floor as the centrifuges as there is nothing to see there. It is more convenient to be on the floor below where the effluent and cake are readily accessible.
- The control room for filters should be on the same floor as the filter because visual inspection of the filter is important.
- Biosolids often release hydrogen sulfide. In addition to the very serious health hazard to operators, even very low levels of hydrogen sulfide corrode copper electrical wires, contacts, and air conditioning coils. Both the operators and the controls need to be protected from hydrogen sulfide.

- Management should be sure safety devices are readily available and that operators use them. Ear plugs should be available in noisy environments. Nitrile, vinyl, or latex gloves are now standard protection when handling biosolids and need to be conveniently available if they are to be used.
- Lifting requirements. The instruction book typically gives the component weights of the equipment. The most versatile and most expensive is a traveling bridge crane. Sometimes, a monorail can be substituted if the principal lift points are in a row. Smaller installations may be well served with an A-frame. Anything over 0.9 to 1.8 Mg (1 to 2 tons) should have an electric hoist, especially if it will be lowered to the floor below. Fork lifts are not precise enough to be a good substitute for a hoist.
- The polymer area may require lifting equipment if drums or totes will be used.
- All plants should have flow meters on the polymer lines. This is especially important during polymer trials, where it is critical to measure the polymer rate.
- A facility that normally operates several dewatering units at once should have a provision to make-down and pump a trial polymer to just one unit.
- Maintenance should have a cabinet with dust-tight doors to store special tools for the disassembly of equipment.
- Consider having a storage room for spare parts in the dewatering building.
- Ventilation is important. Consider a two-mode operation—one level for operators who are only occasionally in the dewatering room, and a higher ventilation standard when someone is working in the room continually.

BIOSOLIDS FEED-PUMP CONSIDERATIONS. Aside from cost, there are two general considerations for pumps feeding dewatering devices.

1. Pumps can produce pulsations in flow and
2. Pumps can shear the biosolids.

The ideal pump would produce a steady, uniform flowrate, with little or no shear. Uniform flowrate is important because one is trying to add polymer at a constant dosage, which clearly is a problem if the feed flow is not uniform. A second problem with pulsing flow is that it causes surges in flow through the dewatering equipment. This aspect is less of a problem with filters, which have some buffering capacity in the thickening, gravity, and wedge sections, than with centrifuges that have no buffering. In the case of a piston pump, during the push stroke the flow to the dewatering device surges, but, when the piston returns, the flow stops completely. As a result, the peak flow is approximately double the average flow. This makes it impossible to meter

polymer accurately to the biosolids. Generally, pumps with check valves (piston and diaphragm pumps) are the worst offenders because the pumps operate at low speeds. As the pump speed increases, the pulsation frequency also increases, and the difference between peak flow and minimum flow is easier to dampen.

The following evaluation of pumps for belt presses and centrifuges is based on the pulsation characteristics of the various pumps. It is not an absolute judgment.

- Centrifugal pumps recommended, except for shear (see below);
- Diaphragm pumps not recommended;
- Double disc pumps okay;
- Peristaltic pumps marginal;
- Piston pumps not recommended;
- Progressive cavity pumps okay; and
- Rotary lobe pumps okay.

Shear is another matter. The assumption is that shearing the biosolids before dewatering results in the break up of the natural floc, which, in turn, requires additional polymer to build the floc back up. Positive displacement pumps are generally low-shear devices and thus are generally recommended. Centrifugal pumps have a very uniform flowrate, but are more likely to shear the biosolids. The worse case is an oversized centrifugal pump operating at fixed speed, with a flow control valve to throttle the discharge, to maintain the flow set point; both the pump and the valve shear the biosolids. A better case would be to have a flow meter control the pump speed. In this manner, the flow control valve is eliminated, and the pump shear is at a minimum. Alternately, the pump speed could charge a manifold, such that at least one flow control valve off of the manifold is 85% open.

CONVEYANCE OF DEWATERED BIOSOLIDS. Once the biosolids leave the dewatering device, the designer is faced with transporting them to the next stage, towards ultimate disposal. The only advice is that simpler is better. A transport path that goes around several corners and rises 6 m (20 ft) in the air will be a difficult system to design and will therefore be expensive to build and costly to maintain. Some specific considerations are the following:

- Dewatered biosolids that free-fall from any significant height will splatter, at least some of the time. This is never a good thing.
- All dewatering devices will put out wet slop from time to time. The biosolids transport system must be designed to handle this.

- Avoid going around corners whenever possible.
- Avoid steep changes in elevation.
- Points of transfer from one conveyor to another are often problem areas.
- All moving parts will eventually need to be replaced. Plan for it in the design.
- Vertical screws and steeply inclined belts work most of the time.

The dewatering operation is at the end of the treatment process. Mistakes and problems upstream come to rest here and ensure that, at least some of the time, the cake volume and texture will be nowhere near that envisioned in the design. Versatility and overdesign is the only solution. Visit other plants and ask questions of the people who work with their design. Be vocal if trouble is foreseen as a result of a proposed design.

ADDITIVES. From time to time, various additives are used to improve the biosolids or mitigate problems. Shredded newsprint, coal, sand, and inorganic chemicals have all been added for one reason or another. Defoamers may be needed to reduce the foaming of the centrate/filtrate, odor control chemicals to reduce those complaints, and oxidants to reduce hydrogen sulfide. Perfumes attempt to conceal the underlying odors; oxidants, such as potassium permanganate and hydrogen peroxide, react chemically with hydrogen sulfide in the sludge and therefore make the environment safer for the operators and reduce the odor. The great majority of plants do not use additives. Many or most of the problems for which these additives are prescribed are really caused by poor operation (or design) in the plant. Obviously, it is preferable to correct the root problem rather than spend money daily to minimize the effect of the problem.

GENERAL CALCULATIONS FOR MECHANICAL DEWATERING. The general calculations for mechanical dewatering are based on analytical analysis of the various streams around the centrifuge. Sample-taking is addressed elsewhere, but one point should be emphasized here: If a sample of the feed biosolids is being sent to the laboratory, avoid sending one where the polymer has already been added. The laboratory must extract a representative sample of the biosolids from the jar full of floc and free water that was sent to them. It is very difficult to get a representative sample out of a biosolids–polymer mixture. Try to pull a valid sample of the feed upstream of the polymer addition.

Nomenclature. By custom, lowercase letters refer to concentrations, and uppercase letters refer to flowrates. For example, in U.S. customary units, a feed rate of 120 gpm

of 2.5% solids biosolids would be expressed as $F = 120$ gpm and $f = 2.5\%$. The dry solids would be expressed as concentration times a flowrate, or

$$\text{Solids loading} = f \times F \; 2.5\% \times 120 \text{ gpm} \times \frac{1}{100\%} \times \frac{60 \text{ min}}{\text{hr}} \times \frac{8.34 \text{ lb}}{\text{gal}} \times \frac{1 \text{ ton}}{2000 \text{ lb}} = 0.75 \text{ tons/h DB (0.7 Mg)} \quad (33.1)$$

Another convention is to refer to the clarified liquid as the effluent, rather than centrate, filtrate, or clarifier overflow. Around all unit processes, two mass balances can be drawn.

Conservation of dry solids; solids in equals solids out:

$$fF = sS + eE \quad (33.2)$$

Conservation of mass; the weight of biosolids in must equal the weight of biosolids out:

$$F = S + E \quad (33.3)$$

where (in U.S. customary units)

F = feed rate, gpm (120 gpm);
f = feed concentration, % (2.5%);
S = solids or cake rate, gpm;
s = solids or cake concentration, % (20%);
E = effluent rate, gpm;
e = effluent concentration, % (0.15%); and
P = polymer rate, gpm (15 gpm).

Other units can be used for concentration and rate, as long as they are consistent. Further, *recovery* is defined as the percentage of dry solids removed in the dewatered solids, divided by the amount of solids in the feed. Or,

$$\text{Recovery} = \frac{sS}{fF} \times 100\% \quad (33.4)$$

Solving Equations 33.2 and 33.3 for E, the effluent rate, and rearranging the result in terms of sS/fF, the percent recovery can be calculated entirely in terms of the feed, effluent, and solids analysis; the feed and other rates do not enter into the calculation at all.

$$\%\text{ Recovery} = \frac{s(f-e)}{f(s-e)} \times 100\% = \frac{20\%(2.5\% - 0.15\%)}{2.5\%(20\% - 0.15\%)} \times 100\% = 95\% \quad (33.5)$$

As a quick logic check, if there are no solids in the effluent, then $e = 0$, and the recovery is 100%. At the other extreme, if the effluent concentration equals the feed concentration, the term $(f - e)$ in the numerator goes to zero, and therefore the recovery is zero. This formula is good for the capture across clarifiers, thickeners, and mechanical dewatering devices. It does not matter what the units for rate and concentration are, as long as they are the same.

Equations 33.2 and 33.3 can be combined with the feed rate and rearranged to allow the calculation of the effluent rate and the solids rate, as follows:

$$\text{The cake rate is } S = F\frac{(f-e)}{(s-e)} = 120 \text{ gpm}\frac{(2.5-.015\%)}{(20\%-0.15\%)} = 14 \text{ gpm of cake} \qquad (33.6)$$

$$\text{The centrate rate is } \mathrm{E} = F\frac{(s-f)}{(s-e)} = 120 \text{ gpm}\frac{(2.5-2.5\%)}{(20\%-0.15\%)} = 106 \text{ gpm of effluent} \qquad (33.7)$$

Not mentioned here is the effect of polymer and rinse water. Commonly, if the volume of polymer or rinse water is less than 10% of the feed solids, the dilution effect is ignored. Similarly, the effect of polymer solids is also ignored, because it is very small compared with the feed solids. Where dilution resulting from polymer water or rinse water is important, the easiest way to compensate for it is to adjust the feed or effluent concentrations before calculating the percent recovery. For example, if F, the feed rate, is 120 gpm, and P, the polymer rate, is 15 gpm, the feed analysis, f_m, measured at 2.5%, can be corrected to take into account the dilution caused by the polymer and determine the calculated feed, f_c, as follows:

$$f_c = F_m\frac{F}{F+P} \qquad (33.8)$$

Using the numbers above, we obtain: $f_c = 2.5\%\dfrac{120 \text{ gpm}}{120 \text{ gpm} + 15 \text{ gpm}}$

where

f_c = corrected feed concentration,
f_m = measured feed concentration, and
P = polymer rate (including any post-dilution).

For a given centrate concentration, the effect of any dilution water is to reduce the recovery level. Similarly, if the effluent is diluted by rinse water, as is commonly the case with

a BFP, the measured effluent concentration will be lowered as a result of the dilution. If the press feed, F, is 120 gpm, and the belt wash water rate, W, is 100 gpm, with the feed concentration at 2.5%, dewatered cake at 20%, and effluent measured as 0.15%, then the formula to correct the effluent concentration for the effect of wash water is as follows:

$$e_c = e_m \frac{E + W}{E} = 0.15\% \frac{106 \text{ gpm} + 100 \text{ gpm}}{106 \text{ gpm}} = 0.29\% \tag{33.9}$$

where

e_c = corrected effluent concentration,
e_m = measured effluent concentration,
E = effluent rate (Equation 33.6), gpm; and
W = wash water rate, gpm.

Using the numbers given above, taking the wash water into account nearly doubles the effluent concentration and therefore reduces the capture from 95 to 90%.

Polymer Dosage. The last formula is the calculation of the polymer dosage. While it makes some sense that the dosage should be calculated as the amount of polymer required to remove 0.9 Mg (1 ton) of solids, that is not how it is defined; it is the amount of polymer per Mg (ton) of feed solids. The formula is commonly expressed as two ratios, followed by a constant.

$$\text{Polymer dose} = \frac{\text{polymer concentration}}{\text{feed concentration}} \times \frac{\text{Polymer rate}}{\text{Feed rate}} \times 2000 \text{ lb/t} \tag{33.10}$$

For metric calculation, substitute the metric 1000 kg/t for the U.S. customary term. The advantage of this formula is that any units can be used for rate (as long as the units are the same for both the feed and the polymer). Using the numbers given earlier (120 gpm of feed, 15 gpm of polymer, 2.5% feed solids, and assuming 0.12% polymer concentration), the following can be calculated using Equation 33.10:

$$\text{Polymer dose} = \frac{0.15\%}{2.5\%} \times \frac{15 \text{ gpm}}{120 \text{ gpm}} \times 2000 \text{ lb/t} = 15$$

The same formula is also used for jar testing, when the sample volume of feed and the sample volume of polymer are substituted for the rate terms. Supposing the same poly-

mer and the same feed solids are used, 15 mL of polymer solution could be added to a 120-mL sample of biosolids, and the very same 7.5-g/kg (15-lb/ton) polymer dosage would be used as was being used on the machine.

BELT FILTER PRESS. This section describes the process variables that affect the dewatering process, operation, and maintenance required to run a BFP in optimum condition. Figure 33.11 is a typical process flow diagram of a BFP.

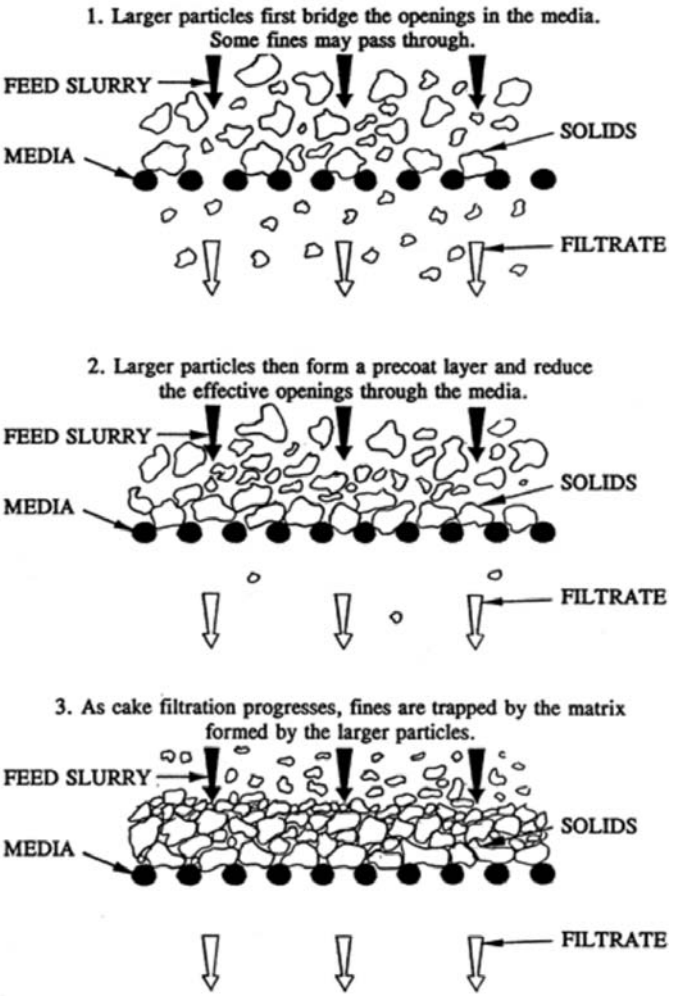


FIGURE 33.11 Filtration process.

Principles of Operation. The operation of a BFP is based on the principles of filtration and comprises the following zones:

- Gravity drainage zone, where the feed is thickened;
- Low-pressure zone; and
- High-pressure zone.

Figure 33.12 illustrates a BFP and the different zones encompassed in the system. In the gravity zone, most of the free water from the flocculation process drains through a porous belt. This is followed by the low-pressure zone, where the thickened feed is subjected to low pressure to further remove water and form a viscous biosolids matrix. In the high-pressure section, the matrix is sandwiched between porous belts passing through a series of decreasing diameter rollers. The roller arrangement progressively increases the pressure, filtering more water from the matrix. There are numerous design differences between the various manufacturers, mostly varying in the relative sizes of the different zones.

Generally, because the operator can see into the press, it is easy to determine what is happening, and the press is therefore easy to operate. Belt filter presses are very quiet,

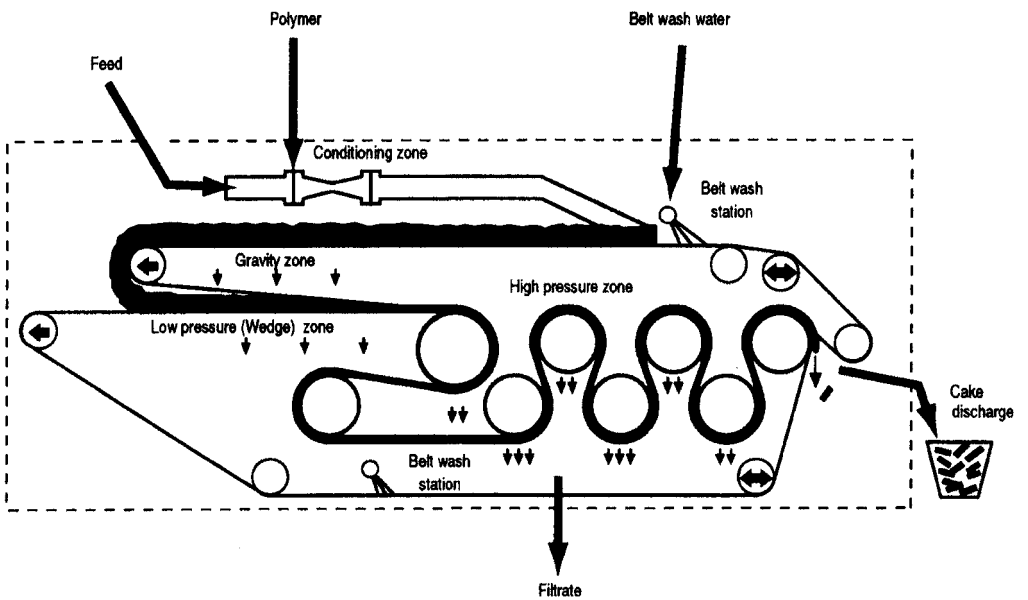


FIGURE 33.12 Belt filter press process flow diagram.

with low power consumption. Also, mechanical failure is easy to recognize, and, while the fix may be time-consuming, it is typically not difficult or expensive, as many parts can be obtained from local suppliers or manufactured locally, making presses relatively inexpensive for mechanics of average skills to repair or overhaul on-site. Negatively, they are messy, odorous, require significant operator attention, and are not very versatile.

Process Variables. There are several process variables that affect the performance of all dewatering systems. In general, dewatering devices must run at 95% capture or better, so capture really is not an operating variable. Of the remaining parameters—cake dryness, loading, and polymer dosage—within limits, the operator can take from one to give to another. For drier cake, one can reduce the loading and/or increase the polymer dosage.

Biosolids Type and Quality. As discussed earlier, the operation of the wet end of the plant determines the quality of the biosolids, which, in turn, greatly affects the dry end.

Polymer Activity. Polymer is selected once per year, but biosolids often change during the course of the year. If the polymer does not react well to the biosolids, performance suffers.

Polymer Addition and Mixing. Most presses have some sort of inline mixing system, which adjusts the amount of mixing given the sludge/polymer. Adding the polymer closer or further from the press can also affect performance.

Cake Dryness. Increased cake dryness comes at the price of lower capacity and/or higher polymer dosage. The ability to obtain higher cake dryness is, to a great extent, a function of the design of the press. Presses with extended gravity zones to better preconcentrate the feed and additional pressure rollers give longer sludge residence times and dryer cake.

Polymer Type and Dosage. Some polymers are designed to obtain drier cakes than others. Likewise, the dosage will increase and decrease with the cake dryness. Some polymers become less effective at higher dosages. This will be apparent from a quick jar test or observing that adding more polymer results in either poorer operation or the same operation.

Hydraulic Loading. Belt filter presses are limited by the volume of water that can go through the belts. As a result, thinner feed solids will result in less quantity of dry solids produced, with all else being equal.

Solids Loading. Likewise, more solids will result in less solids residence time inside of the press and therefore wetter solids, with all else being equal.

Capture. The solids capture is typically fixed by the plant management and is not an operating variable.

Mechanical Variables. Mechanical variables that affect BFP performance include the following:

- Belt composition and condition, speed, and tension;
- Size and number of rollers;
- Feed concentration;
- Polymer concentration;
- Polymer addition and mixing;
- Wash water flow and pressure; and
- Wash water suspended solids concentration,

Operation of the BFP should be monitored with data sheets, such as the one shown in Table 33.5 (BFP spreadsheet). If these data are taken frequently, it is easy for the operator to change one variable at a time to optimize the performance of the BFP. The spreadsheet calculates the cost of disposal, in U.S. dollars per dry ton. This keeps everyone informed of the goal of the dewatering operation. In addition, if further help is required, this is valuable information to aid in troubleshooting of the process.

Sequence of Operation. The sequence of operation for a BFP typically is set up in the following order:

1. Open wash water valve,
2. Start wash water pump,
3. Start pneumatic/hydraulic belt tension system,
4. Start belt drive and dewatered cake conveyor,
5. Start polymer solution feed pump, and
6. Start biosolids feed pump.

Modern presses typically have a one-button start system, so the operator only has to manually start the feed and polymer pumps. In any event, one benefit of filling out the operating log is that the operating conditions the last operator used are known, as are the conditions of the previous week and month.

The BFP is equipped with a series of alarms that shut down the unit if one of the following situations arise:

- Belt breakage,
- Belt misalignment,

TABLE 33.5 Belt filter press data sheet.[a]

Name of plant: _____ Telephone: _____
Address: _____ Date: _____
Sludge type: _____ Blend: _____
Contact name: _____ Press size:_____ (m)

Run #	1	2	3	4	5
Time (HH:MM)					
Feed pH					
Feed temperature, °F					
Feed alkalinity, mg/L					
Feed ash content, %					
Feed solids, % TS[b]					
Hydraulic loading (gpm)					
Solids loading, lb/hr					
Cake solids, % TS					
Cake thickness, in.					
Polymer type; dry, liquid					
Polymer number					
Polymer solution concentration, % TS					
Polymer flowrate, gpm					
Polymer dose, lb/ton					
Filtrate flow, gpm					
Filtrate TSS,[c] mg/L					
Inline mixer size, in.					
Retention time, sec					
Capture, %					
Belt type					
Belt speed, m/min					
Hydraulic pressure, psi					
Wash water pressure, psi					
Wash water flow, gpm					
Wash water TSS, mg/L					

[a]1 m^3/h = 4.4 gpm; 1 kg = 2.204 lb; 1 ton = 2 000 lb; (°F – 32)0.555 6 = °C; 1 psi = 6 893 Pa; 1 lb/ton = 0.5 g/kg; 1 metric ton = 1.1 ton; 1 m = 39.37 in.
[b]TS = total solids.
[c]TSS = total suspended solids.

- Hydraulic or pneumatic unit fault,
- Low wash water pressure,
- Emergency cord surrounding the BFP is pulled,
- Stop button in the BFP panel is pressed,
- Solution polymer feed pump failure,
- Conveyor shutdown/storage bin overfilling,
- Biosolids feed pump failure, or
- Dilution water failure.

Belt Filter Press Optimization and Troubleshooting. After the cake solids, solids loading, and capture rate have been specified, adjustments are made to the BFP dewatering process and the polymer system to achieve those values. After the BFP is in operation, the approximate cake solids can be determined quickly (approximately 10 minutes) with a high-energy microwave oven or other such device.

If the belt wash water is included in the filtrate sample, then the actual filtrate analysis is diluted by the belt wash water and needs to be taken into account in calculating the capture. From a practical standpoint, the experienced operator can judge the cake and filtrate quality quite well by eye, and laboratory testing is used to confirm his or her estimate.

The computed values should be compared with the values previously achieved by the BFP operation. If low cake solids, low capture, low solids loading, or high polymer dosage are obtained, the following procedures illustrate some measures that can be taken to improve the process.

All filtration devices are sensitive to the amount of water that can filter through the cake. Generally, thicker feed dewaters better than thinner feed material. Increasing the polymer can sometimes compensate for poor process results caused by thinner feed solids.

As with other devices requiring polymer, problems in the polymer make-down system can also lead to problems in dewatering. Belt filters benefit from a polymer injection ring and some sort of mixing device. The injection ring is a spool piece with six or eight hoses adding the polymer around the circumference of the feed pipe. The hoses carrying the polymer to the ring occasionally plug with solids and need to be cleaned. When some of the hoses plug, the polymer is poorly distributed and, if uncorrected, require excess polymer. The mixing device is a weighted check valve, creating an adjustable amount of turbulence. More elaborate devices include static or mechanical mixing. Trial and error is necessary to determine the best setting of the mixing device. As with all optimization, the "best" setting often changes with the sludge, the polymer, or the dewatering goals.

Low Cake Solids. To improve this situation, the following steps can be taken:

- Adjust belt speed. The belt speed should be decreased in small increments (approximately 10%), to increase cake thickness. A thicker cake increases the shear rate exerted by the outer belt on the cake as it goes around the pressure rollers in the high-pressure zone. Let the BFP stabilize for 15 to 20 minutes, take a cake sample, and compare it with the previous cake solids reading.
- Adjust polymer flow/polymer dosage. A small increase in polymer dosage could result in faster drainage in the gravity zone, and less water to remove through the belts will produce a drier cake. This does increase the operating cost. Excessive polymer can slime the belts, halting dewatering, until the mess can be cleaned out. Thus, there is an upper limit to the effective use of polymer. Let the BFP stabilize for 15 to 20 minutes, take a cake sample, and compare it with the previous cake solids reading.
- Adjust hydraulic/pneumatic belt tension. Increase the belt tension in 10 to 15% increments. At some point, the higher pressure will press the biosolids into the belt weave, blinding the belts. Let the BFP stabilize for 15 to 20 minutes, take a cake sample, and compare it with the previous cake solids readings. Higher belt tension can shorten the belt life.
- Adjust the inline polymer mixer. The floc size is extremely important to the dewaterability of the sludge. The polymer dosage affects the mixing energy.

Low Capture Rate. This is typically caused by squeezing cake out from the lateral sides of the belts in the high-pressure zone. To correct this situation, the following steps can be taken:

- Adjust belt speed. Increase belt speed gradually until the cake ceases to squeeze out from the lateral sides of the belts. Let the BFP stabilize for 15 to 20 minutes, and take samples of the filtrate and cake solids.
- Adjust polymer flow/polymer dosage. A small increase (or sometimes decrease) in polymer dosage could result in faster drainage in the gravity zone, reducing the water content of the biosolids and allowing higher cake pressures in the high-pressure zone. Let the BFP stabilize for 15 to 20 minutes and take samples of the filtrate and cake solids.
- Adjust belt tension. Decrease belt tension gradually, until the cake stops squeezing out from the lateral sides of the belts. Let the BFP stabilize for 15 to 20 minutes, and take filtrate and cake solids samples.

Low Solids Loading.

- Make sure the gravity section support structure is clean. Solids built up on the wiper bars can lead to lower drainage rates.
- An obvious source of low solids loading is a decrease in solids concentration or flowrate of the biosolids feed. This can be corrected by taking a sample to determine the feed solids concentration and also checking the feed pump for wear or blockage.
- Less obvious is the gradual blinding of the belts. This can be the result of inadequate belt washing or chemical blinding. Manually cleaning the belts with a high-pressure hose may restore at least some of the drainage.

Maintenance. The following procedures will extend the life of the BFP and reduce its operating cost:

- Wash down the BFP every day after finishing the dewatering shift. This prevents cake from drying and accumulating in different sections of the BFP.
- Check to be sure all rollers are turning freely.
- Check the press weekly for damaged bearings.
- Check the grinder that prevents large particles from entering the press twice per year.
- Follow the manufacturer's operations and maintenance manual lubrication schedule. This extends the life of the roller bearings and belt drive motor.
- Clean the wash water nozzles as frequently as necessary (this depends on the quality of the wash water). This ensures proper cleaning of the belts.
- Inspect and change biosolids containment and washbox seals, as necessary.
- Inspect and clean doctor blades from any accumulated debris, hair, or any other foreign materials.
- Clean the chicanes (plows) in the gravity section after shutting down the press.

For any other maintenance of complex mechanical parts of the BFP, contact the manufacturer for advice.

Safety Considerations. The following guidelines should be implemented to avoid injuries:

- Watch out for spills of water, biosolids, and polymer; all are serious slip hazards.
- Do not remove solids or objects from the belts in the roller pressure section while the machine is in motion. If an object falls on the belts, try to stop the unit and remove it before it enters the roller pressure section.

- Never reach into an operating press with a hand.
- Adequate ventilation should be provided to avoid breathing hydrogen sulfide buildup. Also, the belt spray creates a lot of aerosols; the ventilation system should be maintained to keep them out of the room air. If the press is equipped with covers, keep them in place during operation. Some cover designs are better than others, and the cover design should be considered in any purchase decision.

DEWATERING CENTRIFUGES. This section describes the process variables that affect the dewatering process and the operation and maintenance required to run a centrifuge in optimum condition.

Principles of Operation. Centrifugation is the process of separating solids from liquids by the process of sedimentation, enhanced by centrifugal force. Thus, the plant thickeners and clarifiers, which also operate on the principle of sedimentation, are an accurate analogy to the centrifuge. In the clarifiers, feed flows across the surface of the clarifier to the discharge weirs. As feed flows across the surface, the solids settle out—first the larger and denser particles, and then the smaller and lighter ones. A rake turns slowly and pushes the solids to the discharge point. The rake is connected to a gear box, which, in turn, is driven by a motor. When the solids reach the discharge point, they accumulate, until the underflow pump removes them. The centrifuge is just the same.

The centrifuge (Figures 33.13 and 33.14) is a cylindrical drum that rotates at high speeds to develop centrifugal force. The force increases by the square of the bowl speed, so small changes in speed result in larger changes in centrifugal force. When a slurry enters the interior of a rotating centrifuge, it flows across the annular surface of the pool, to the discharge weirs (dams). As the liquid flows from the feed area to the weirs, the solids settle outward towards the bowl wall. The speed of the screw conveyor controls the discharge rate, which, in turn, determines the depth of the sludge blanket inside the centrifuge. The scroll drive motor is set to turn the scroll at a slightly different speed than the bowl and thus scrapes the solids along the bowl, up a conical section, and out of the centrifuge. This difference in revolutions per minute between the bowl and scroll is called the *differential speed* and serves the same purpose of controlling the biosolids blanket level in a centrifuge that the underflow pump does on a secondary clarifier. All centrifuges use some sort of device to drive the screw conveyor and also use some sort of variable-speed drive. The centrifuge has two motors—the larger one, called the *bowl drive*, which turns the bowl, and a smaller device, called the *scroll drive*, which controls the conveyor speed.

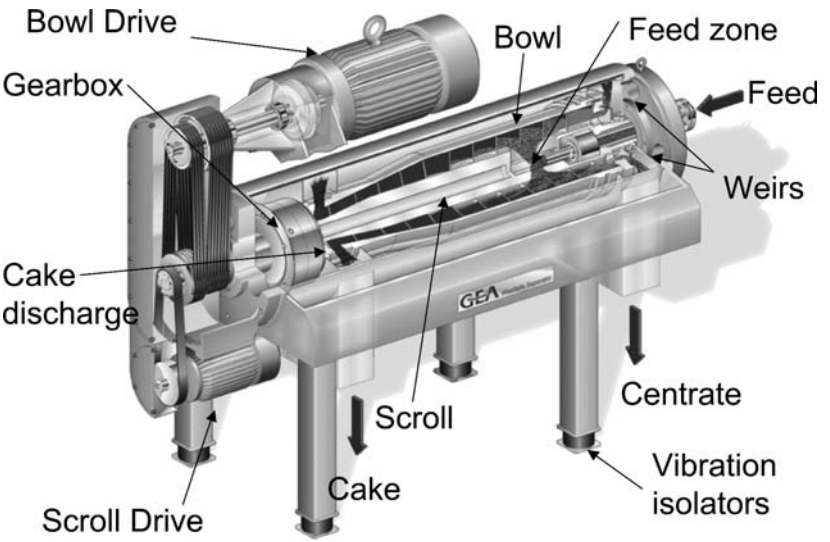


FIGURE 33.13 Centrifuge cutaway (courtesy of Westfalia Separator, Inc., Northvale, New Jersey).



FIGURE 33.14 Centrifuge disassembly (courtesy of Andritz, Arlington, Texas).

Traditionally, centrifuge illustrations suggest that the solids are scrolled out of the pool and drain on the beach area. This does not happen in wastewater processes. The pool level is at or above the solids discharge. There is no dry beach. Filtration is not a mechanism for dewatering in wastewater centrifuges—the only mechanism is sedimentation.

There are numerous design options within the centrifuge, as Figures 33.13 and 33.14 show. Manufacturers introduce these features to improve the product and provide product differentiation. Very few features are patented; therefore, the choice of design is open to all manufacturers. Manufacturing cost drives the design.

A centrifuge can thicken or dewater the biosolids with only a minor change in the weir setting (also called *pond setting*). Likewise, it can dewater biosolids to a moderate consistence at low polymer dose or produce very dry solids using higher polymer dosages. The centrifuge is a naturally sealed unit and is easy to connect to an odor control system. Centrifuges are unique in that the torque developed on the screw conveyor inside the centrifuge (when dewatering) is proportional to the cake viscosity plus assorted drag and mechanical inefficiencies. When the centrifuge is dewatering biosolids, the viscosity of the biosolids is large compared with the mechanical drag, so that, with most controllers, the operator can set a torque level and have the centrifuge operate at a fixed cake dryness. This makes automatic operation much simpler and reduces the need for supervision. Unfortunately, when the centrifuge is thickening a biosolids, the torque resulting from viscosity of the biosolids is small in comparison with the mechanical drag, so that autotorque does not work. An Andritz (Graz, Austria) centrifuge is depicted in Figure 33.14.

Centrifuges also have the reputation of being noisy and prone to vibrate, have weak gear reducers, and require frequent and expensive off-site repairs. To the extent that the manufacturer designs and manufactures them well, these problems are mitigated. Generally, it costs more to build a centrifuge with wear parts that can be easily removed when worn out, with new ones installed on-site. Similarly, hard surfacing materials with very long service lives cost more money than those that wear out quickly. It costs more to build a centrifuge that will operate for 20 000 hours or more with no mechanical failures than one that must be rebuilt every 6000 hours. On the other hand, dewatering will occur for 600 to 1000 hours per year, so a centrifuge that will operate for 6000 hours is not so bad.

Math Specific to Centrifuges. There are a few equations that are particularly useful with centrifuges. The centrifuges are rated by their manufacturer based on the specific gravity of the dewatered solids and the operating speed. The g force is a measure of the acceleration developed in the centrifuge and is proportional to the square of the

speed. The g force at the bowl wall of a 74-cm (29-in.) diameter centrifuge rotating at 2600 r/min is as follows:

$$\begin{aligned} g \text{ force} &= 0.0000142 \times (\text{r/min})^2 \times \text{diameter (in.)} \\ &= 0.0000142 \times (2600)^2 \times 29 \text{ in.} = 2784\, g \end{aligned} \tag{33.11}$$

This means that a 0.5-kg (1-lb) imbalance on the bowl wall would generate a force of 1263 kg (2784 lb) and create quite a bit of vibration.

Process Variables. There are several process variables that affect the performance of all dewatering systems. In general, dewatering devices must run at 95% capture or better, so capture really is not an operating variable. Of the remaining parameters—cake dryness, loading, and polymer dosage—the operator can take from one to give to another. For drier cake, one can reduce the loading and/or increase the polymer dosage.

Biosolids Type and Quality. As discussed earlier, the operation of the wet end of the plant determines the quality of the biosolids, which, in turn, greatly affects the dry end.

Polymer Activity and Mixing with the Biosolids. Polymer is selected once per year, but biosolids often change in the course of the year. If the polymer does not react well to the biosolids, performance suffers. Also, adding the polymer closer to or further from the centrifuge will affect performance.

Cake Dryness. Increased cake dryness comes at the price of lower capacity and/or higher polymer dosage. The ability to obtain higher cake dryness, to a great extent, is a function of the design of the centrifuge.

Polymer Type and Dosage. Some polymers are designed to obtain drier cakes than others. Likewise, the dosage will increase and decrease with the cake dryness. Some polymers become less effective at higher dosages. This will be apparent from a quick jar test or observing that adding more polymer results in either poorer operation or the same operation.

- Hydraulic loading. Centrifuges are less limited by the volume of water that passes through the centrifuge than filtration devices. As a result, thinner feed solids will have less effect on performance than in filtration devices.
- Solids loading. The solids residence time is important. If there are more biosolids to dewater, there will be less solids residence time and therefore wetter solids, with all else being equal.

- Capture. The solids capture is generally fixed by the plant management, and is not an operating variable.
- Sludge temperature. Centrifuge performance is linked to sludge temperature—warmer is better up to a limit of ~60 °C (140 °F).

Performance Level. Designing and building a centrifuge for high performance (i.e., dry cake and high hydraulic capacity) and long service life is expensive. There is a much greater probability that a more expensive centrifuge will have these attributes than will an inexpensive centrifuge.

Mechanical variables that affect the centrifuge performance include the following:

- Conveyor torque and/or differential speed,
- Bowl speed (within limits),
- Weir setting, and
- Polymer addition point.

Differential Speed—Scroll Torque. The scroll drive device allows the operator to change the differential speed between the bowl and the scroll (conveyor). Changing this differential speed changes the cake removal rate, which, in turn, changes the height of the solids blanket within the centrifuge, just as changing the underflow pumping rate changes the blanket level in a thickener. At low differentials, the biosolids blanket height increases, and the cake becomes drier. As the blanket rises, the solids may carry over into the centrate. The operator would respond by increasing the polymer rate to restore the centrate quality, or by increasing the differential speed to reduce the biosolids blanket. Similarly, increasing the differential speed increases the biosolids removal from the centrifuge and lowers the cake level. This results in wetter cake, but with cleaner centrate, allowing the operator to reduce the polymer rate.

Torque Control. In recent years, nearly all centrifuges have a controller that allows the operator to choose a scroll drive load or torque set point, and the controller then adjusts the differential speed to maintain that set point. In this manner, the torque and therefore the cake dryness is fixed. One way of looking at the centrifuge is that it is a very expensive viscometer. The conveyor is turning at a controlled speed immersed in biosolids. The effort or torque needed to turn the conveyor is measured by the scroll drive device. As the cake becomes drier, its viscosity increases, which, in turn, increases the torque or load on the scroll drive. When operating in load control, the controller automatically adjusts the differential revolutions per minute to maintain a constant torque level, and the operator's only task is to observe the centrate quality from time to time and adjust the polymer rate to maintain the desired centrate quality. This is a really simple control; one of its virtues is that the major operating cost—cake

dryness—is fixed, and any operator error shows up in the centrate, which is easy to see and is not so costly if it is off slightly.

Bowl Speed. Centrifuges have a nameplate speed rating for a particular solids density. Each speed corresponds to a particular *g* force, and it is *g* force that drives the separation. Generally speaking, when the bowl speed is increased from 1800 to 2000 *g*, to 2500 *g* and sometimes 3000 *g*, and the pond is properly set, the process performance improves. Unfortunately, the power consumption, shear on the biosolids, erosion, noise, and vibration also increase with *g* force. The power consumption goes up proportionally to the *g* force. However, most centrifuges currently sold typically operate above 2000 *g*. Often, the centrifuge is operating at a lower speed than that for which it is rated because it is not designed to run continuously at the higher speed without excessive, noise, vibration, and maintenance. In theory, raising the *g* force should raise the centrifuge performance. Consult the manufacturer of the centrifuge for a recommendation on operating speed changes.

Weir Setting. The weir setting is a somewhat misunderstood operating variable. Considering the pool surface (the liquid–air interface within the centrifuge), raising the pool surface reduces pond radius and thus reduces the surface area of the pool where separation takes place. That this will give better centrate quality and the same or dryer cake is counterintuitive, but true. The drawback to operating with a deep pond is that liquid pours out of the centrifuge upon startup, and, the deeper the pond, the longer it takes to "make seal," which is the term for the discharge from the solids end to transition to dewatered cake. Do not assume that the pond setting on the centrifuge is the best one to use. Each year or two, try changing the pond up and down by approximately 4 mm to see which setting is best.

Polymer Addition Point. Most manufacturers recommend at least four polymer addition points. In general, if the polymer forms very weak floc, then closer to the centrifuge is better. The stronger the reactions are between the polymer and the biosolids, the further upstream (ahead) of the centrifuge the polymer should be added. As a general recommendation, addition points should be 20 to 30 m (60 to 75 ft) ahead of the centrifuge, 12 m (25 ft) ahead of the centrifuge, just in front of the flex coupling to the feed tube, and internal to the centrifuge. Some centrifuges have the feature of adding polymer inside the centrifuge, either in the feed zone or into the pool area. It is important to make the polymer additions convenient to use. The best design uses a manifold with valving for several addition points next to one another.

Operation. The operation of the centrifuge should be monitored with data sheets similar to that shown in Table 33.6. In a well-designed installation, the SCADA system

TABLE 33.6 Centrifuge data sheet.

Owner	Marion Haste WWTP
Sludge	Anaerobically Digested
Centrifuge	Bio Boogey 44
SERIAL NO:	93-DDN2500
Poly Type	Flocking Good FG1

Date	Run No.	Pond No.	Bowl Rpm	Delta Rpm	Feed Rate GPM	Feed Conc. %SS	Eff. Conc. %SS	Cake Conc. %TS	Feed tons/hr	Wet Cake tons/hr	Dry Cake tons/hr	Poly Conc. %	Load %	Poly Rate GPM	Poly Dose #/TDS	REC. %
3/4	1	14.7	2600	3.3	120	2.4	0.35	21	0.7	3.0	0.63	0.20	25	12.7	17.6	86.9
	2	14.7	2600	2.9	120	2.4	0.08	21	0.7	3.3	0.70	0.20	25	12.7	17.6	96.9
	3	14.7	2600	2.7	120	2.3	0.07	23.5	0.7	2.9	0.67	0.20	35	14.3	20.7	97.2
	4	14.7	2600	2.5	120	2.35	0.14	24.5	0.7	2.7	0.67	0.20	39	16.6	23.5	94.6
	5	14.7	2600	2.4	120	2.3	0.19	25.5	0.7	2.5	0.64	0.20	41	18.5	26.8	92.4
	6	14.7	2600	2.3	120	2.25	0.17	26	0.7	2.4	0.63	0.20	47	20.3	30.1	93.1
	7	14.7	2600	2.9	120	2.3	0.08	26.3	0.7	2.5	0.67	0.20	55	22.8	33.0	96.8
	8	14.7	2600	2.7	120	2.1	0.10	26.8	0.6	2.2	0.60	0.20	64	22.5	35.7	95.6

would store the data and automatically calculate the capture, polymer dosage, and dewatering cost. In addition, if further help is required, these sheets provide a ready record to aid in troubleshooting of the process.

Sequence of Operation. Because centrifuge construction and components vary, the manufacturer should be consulted for specific startup instructions. The following considerations apply to most units:

- Confirm operation of biosolids pumps, the polymer system, dewatered cake conveyor, and centrate return pumps.
- Open such valves as will enable polymer and feed biosolids.
- Press start button. Clear the alarm panel.
- When the centrifuge transitions from start to run, set the differential at minimum speed.
- Start the polymer and the feed at 25% of normal flow.
- When the centrifuge seals, increase the feed and polymer to 60% of normal flow, and change operation to load control.
- When the centrifuge reaches equilibrium, increase the feed and polymer to normal rates.
- In many installations, the centrifuge can be started in load control without causing torque trips. It is quicker to reach steady-state conditions in speed control.

The centrifuge is typically equipped with the following alarms:

- High torque alert and high torque alarm,
- High vibration alert and high vibration alarm,
- High bearing temperature,
- High motor temperature,
- Pump failure, and
- Biosolids conveying failure.

Furthermore, there is often an interlock to prevent the centrifuge from starting when the cover is open.

During operation, the operator should check for the following:

- On circulating oil systems, check the oil level and the flow of oil to the bearings;
- Flow of cooling water and oil temperature, to ensure it is operating in the proper range;

- Machine vibration;
- Ammeter reading on the bowl motor;
- Bearings for unusual noise;
- Bearing temperatures, by touching them;
- System for leaks;
- Centrate quality; and
- Scroll drive torque.

Because the centrifuge will shut itself down in the event of a fault, the operator typically only looks at the mechanical parameters once per shift.

Centrifuge Data Sheet. The centrifuge operation will be much better if the operators fill out the centrifuge data sheet (Table 33.6) once per shift. To be useful, an interactive spreadsheet is needed, to which operators enter raw data and the program performs calculations including disposal cost, polymer use cost, and total cost. There is value in the operators seeing the cost of dewatering for themselves and also for others.

Temperature Effects. Centrifuges operate on the density difference between solids and liquids. As the temperature rises, the density of water decreases. The density of the solids is not very affected by temperature. Numerous tests have shown that every increase of 5 °C (9 °F) raises the cake solids by 2 percentage points. The upper limit is approximately 60 to 65 °C (140 to 150 °F) when the polymer begins to break down. The BOD in the centrate edges up also, but not to the point of causing unnecessary concern. Considering that this has been known for years, few, if any, plants take advantage of it because it takes a lot of energy to heat the sludge and there are concerns that odors may increase.

Process Control. The following shutdown procedures are suggested:

- Stop biosolids and polymer feed to the centrifuge,
- Add flush with water (effluent water is acceptable) until the centrate is clear and the torque level begins to drop,
- Turn the centrifuge off,
- Continue flushing at 25% of normal feed flow until the centrifuge reaches 7 to 800 r/min, and
- Turn off the lubrication system and cooling water when the unit is completely stopped.

The purpose of flushing is to remove solids from the centrifuge. If no solids are coming out, then the flushing serves no purpose.

Troubleshooting. *Obtaining Drier Cakes.* Chances are, the polymer was chosen to achieve a given biosolids dryness. If a drier cake is needed, it will probably be necessary to change to a different polymer, so the polymer supplier will need to be involved. Likewise, the weirs may be set too low. Consider how long it takes to seal the centrifuge. If it seals very quickly (i.e., in 1 or 2 minutes), chances are the weir plates are set lower than is ideal for dry cake. Raise them in 5-mm (radial) increments, until it takes 5 to 8 minutes to seal the centrifuge. For the same torque level, the centrifuge should now operate at a lower differential, and the centrate will be cleaner. Increase the torque set point until more polymer will not clean it up or torque runs out.

Reducing the Polymer Consumption. Common causes of high polymer consumption are the following:

- Poor quality feed biosolids. See the "Operating Principles for Dewatering" section.
- If the biosolids is very viscous, add dilution water to the polymer. The polymer has to reach every biosolids particle to capture it in a floc, and lowering the viscosity helps.
- Change the polymer addition point. Most manufacturers recommend four addition points.
- Higher polymer consumption results in less aging time for the polymer solution, which, in turn, results in increased polymer usage. Check to see that the polymer aging time is sufficient.
- The biosolids do not react well with the polymer. Check the reference sample of polymer in the laboratory refrigerator to see that the polymer currently on-site reacts at least as well as that the vendor field tested. See the polymer supplier to determine if a different polymer will do better than the one being used.

Ferric salts will result in lower polymer dosages, although the polymer savings alone will not pay for the cost of the ferric salts.

Increasing Capacity.

- Increasing the feed rate or the feed solids rate will reduce the solids residence time. This will result in wetter cake.
- More polymer will offset this somewhat.
- As mentioned earlier, the difference in height between the pond level and the solids discharge level is important. When the feed rate changes, the crest over the dams changes as well. Higher cresting over the weirs may result in too high a ΔH, and the weirs need to be lowered a few millimeters (Figure 33.15).

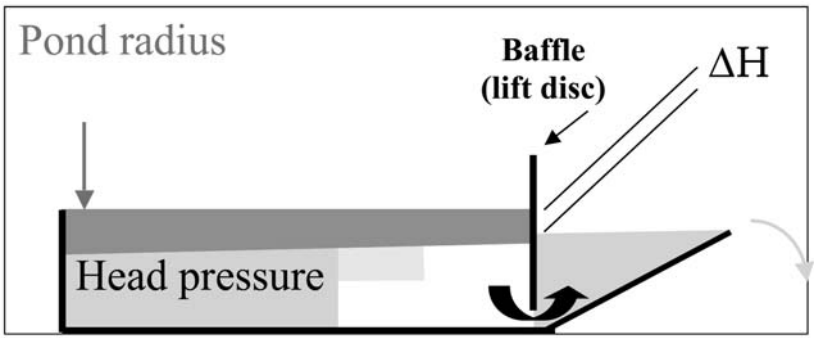


FIGURE 33.15 Differential head pressure.

- Increasing the feed solids concentration, thereby lowering the feed rate, helps as long as the feed is not too viscous and does not run the risk of going septic.
- Operating for more hours or operating more centrifuges will help.
- Add ferric chloride.

Table 33.7 presents a troubleshooting guide for centrifuges that enables the operator to identify problems early and determine their possible solutions.

VACUUM AND PRESSURE FILTERS. ***Inorganic Chemical Conditioning.*** Inorganic chemical conditioning is associated with rotary vacuum filters and pressure filtration dewatering. The chemicals typically are lime and ferric chloride. Ferrous sulfate, ferrous chloride, and aluminum sulfate are less commonly used.

Lime. Vacuum filters and filter presses commonly use lime and ferric chloride to make the sludge easier to filter and improve the release of the sludge from the filter media. Lime is available in two dry forms—quicklime (calcium oxide) and hydrated lime [$Ca(OH)_2$]. When using quicklime, it is first slurried with water and converted to calcium hydroxide, which is then used for conditioning. Because this process (known as *slaking*) generates heat, special equipment is required. Quicklime is typically available in three grades—high (88 to 96% calcium oxide), medium (75 to 88% calcium oxide), and low (50 to 75% calcium oxide). Because the grades can affect the slaking ability of the material, this should be considered before purchase. In general, only quicklime that is highly reactive and quick-slaking should be used for conditioning. Quicklime must be stored in a dry area, because it reacts with moisture in the air and can become unusable.

Hydrated lime is much easier to use than quicklime, because it does not require slaking, mixes easily with water with minimal heat generation, and does not require

TABLE 33.7 Troubleshooting for centrifuges.

Indications/ Observations	Probable cause	Action
Overall performance inadequate	The sludge no longer reacts well with the polymer	Check plant operations upstream, the polymer make-up system, and the polymer quality. If there is no obvious cause, see polymer vendor for help
	Excessive feed rate	Try lowering the feed rate
	Feed solids too thick	Conduct jar tests with diluted polymer try adding post dilution water to polymer, or thinning out the feed solids
	Raise bowl speed	Check with the centrifuge manufacturer before you do this.
	Pond depth too low	Check weir setting. Raise pond level by ±6 mm
High torque	Cake solids too viscous	Reduce torque setting to obtain wetter, less viscous cake
		Try a different polymer. Some polymers generate more torque than others
Centrifuge won't seal	The sludge no longer reacts well with the polymer	See above
	Pond setting too high	Lower pond by ±6 mm. This will buy time until you solve the problem
Erratic performance	Feed or polymer variations	Try to maintain uniform feedstock. Check polymer batches to see that they are uniform. It may be necessary to change the pond so as to function OK with all sludges, and great with none
High, intermittent vibration	Poor scrolling of the sludge inside the centrifuge	Lowering the bowl speed by several hundred rpm usually works. Alternately try deeper ponds, and/or higher feed rates
Vibration rising slowly over a week	Conveyor bearing failing	Disassemble and check bearings
	Solids blocking feed zone of clogging conveyor	Shut down, flush, and restart. If problem persits, try lowering the bowl speed.
Vibration rising quickly	Shut down immediately, and check bearing temperature	Call maintenance to see if the main bearings are bad
Continuous high vibration	Solids between the feed zone and rear conveyor bearing	Shut down, remove feed tube, and pressure wash
	Serous mechanical problems	Shut down and disassemble. Check for erosion, worn metal, bent flights, and bearings

any special storage conditions. Because hydrated lime is more expensive and less available than quicklime, quicklime should be used for applications that require more than 2 to 3 ton/d. This means that typically only larger WWTPs will use quicklime.

Lime typically is used in conjunction with ferric iron salts. Although lime has some slight dehydration effects on colloids, odor reduction, and disinfection, it is used because it improves filtration and release of the cake from the filter media. The lime reacts with bicarbonate to form a precipitate of calcium carbonate, which provides a granular structure that increases porosity and reduces compressibility of the biosolids.

Dosage Requirements. Iron salts are added at a dose rate of 20 to 62 kg/metric ton (40 to 125 lbs/ton) of dry feed solids, whether or not lime is used. Lime dosage varies from 75 to 277 kg/metric ton (150 to 550 lbs/ton) of dry solids dewatered. Table 33.8 lists typical ferric chloride and lime dosages. However, some organic polymers can be used with lime instead of ferric chloride.

Inorganic chemical conditioning greatly increases the mass of solids to be discarded. The operator should expect 0.5 kg (1 lb) of additional chemical solids for every 0.5 kg

TABLE 33.8 Typical conditioning dosages of ferric chloride and lime for municipal wastewater sludges.[a,b]

	Vacuum filter		Pressure filter	
Sludge	**$FeCl_3$[c]**	**CaO[d]**	**$FeCl_3$**	**CaO**
Raw sludges				
Primary	40–80	160–200	80–120	220–280
Waste activated	120–200	0–320	140–200	400–500
Primary/trickling filter	40–80	180–240		
Primary/WAS[e]	50–120	180–320		
Primary/WAS (septic)	50–80	240–300		
Elutriated anaerobically digested sludges				
Primary	50–80	0–100		
Primary/WAS	60–120	0–150		
Anaerobically digested sludges				
Primary	60–100	200–260		
Primary/WAS	60–120	300–420		
Primary/trickling filter	80–120	250–350		
Thermally conditioned sludges	None	None	None	None

[a]All values shown are for pounds of either $FeCl_3$ or CaO per ton of dry solids pumped to the dewatering unit.
[b]1 lb/ton = 0.5 kg/metric ton.
[c]Ferric chloride.
[d]Calcium oxide.
[e]Waste activated sludge.

(1 lb) of lime and ferric chloride added, and also more attendant water. This increases the total amount of biosolids for disposal and lowers its fuel value for incineration. With the development of polymers, the use of inorganic conditioning and related processes have declined severely.

Other Types of Conditioners. Other types of inorganic materials have been used as conditioning agents. Cement kiln dust fly ash, power plant ash, and biosolids incinerator ash have been used to increase the dewatering rate, improve cake release, increase cake solids, and, in some cases, reduce the dosage of other types of conditioning agents.

Pressure Filters. Principles of operation, process variables, process control, troubleshooting, startup and shutdown procedures, safety concerns, and maintenance considerations are described below. Figure 33.16 illustrates a plate and frame press.



FIGURE 33.16 Plate and frame press (courtesy of Siemens Water Technologies Corp.).

Principles of Operation. Filter presses for dewatering are generally either recessed plate filters or diaphragm filter presses. A typical pressure filter is illustrated in Figure 33.17. With the advent of better organic polymers, belt filters and centrifuges have largely displaced filter presses in the market. Filter presses can be attractive in unusual circumstances.

The fixed-volume recessed plate filter press (Figures 33.17, 33.18, and 33.19) consists of a series of plates, each with a recessed section that forms the volume into which the feed enters for dewatering. Figure 33.17 shows the general external mechanics of the basic filter press. Filter media or cloth, placed against each plate wall, retains the cake solids while permitting passage of the filtrate. The plate surface under the filter media is specifically designed with grooves between raised bumps to facilitate passage of the filtrate while holding the filter cloth.

Before pumping into the press, the feed must be chemically conditioned to flocculate the solids and release the water held within the solid mass. Most typical conditioning systems use inorganic chemicals and organic polymers.

Principles of Conditioning. Conditioning is performed to increase particle size by combining small particles into larger aggregates. Conditioning is a two-step process consisting of coagulation and flocculation. Coagulation involves the destabilization of the

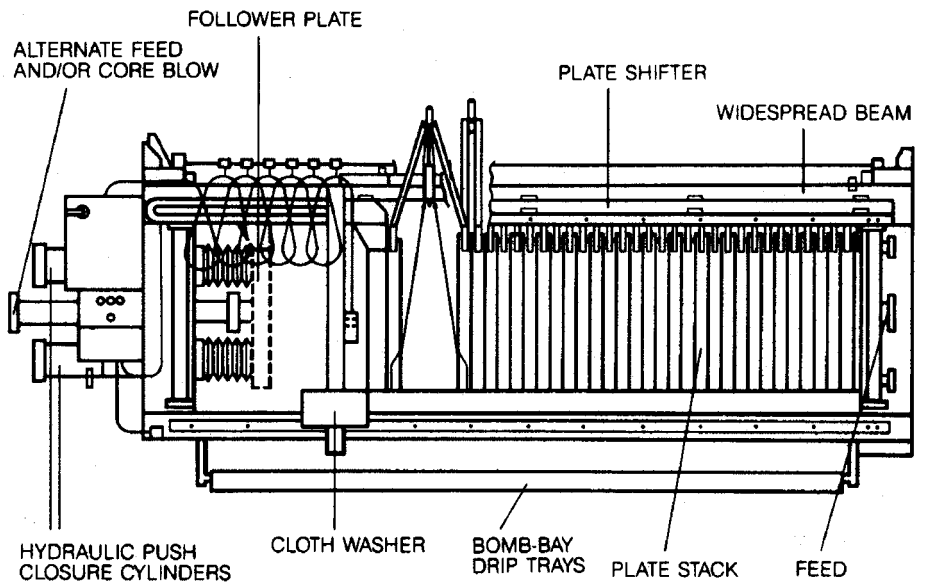


FIGURE 33.17 Fixed-volume recessed plate filter press.

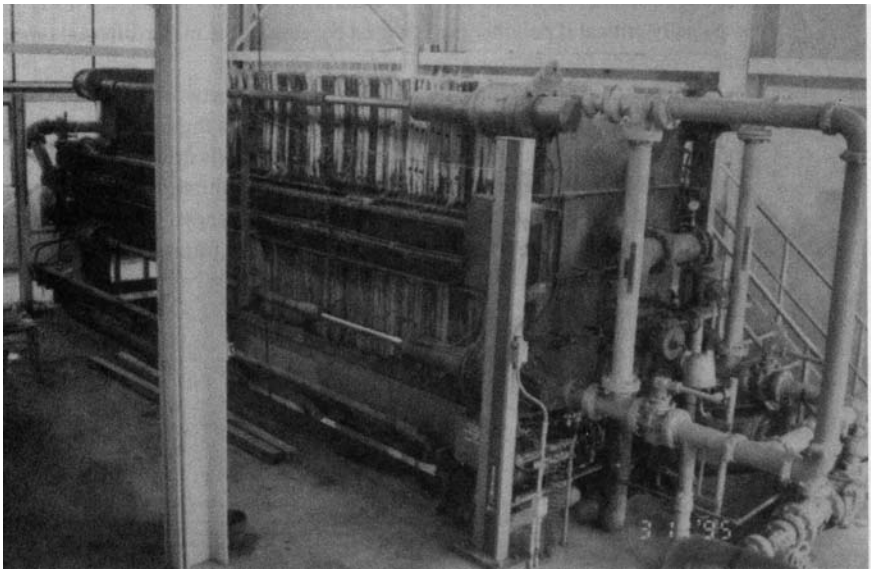


FIGURE 33.18 Fixed-volume recessed plate filter press.

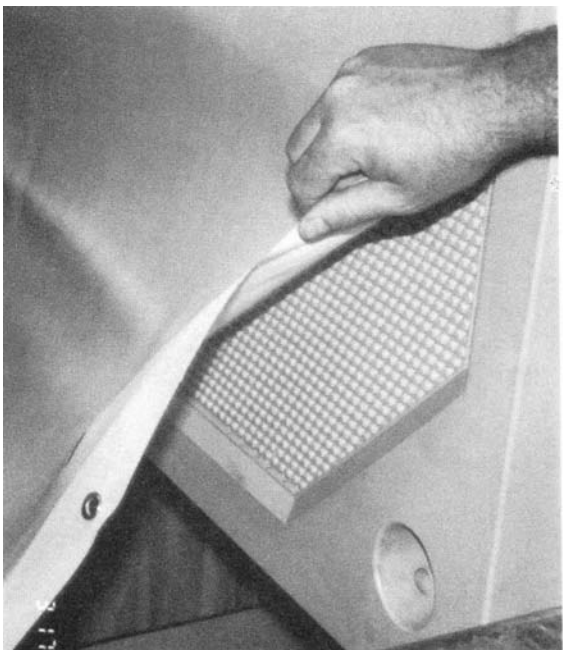


FIGURE 33.19 Plate drainage holes behind cloth on fixed-volume recessed plate filter press.

negatively charged particles by decreasing the magnitude of the repulsive electrostatic interactions between the particles.

The second step—flocculation—is the agglomeration of colloidal and finely divided suspended matter after coagulation by gentle mixing.

Inorganic Chemical Conditioning. Inorganic chemical conditioning is associated principally with vacuum and pressure filtration dewatering. The chemicals typically are lime and ferric chloride. Ferrous sulfate, ferrous chloride, and aluminum sulfate are also used, although less commonly.

Ferric Salts. Ferric chloride solutions typically are used at the concentration received from the supplier (30 to 40%); however, some WWTPs dilute the ferric chloride to approximately 10% to improve mixing and reduce the acidity and corrosivity of the material. This can be done in day tanks or inline. Dilution may lead to hydrolysis reactions and the precipitation of ferric chloride crystals.

An important consideration in the use of ferric chloride is its corrosive nature. It reacts with water to form hydrochloric acid, which attacks steel and stainless steel. When diluted with biosolids, the acidity is neutralized by the alkalinity of the biosolids and thoroughly diluted so that the end product is quite benign. Interlocks must be used to ensure that ferric chloride is always added to biosolids in the proper ratio and is never pumped into biosolids lines or process equipment by itself.

Special precautions must be taken when handling this chemical. The best materials are epoxy, rubber, ceramic, polyvinylchloride, and vinyl. Contact with the skin and eyes must be avoided. Rubber gloves, face shields, goggles, and rubber aprons must be used at all times. Ferric chloride can be stored indefinitely without deterioration. Customarily, it is stored in aboveground tanks constructed of resistant plastic and surrounded by a containment wall. Ferric chloride can crystallize at low temperatures, which means that the tanks must be kept indoors or heated.

Lime. Lime typically is used in conjunction with ferric iron salts, principally because it increases porosity and aids in the release of cake. Inorganic chemical conditioning increases the mass of solids to be discarded. The operator should expect 0.5 kg (1 lb) of additional chemical solids for every 0.5 kg (1 lb) of lime and ferric chloride added.

High-pressure pumps force the feed into the space between the two plates. The filtrate passes through the cake and the filter media and out of the press through special ports drilled in the plate. Figure 33.20 shows a schematic of a typical pressure filtration system.

Pumping continues up to a given pressure and is stopped when solids and water fill the void volume between the filter cloths and filtrate flow slows to a minimal rate. The press then opens mechanically and the cake is removed, one chamber at a time.

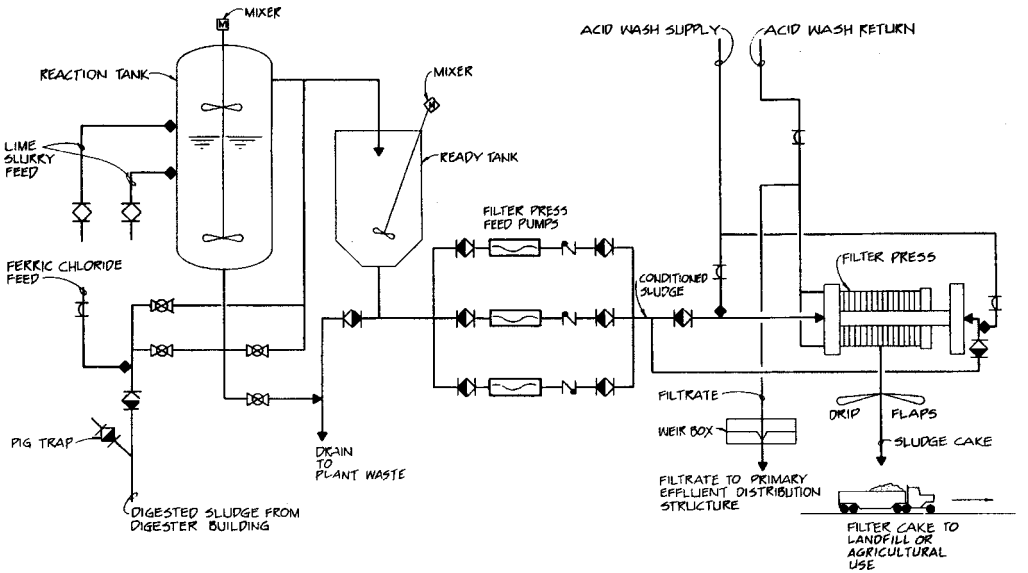


FIGURE 33.20 Schematic of a typical filter press system.

A variation of this process is the diaphragm press. After the press is full, the diaphragms are pressurized up to 1380 to 1730 kPa (200 to 250 psi) using either air or water, which expands the diaphragm and presses out more water.

Process Variables—Chemical Conditioning. Polymers have a narrow range of effective dosage. A dose that is too low or too high will result in a wet cake. Lime and ferric chloride have a broader range of effective dosage. While it is desirable for an operator to reduce the chemical usage to reduce costs, if erratic equipment operation or erratic feed qualities occur a higher lime dose typically will protect against a wet cake. Polymer conditioning requires much less chemical per unit mass of solids dewatered, which results in more room in the press for organic biosolids, and increased capacities.

- Ideally, the solids capture is 99%. A torn cloth immediately results in a filtrate flow that is very dirty and heavy with solids.
- Feed solids concentration. A very thin feed may blow out through the plate surfaces during the initial high-volume fill of the press because there would be too much filtrate flow for the drain capacity. A thin feed will at least require a longer filtration time and produce a wetter cake. A thick feed typically will produce a drier cake with a much shorter filtration time.

For a conventional filter press, the operator can control the following machine variables:

- Feed pressure. There are two differential operating ranges for filter presses—656 to 897 kPa (95 to 130 psi) and 1380 to 1730 kPa (200 to 250 psi).
- Feed application rate, by pacing the flow to the filter press.
- Overall filtration time, including such variables as the time at each pressure level in multiple pressure level operations.
- Use and amounts of precoat or body feed. Typically, precoat is unnecessary when inorganic chemicals, such as lime and ferric chloride, are applied. Precoat may be needed if particle sizes are extremely small, filterability varies considerably, or a substantial loss of fine solids to and through the filter media is anticipated.
- Conditioning chemicals, type, dosage, location, and mixing efficiency. Polymer addition versus lime and ferric chloride conditioning typically are not interchangeable, as each chemical requires special mixing and flocculation energies and reaction times. Polymers only need a quick mix before injection to the press. Modifications to the piping and mixing systems are typically needed if a change in the type of chemical for conditioning is desired.
- Flocculation efficiency and energy vary with the type of chemical being used. Polymer floc shears easily and remains stable for only a few minutes. Lime floc is more durable and remains stable for a few hours.
- Filter media. Filter cloth media vary widely, with different filament composition, weave pattern, and weave tightness. A typical cloth for dewatering organic biosolids is made of polypropylene filaments woven to obtain 2.3 to 3.4 m^3/min (80 to 120 scfm) porosity.

Process Control. Typical operation of the filter press requires visual checks of equipment conditions before starting the automatic filter cycle. Most pressure filter installations have an automatic device that closes the filter plates and clamps them together. Before closing, the plates and filter cloth need to be inspected.

After the chemical solution has been prepared, and the day or ready tank contains sufficient feed stock, the filtration cycle can begin. Initially, a high feed rate is desired to fill the press evenly and completely in a relatively short time. Either multiple pumps or a high-volume, low-pressure pump is used for this initial quick fill. After the internal liquid pressure reaches approximately 380 kPa (55 psi), all feed pumps shut down, except for a small-volume, high-pressure pump that continues up to a given pressure. As the solids concentration in the filter press chambers increases, the filtration pressure

will increase. After reaching the maximum pressure—typically 656 to 897 kPa (95 to 130 psi)—the pressure and the filtration cycle continue until a predetermined cake concentration is achieved.

Some presses are depressurized by initiating the core blow process, which removes wet solids that remain in the central feed core. If a core blow process is not included, some liquid will drain out the bottom when the press is opened.

1. Place the drip trays in the open position.
2. Retract the hydraulic ram.
3. Start the automatic plate shifter sequence to separate and jar the plates, one at a time, to drop the dewatered cake into the container below. Some of the cake may have to be removed with plastic scrapers. Note that poor cake release from the cloth may indicate improperly conditioned feed. A high lime dosage for the following filtration cycle may remove most of the residual wet solids from the cloth, or the filter cloth may need to be washed, as recommended in the manufacturer's literature.

Troubleshooting. Table 33.9 is a troubleshooting guide for pressure filters that will help operators to identify problems and determine their possible solutions.

Startup and Shutdown Procedures. Because each system has unique equipment with unique system interlocks, it is imperative that operators be thoroughly trained in the startup and shutdown procedures for their particular pressure filter system. Following are some general guidelines on startup and shutdown.

Whenever major changes occur to the chemical and biosolids feeds, the operator should perform a laboratory vacuum filtration test to confirm that the water will release from the solids. Additional testing is sometimes performed, such as a leaf test or a capillary suction test.

Also, before startup after major maintenance procedures and during each cake discharge cycle, the operator should check each filter plate and cloth as follows:

- Filter cloths should be attached to the plates without folds and be free of dirt or foreign objects;
- No objects should be on top of or between the plates; and
- The cloths should be observed for tears, especially at the center feed seams and at the boss (intermediary support) points.

Without these checks, the press can be damaged, and operation of the stem can be jeopardized. If lime is used, mix the proper concentration before biosolids transfer. Typi-

TABLE 33.9 Troubleshooting guide for pressure filtration.

Indicators/ observations	Probable cause	Check or monitor	Solutions
Plates fail to seal	Hydraulic pressure too low	Manufacturer's recommended pressure	Adjust to specifications
	Feed pressure too high	Feed pump pressure	Adjust to proper range
	Rags or solids on plate seal surfaces	Plate sealing surfaces	Inspect sealing surfaces during discharge and clean as needed
Cake discharge is difficult—wet cake	Inadequate precoat	Prevent feed	Increase precoat, feed at 172–276 kPa (25–40 psig)
	Improper conditioning	Conditioner type and dosage	Change conditioner type or dosage based on history or bench vacuum filter test
	Filtration time too short	Filtration time, filtrate flowrate, and feed pressure	Extend filtration cycle time
Filter cycle times excessive	Conditioned sludge too old	Time since conditioning	Do not save old conditioned sludge, or add extra lime before using
	Feed solids too low	Operation of thickening process	Improve solids thickening to increase solids concentration in press feed
	Improper precoat feed	Precoat feed	Decrease precoat feed substantially for a few cycles, then optimize
	Filter media plugged/ calcium buildup in media	Filter media	Wash filter media/acid wash (inhibited hydrochloric acid)
Dirty filtrate	Ripped cloth or cloth with too high a porosity	Inspect all cloths	Replace damaged or incorrect cloths
	High feed pressure	Check operating history	Adjust feed pressure within specifications
Frequent media binding	Precoat inadequate	Precoat feed	Increase precoat
	Initial feed rates too high	Pump rate	Develop initial cake more slowly
	Improper conditioning	Conditioning dosage	Change chemical dosage
	Cloth with too low a porosity	Inspect all cloths and consult with manufacturer	Replace incorrect cloths
Excessive moisture in cake	Improper conditioning	Conditioning dosage	Change chemical dosage
	Filter cycle too short	Correlate filtrate flowrate with cake moisture content	Lengthen filter cycle

TABLE 33.9 Troubleshooting guide for pressure filtration (*continued*).

Indications/ observations	Probable cause	Check or monitor	Solutions
Sludge blowing out of press	Obstruction, such as rags, in the press forcing sludge between plates	Feed pressure	Shut down feed pump, hit press closure drive, restart feed pump; clean feed eyes of plates at end of cycle
	Cake complete	Feed pressure, filtrate flowrate, and filtration time	Shut down press and unload cake

cally, a 10% lime slurry solution is used, with a 1.06 specific gravity, as measured by a hydrometer.

The details of the press cycle vary greatly with the press design and will not be discussed here.

Safety Concerns. Following are some safety concerns for the operation of pressure filters. As always, complete site-specific safety procedures must be written, approved, and followed for each facility.

- Many presses are very noisy when in operation. Hearing protection may be needed.
- Never insert objects between the press plates as they are being discharged without first shutting the unit down by tripping the light curtain or flipping the emergency shutdown switch.
- Lime treatment results in considerable ammonia fumes being released during cake discharge. Make sure that adequate ventilation pulls these fumes away from the operator, preferably with a high-capacity, down-draft blower system. If an adequate ventilation system is not operational, then, if approved, short-term exposure may be allowed, if an approved ammonia respirator is worn by all personnel assisting with the cake discharge.
- Hydrochloric acid washing of the press releases volatile acid fumes, which should not be inhaled or exposed to moist body tissues, such as eyes and lungs. A high-capacity ventilation system, as previously noted, is essential. If approved, short-term exposure may be allowed with an approved respirator and complete coverage of all exposed skin.
- Lime powder is very caustic when it contacts moist body tissues. Therefore, an approved respirator and complete coverage of all exposed skin is necessary when working around lime.

Maintenance Considerations. Follow all equipment manufacturer's recommendations. Some typical areas that need special attention are as follows:

- The plate handles and the frame rails require frequent grease application to prevent binding and excessive wear.
- The plate shifter chain or other plate shifting devices require frequent lubrication.
- Even if a shredder is used before the conditioning step, rags will quickly accumulate on all mechanical mixer blades. These need to be removed frequently to prevent damaging the mixer gears and shaft bearings from operating out of balance. Some facilities have removed their mechanical mixers and converted to air mixing to avoid ragging problems.
- Lime systems scale up and plug over time and are unpleasant and potentially hazardous for operators to clean out. Some WWTPs have switched from quicklime to hydrated lime to avoid maintaining lime slakers.
- When lime is used, cloth and plate washing may require both an acid and a water wash because lime causes scaling.
- Ferric chloride, hydrochloric acid, lime, and ammonia cause considerable corrosion to metal surfaces, such as the plate handles with their retaining bolts, the shifter chain, and even steel plates under a hard rubber cover. Frequent cleaning and lubrication are necessary to reduce corrosion. Powder-coated steel handles, polypropylene plates, and polytetrafluoroethylene-coated frame rails have been used by some facilities to reduce corrosion problems. Also, adding an inhibitor to hydrochloric acid will reduce its metal corrosion properties.
- From time to time, the cloths and gaskets will have to be removed, the plates pressure cleaned, and new cloths and gaskets cut and installed.

Vacuum Filters. *Principles of Operation.* Until the mid-1970s, vacuum filtration was the most typical means of mechanical dewatering. The principal variations among filters was the filter medium itself. Some of those used were natural and synthetic fiber cloth, woven stainless steel mesh, and coil springs.

With the development of effective polymers, centrifuges and BFPs have replaced most vacuum filters. A vacuum filter consists of a horizontal cylindrical drum that rotates while partially submerged to approximately 20 to 35% of its depth in a vat of previously conditioned feed. The filter drum is partitioned into several compartments or sections (Figure 33.21). A pipe connects each compartment to a rotary valve. Bridge blocks in the valve divide the drum compartments into three zones—the cake formation zone, cake drying zone, and cake discharge zone.

The submerged zone is the cake formation zone. A vacuum applied to the submerged zone causes the filtrate to pass through the media and solids particles to be

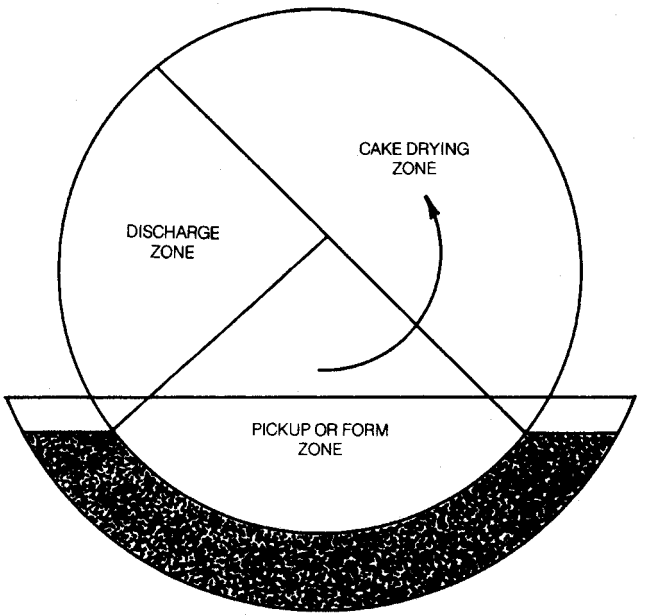


FIGURE 33.21 Operating zones in a rotary vacuum filter.

retained on the media. As the drum rotates, each section successively is carried through the cake formation zone to the cake drying zone. The cake drying zone begins when the filter drum emerges from the feed vat. The cake drying zone occupies 40 to 60% of the drum surface and ends at the point where the internal vacuum is shut off. At this point, the cake and drum section enter the cake discharge zone, where cake loosens and falls from the media. Figure 33.21 illustrates the various operating zones encountered during a complete revolution of the drum.

Process Variables. The principal variables that affect vacuum filter operation are as follows:

- Chemical conditioning,
- Filter media type and condition,
- Drum submergence,
- Drum speed, and
- Vacuum level.

Chemical conditioning most significantly influences dewaterability, because it changes the physical and chemical nature of the feed. Conditioning agents produce a

feed that releases water more freely, thereby producing a drier cake. Conditioning agents also add to the solids to be discarded.

Drum submergence, the percentage of time the filter drum is submerged in the feed vat, typically varies between 15 and 25%. Increasing the submergence of the drum increases the filter cycle time devoted to cake formation, but reduces the cake drying ratio. This produces a thicker, but wetter, cake.

Drum speed affects the filter cycle time. Increasing the drum speed shortens both cake formation and cake dewatering cycles. Such action can produce a wetter cake, but increased filter yield, and vice versa. Drum speed also affects cloth cleaning. A higher speed decreases the time that the cloths are washed.

The vacuum is controlled by the drum design, drum speed, and vacuum pump size. The required vacuum level is also affected by the liquid level in the vat and the type of conditioning. For a dry cake, the vacuum typically ranges from 51 to 68 kPa (15 to 20 in. Hg). The lower the vacuum, the wetter the cake will be.

PREVENTIVE MAINTENANCE

At one time, labor was no problem at the plant, and most repairs were done in-house. Now, with a lot of pressure to reduce manpower, it is often more attractive to outsource the more time-consuming or specialized repairs. Management of the maintenance department becomes a key asset. They are the ones who supervise repairs and discuss repair methods with vendors. Repair of a million dollar centrifuge is much like repair of a car. Some jobs are for the dealer, some can be done by the owner, and some can be done by the local repair shop. Most repairs are more or less generic. Examples are broken fasteners, worn or damaged parts that can be removed and replaced, and worn or broken parts that can be repaired.

A good knowledge of mechanical things is essential. Likewise, knowledge of the capabilities of local and specialized repair firms is also valuable. It is hard to learn these things out of a book, but an intelligent person asks questions and considers the answers carefully.

As a rule, using the original manufacturer's parts, lubricants, repair services, and service intervals should result in better service life. Typically, it will also cost more. There are a number of alternatives for the operator to consider.

LUBRICATION. The manufacturer's instruction book may list oil change intervals for the worst-case scenario. However, if oil is sent out for analysis, and it meets new oil standards, then it does not need to be changed. Keep periodically testing the oil, to determine when it begins to break down, and adjust the lubrication schedule accordingly.

Consider buying lubricants in bulk directly from the lubricant manufacturer. Purchasing individual tubes of grease when 12 tubes are recommended to flush a bearing is not a good idea. Consider substituting generic lubricants. Most applications are standard, and a knowledgeable lubrication engineer should be able to select a suitable substitute.

BEARINGS. The same applies to bearing changes. When a bearing is removed, consider sending it out for analysis, and adjust the bearing change interval based on that analysis. When possible, buy the bearings from the bearing manufacturer rather than the equipment manufacturer. An internet search could locate other manufacturers who make a similarly rated bearing and will sell it at an even lower price. Or, if it is a common bearing application, it may be more convenient to go to the local bearing and drive store and pick one up. Unusual bearings and unusual applications involve a risk when substitutions are used. Ask other owners of the equipment for their experiences.

REPAIRS. The easiest repairs are simple replacements. When a part is worn out, a new one can be purchased and installed. Even specialized parts, such as grinder teeth and gearbox parts for specific brands and devices, are available from third-party parts suppliers. The trick is finding them and determining if their quality is adequate. One source of information is the annual WEFTEC conference. Each year, there are parts and repair specialists who set up booths at the convention, and attendees can meet with a dozen or more each day. It may be worth sending someone from the maintenance department to the conference to interview them.

DEALING WITH THE REPAIR SHOP. Many repairs are more or less standard. Shafts become grooved, metal wears away, and bearing surfaces warp to become egg-shaped (out of round). Unless there is something special about these sorts of repairs, a local repair shop can probably do a very good job with them. To begin with, tell the repair shop staff specifically what they need to do. Do not send in a piece of hardware and simply say "fix it." If there is something unusual about the failure, tell them that also. A pump with a bad bearing will get a different treatment than a pump with bearings that fail repeatedly. The repair person will not know the history of the piece until they are told. Solicit bids from several sources. Take digital photos, and send them to the following:

- The manufacturer of the equipment,
- Manufacturers who make similar equipment, and
- Independent repair shops that are dependable.

Take advantage of expertise. Ask the following questions:

- What repair options are there?
- Why did it fail, and is there something that can be done to prevent it from happening again so soon?
- Is there something that can be done now to reduce the repair cost next time?

For example, a typical seal surface can be chrome-plated and ground back to dimension; it can be built up with weld and ground back; or it can be machined out and a replaceable sleeve installed. It is important to consider which is the best fix in a particular case.

If, in the end, it is determined that the problem is something only the original manufacturer should work on, a price can be negotiated. When the equipment is sent to someone for big repairs, demand a full report of what was done, including the return of replaced parts. The report should document the damage found, with digital photos, and a description of the repair method. The report should list, by name and part number, all of the parts used, the price paid for them, and the name of the company who made the parts. While this might seem excessive, all of this is information that the repair shop needed to calculate the price of the job.

DATA COLLECTION AND LABORATORY CONTROL. Process control is the keystone for optimum performance of a dewatering system. The operator needs to keep records of all dewatering performance parameters. Sample points must be located at various places throughout the system. For mechanical dewatering systems, at least twice per shift, a sample should be taken of the feed biosolids, cake discharge, and filtrate or centrate. However, composite sampling at these three locations is better than grab sampling because a composite sample will give a better picture of performance. Total solids should be determined for the feed and cake samples and total suspended solids determined for the filtrate.

Standard Methods for the Examination of Water and Wastewater (APHA et al., 2005) is the principal source for all laboratory protocol. The operator needs to make the following types of calculations:

- Calculation of dilute polymer concentration from a water solution of polymer, liquid polymers, and dry polymers; and
- Calculation of polymer use and cost of solids dewatered.

Successful dewatering depends on periodic, frequent laboratory tests to check the polymer dosages. Regular tests are critical. Furthermore, it is vital that the operator

understands the conditioning process. By observing the feed, filtrate, and cake, and by properly adjusting polymer dosages, the operator can ensure optimum performance of the dewatering system.

SAFETY AND HOUSEKEEPING. The phrase "accidents do not happen, they are caused" may be overused, but it is true. Common sense and a thorough understanding of the equipment and processes are essential to a safely operating WWTP. Before operating any conditioning or dewatering system, the best safety precaution is that all personnel involved read and thoroughly understand the operation and maintenance manuals provided by the process equipment suppliers.

Good WWTP housekeeping can prevent many accidents. Equipment should always be kept in first-class condition. Unsafe actions and conditions should be corrected.

Employees have the responsibility of safety to themselves, their fellow workers, and the WWTP. Cutting corners or taking chances while operating or maintaining equipment is not advisable. Refer to Chapter 5 for a thorough discussion of safety procedures and a listing of WWTP safety references.

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Symbols and Acronyms

A	Area of transmission loss
A^2/O	Anaerobic/anoxic/oxic
AC	Alternating current
A/O	Anoxic/oxic
ABF	Activated biofilter
ACOE	Army Corps of Engineers
AD	Apparent density
ADA	Americans with Disabilities Act
AD/AT	Factor representing number of diffusers per unit area of basin
ADF	Average daily flow
AE	Aeration (electrical) efficiency
AIDS	Acquired immune deficiency syndrome
AIHA	American Industrial Hygiene Association
$AlCl_3$	Aluminum chloride
$Al_2(SO_4)_3$	Aluminum sulfate
AMA	American Management Association
AMB	Approximate mass balance
ANSI	American National Standards Institute
APHA	American Public Health Association
APWA	American Public Works Association
ASA	American Standards Institute
ASCE	American Society of Civil Engineers
ASD	Adjustable speed drives
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASM	Activated sludge models
ASM2	Activated sludge models, second model

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ASM3	Activated sludge models, third model
ASP	Application service provider
ATAD	Autothermal thermophilic aerobic digestion
AST	Activated sludge treatment
ATS	Automatic transfer switch
AWWA	American Water Works Association
AWWARF	American Water Works Association Research Foundation
Ax	Anoxic
AxSF	Anoxic step feed
B	Y-axis intercept
BACT	Best available control technology
BBP	Blood-borne pathogen
BEP	Best engineering practices
BEPs	Best efficiency points
BETX	benzene, ethyl benzene, toluene, and xylene isomers
BF/AS	Biofilter/activated sludge
BFP	Belt filter press
BHC	Benzenehexachloride
BioP	*Acinetobacter*
BioP	Biological phosphorus
BMPs	Best management practices
BMR	Baseline monitoring report
BNR	Biological nutrient removal
BOD	Biochemical oxygen demand
BOD_5	Five-day biochemical oxygen demand
BOD_{2INF}	Influent BOD
BOT	build–own–transfer
BOOT	build–own–operate–transfer
BPR	Biological phosphorus removal
BrCl	Bromine chloride
BTU	British thermal unit
CH_3COOH	Acetic acid
$C_2H_4O_3$	Peracetic acid
C	Carbon
C	Constant: 0.25 for fecal coliform and 0.9 for total coliform
CF	Float solids concentration (percent) at the top of the unit
C_s	Specific heat of sludge
C:N	Carbon-to-nitrogen ratio
CAC	Combined available chlorine
CAD	Computer-aided design
CaO	Calcium oxide
$CaCO_3$	Calcium carbonate
$Ca(OH_2)$	Calcium hydroxide
$Ca(OCl)_2 \cdot 4\ H_2O$	Calcium hypochlorite

CAS	Chemical Abstracts Service
CAS	Conventional activated sludge
CBOD	Carbonaceous biochemical oxygen demand
$CBOD_5$	Five-day carbonaceous biochemical oxygen demand
$CBOD_{5,IN}$	Influent carbonaceous biochemical oxygen demand
$CBOD_{5,SE}$	Secondary effluent carbonaceous biochemical oxygen demand
CCP	Composite Correction Program
CDs	Computer disks
CD-ROM	Compact disc read-only memory
CDX	Central data exchange
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFD	Computational fluid dynamics
CFM	Computational fluid mixing
CFR	*Code of Federal Regulations*
CFU	Colony forming units
CH_4	Methane
CHIP	Chemicals Hazard Information and Packaging Regulations
CIUs	Categorical industrial users
Cl_2	Chlorine
ClO_2	Chlorine dioxide
CM	Corrective maintenance
CMMS	Computerized maintenance management systems
CMOM	Capacity, management, operation, and maintenance
C:N	carbon-to-nitrogen ratio
CPE	Comprehensive performance evaluations
CPU	Central processing unit
CO	Carbon monoxide
CO_2	Carbon dioxide
COD	Chemical oxygen demand
COTS	Commercial off-the-shelf
CPR	Cardiopulmonary resuscitation
CPVC	Chlorinated polyvinyl chloride
CSF	Clarifier safety factor
CSOs	Combined sewer overflows
CST	Capillary suction time
CSTRs	Completely stirred tank reactors
CT	Contact time
CWA	Clean Water Act
CWF	Combined waste stream formula
CWSRF	Clean Water State Revolving Fund
D	Diameter
D	UV dose
dB	Depth of float below the water level

dW	Height of float above water level
dB + dW	Total float depth
DAF	Dissolved air flotation
dB	Decibels
DBO	Design–build–operate
DBPs	Disinfection byproducts
DC	Direct current
DCS	Distributed control systems
DDD	dichlorodiphenyldichloroethane
DDE	dichlorodiphenyldichloroethylene
DDT	dichlorodiphenyltrichloroethane
DMRs	Discharge monitoring reports
dN	Denitrification
DNA	Deoxyribonucleic acid
d*N*/d*t*	Rate of change of the number of organisms population
DO	Dissolved oxygen
DOB	Depth of blanket
DOT	Department of Transportation
DPAM	Dry polyacrylamide
DPIV	Digital particle image velocimetry
DV	Digester volume
DWP	Dynamic wet pressure
E	Effluent rate
E	Effluent concentration
e_c	Corrected effluent concentration
e_m	Measured effluent concentration
EBPR	Enhanced biological phosphorus removal
ED_{50}	Effective dose at the 50% level
EDMS	Electronic document management system
EHS	Extremely hazardous substances
EH&S	Environmental Health and Safety
EM	Electromotive force
EMP	Energy management plan
EMS	Environmental management system
EPAct	Energy Policy Act
EPAM	Emulsion polyacrylamide
EPCRA	Emergency Planning and Community Right-to-Know Act
EQ	Exceptional quality
ERG	Enforcement response guide
ERP	Enforcement response plan
U.S. EPA	U.S. Environmental Protection Agency
ES	Extended Service
ESD	Egg-shaped digesters
ESEERCo.	Empire State Electrical Energy Research Corporation

E_x	Ultraviolet reactor dispersion coefficient
F	Force
F	Feed rate
f	Feed concentration
F:M	Food-to-microorganism ratio
FAC	Free available chlorine
f_c	Corrected feed concentration
Fe	Iron
$FeCl_2$	Ferrous chloride
$FeCl_3$	Ferric chloride
FEMA	Federal Emergency Management Agency
f_m	Measured feed concentration
FF/SG	Fixed-film and suspended growth processes
FFT	Fast Fourier transform
FIS	Financial information system
FOG	Fats, oil, and grease
FR	Federal Regulations
FRP	Fiberglass-reinforced plastic
FSS	Fixed suspended solids
FWA	Flow-weighted average
G	Balance quality grade number
GAC	Granular activated carbon
GALPs	Good automated laboratory practices
GASB	Government Accounting Standards Board
GBT	Gravity belt thickener
GC	Gas chromatography
GFI	Ground fault interrupter
GISs	Geographic information systems
GPS-X	General purpose simulator
GS	General service
GW&PCA	Georgia Water and Pollution Control Association
H	Head
H_2	Hydrogen
HAZCOM	Hazardous Communication Standard
HID	High-intensity discharge
HO	High output
H/O/A	Hand-off-auto
HCO_3^-	Biocarbonate
HS^-	Hydrosulfide
H_2CO_3	Carbonic acid
H_2O	Water
H_2O_2	Hydrogen peroxide
H_2SO_4	Sulfuric acid
H_2S	Hydrogen sulfide

H_3PO_4	Phosphoric Acid
HCl	Hydrochloric acid
HDPE	High-density polyethylene
HGL	Hydraulic grade line
HIV	Human immunodeficiency virus
h_L	Headloss
HLR	Hydraulic loading rate
HOA	Hand-off automatic
H/O/A	Hands/off/automatic
HOBr	Hypobromous acid
HOCl	Hypochlorous acid
HP	Horsepower
HPO	High-purity oxygen
HS-$1^{A/M}$	Start/stop handswitch
HS-$2^{S/S}$	Automatic/manual handswitch
HRMS	Human resources management system
HRR	High resolution redox
HRT	Hydraulic residence (retention) time;
HVAC	Heating, ventilation, and air conditioning
I	Intensity of UV radiation
I&C	Instrumentation and control
ICMA	International City and County Management Association
IFAS	Integrated fixed-film activated sludge
IMLR	Internal mixed-liquor recirculation
IRS	U.S. Internal Revenue Service
ISO	International Organization for Standardization
ISV	Initial settling velocity
IT	Information technology
$iTSS_{2INF}$	Inert total suspended solids in secondary influent
IUs	Industrial users
IWA	International Water Association
JHB	Johannesburg
K	Disinfection rate constant
k	Organism die-off rate constant
k	Rate constant
$KMnO_4$	Potassium permanganate
KVAR	Kilovar
L	Concentration of organisms after ultraviolet exposure
L	Effective length of rectangular draft
L_0	Concentration of organisms before ultraviolet exposure
LAN	Local area network
LiCl	Lithium chloride
LIF	Laser-induced fluorescence
LC_{50}	Lethal concentration at the 50% level

LDA	Laser Doppler anemometry
LE	Ludzack–Ettinger
LEL	Lower explosivity limit
LIMS	Laboratory information management systems
LMMSS	Lockheed Martin Michoud Space Systems
LP–LI	Low pressure–low intensity
μ	Biomass growth rate
μ_{max}	Maximum growth rate
m	Slope of straight line
M	Mass
M_{Ox}	Mass of oxic zone
MAs	Member associations
MAHL	Maximuum allowable headworks loading
MBRs	Membrane bioreactors
MCCs	Motor control center
MCRT	Mean cell residence time
$MCRT_{MIN}$	Minimum mean cell residence time
$MCRT_{Ox}$	Oxic zone mean cell residence time
$MgNH_4PO_4$	Magnesium ammonium phosphate
MIL	Moisture indicator light
MIS	Management information system
ML	Mixed liquor
mLE	Modified Ludzack–Ettinger
MLR	Mixed-liquor recycle
MLR_{Ax}	Denitrified mixed-liquor recycle
MLR_{Ax}	Mixed-liquor recycle anoxic zone
MLR_{ox}	Mixed-liquor recycle oxic zone
MLSS	Mixed-liquor suspended solids
MLVSS	Mixed-liquor volatile suspended solids
MMR	Mumps, Measles, and Rubella
MOP	Manual of Practice
MPN	Most probable number
MS	Mass spectrometry
MSDS	Material safety data sheet
MW	Medium wave
MWWTP	Minneapolis (Minnesota) Wastewater Treatment Plant
N	Effluent bacteria density after ultraviolet radiation
N	Rotating speed
N	Number of surviving organisms per unit volume at any given time
N	Speed
N/*d*N	Nitrify/denitrify
N_0	Influent bacteria density before ultraviolet radiation
N_2	Nitrogen
NaCl	Sodium chloride

$Na_2Al_2O_4$	Sodium aluminate
Na_2CO_3	Sodium carbonate
Na_2SO_3	Sodium sulfite
$NaClO_2$	Sodium chlorite
$NaHCO_3$	Sodium bicarbonate
NaOCl	Sodium hypochlorite
NaOH	Sodium hydroxide
NaS_2O_5	Sodium metabisulfite
NACWA	National Association of Clean Water Agencies
NASA	National Aeronautics and Space Administration
NBP	National Biosolids Partnership
NBOD	Nitrogenous biochemical oxygen demand
NEC	National Electric Code
NEMA	National Electrical Manufacturers Association
NFPA	National Fire Protection Association
NH_3	Ammonia
NH_3-N	Ammonia as nitrogen
NH_3-N_{IN}	Influent total ammonia-nitrogen
NH_3-N_{SE}	Influent total Kjeldahl nitrogen
NH_4^+	Ammonia ion
NH_4HCO_3	Ammonium bicarbonate
NH_4OH	Ammonium hydroxide
NIOSH	National Institute for Occupational Safety and Health
NO_2^-	Nitrite
NO_3^-	Nitrate
$NO_{3,\,IN}$	Influent nitrate concentration
$NO_{3,\,SE}$	Secondary effluent nitrate concentration
NO, NO_2, and **NO_x**	Nitrogen oxides
NOD	Nitrogenous oxygen demand
NO_X	Nitrogen oxide
NOx_{2EFF}	Secondary effluent nitrogen oxide concentration
NPDES	National Pollutant Discharge Elimination System
NPSH	Net positive suction head
NRC	National Research Council
NTU	Nephelometric turbidity unit
NWRI	National Water Research Institution
NYSERDA	New York State Energy Research and Development Authority
O&M	Operations and maintenance
O_2	Molecular or free oxygen
O_3	Ozone
OC	Oxygenation capacity
OCI^-	Hypochlorite ion
OCP	Operator control panel
OD	Oxygen demand

OH^-	Hydroxyl
OMS	Operations management system
ORP	Oxidation–reduction potential
OSHA	Occupational Safety and Health Act
OTE	Oxygen transfer efficiency
OTR	Oxygen transfer rate
OTMAX	Oxygen transferred to the mixed liquor
OUR	Oxygen uptake rate
Ox	Aerobic or oxic
αFk_La	Oxygen mass transfer coefficient
P	Brake horsepower
P	Phosphorus
P	Polymer rate
P	Predictive
P	True power
P3	Public–private partnerships
P_{atm}	Absolute atmospheric pressure
P&IDs	Process and instrumentation drawings
PAM	Polyacrylamide
PASS	Pull, aim, squeeze, sweep
P_B	*Brake power*
P_M	Wire or motor power
P_{atm}	Absolute atmospheric pressure
P_{vp}	Fluid vapor pressure
P_W	Water power
PAOs	Phosphorus-accumulating organisms
PAC	Powdered activated carbon
PCs	Personal computers
PCBs	Polychlorinated biphenyls
PCS	Process control system
PD	Positive displacement
PDA	Personal digital assistant
PDM	Predictive maintenance
PELs	Permissible exposure limits
PFC	Power factor correction
PFRP	Processes to further reduce pathogens
PLCs	Programmable logic controllers
PM	Preventive maintenance
PMP	Planned maintenance program
PMS	Personnel management system
PO_4^-	Phosphate
POs	Purchase orders
POTWs	Publicly owned treatment works
PP	Polypropylene

PPE	Personal protective equipment
P/PM	Predictive/preventive maintenance
PR	Pumping rate
PSA	Pressure swing adsorption
PSRPs	Processes to significantly reduce pathogens
PRV	Pressure-reducing valve
PTFE	Polytetrafluoroethylene
PUCs	Public utilities commissions
PVC	Polyvinyl chloride
PVDF	Fluorinated polyvinylidene
Q	Digester transmission loss
Q	Flow capacity
Q	Sludge heating requirement
Q	Reactive power
$\mathbf{Q_{digested\ sludge}}$	Volumetric flowrate of the digested sludge
$\mathbf{Q_{feed}}$	Volumetric flowrate of the feed sludge
$\mathbf{Q_{2INF}}$	Secondary influent flow
Q_{IN}	Influent wastewater flowrate
$\mathbf{Q_S}$	Solids loading rate
Q_{WW}	Wastewater flow
QA	Quality assurance
QAP	Quality assurance plan
QAPP	Quality assurance project plan
QAU	Quality assurance unit
QC	Quality control
$\mathbf{Q_{RAS}}$	Return activated sludge flow
$\mathbf{Q_{WAS}}$	Waste activated sludge flow
RAS	Return activated sludge
RBCs	Rotating biological contactors
RCM	Reliability centered maintenance
RCFA	Root-cause failure analysis
RCRA	Resource Conservation and Recovery Act
RDT	Rotary drum thickeners
RF/AS	Roughing filter activated sludge
RFP	Request for proposals
RFQ	Request for qualifications
RMP	Risk management program
RNA	Ribonucleic acid
RTDs	Resistance temperature detectors
S	Solids or sludge mass flowrate
S	Solids or cake rate
S	Apparent power
s	Solids or cake concentration
SA	Surface area

SAE	Standard aeration (electrical) efficiency
SAR	Sodium adsorption ratio
SARA	Superfund Amendments and Reauthorization Act
SARS	Severe acute respiratory syndrome
SBOD	Soluble biochemical oxygen demand
SBR	Sequencing batch reactors
SCADA	Supervisory control and data acquisition
SCBA	Self-contained breathing apparatus
SDNRs	Super digital noise reductions
SGT-HEM	Silica gel treated *n*-hexane extractable material
SIK	Timer, indicator, and control
SIU	Significant industrial user
SK	Spulkraft
SLA	Service level agreement
SLR	Solids loading rate
SMR	Self-monitoring report
SNDN	Simultaneous nitrification/denitrification
SO_2	Sulfur dioxide
SOL	Soluble organic loading
SOPs	Standard operating procedures
SOTR	Standard oxygen transfer rate
SOUR	Specific oxygen uptake rate
SP	Soluble phosphorus
SPAM	Solution polyacrylamide
SPCC	Spill prevention and countermeasures control
SPDES	State Pollution Discharge Elimination System
SRF	State Revolving Fund
SRT	Solids residence (retention) time
SS	Suspended solids
SSO	Sanitary sewer overflow
SSV	Settled sludge volume
STOWA	Foundation for Applied Water Research
SVI	Sludge volume index
SWD	Side-water depth
t	Time of exposure
T_i	Temperature of influent
T_o	Digester operating temperature
T_s	Temperature of surroundings
T	Turbidity
t_C	Float scraper cycle time
t_{OFF}	Time that the scraper is off during a given cycle
t_{ON}	Time that the scraper is on during a given cycle
TCDD	tetrachlorodibenzo-*p*-dioxin
TD	Tetanus and diphtheria

TDH	Total dynamic head
TDS	Total dissolved solids
TF	Trickling filter
TF/AS	Trickling filter/activated sludge
TF/RBC	Trickling filter/rotating biological contactor
TF/SC	Trickling filter/solids contact
THMs	Trihalomethanes
TIMS	Training information management system
TKN	Total Kjeldahl nitrogen
$\mathbf{TKN_{SE}}$	Secondary effluent TKN
TOC	Total organic carbon
TOD	Total oxygen demand
TOL	Total organic loading
TP	Total phosphorus
TPAD	Temperature-phased anaerobic digestion
TR	Turnover rate
TRE	Toxicity reduction evaluation
TSCA	Toxic Substances Control Act
TS	Total solids
TSS	Total suspended solids
$\mathbf{TSS_{2EFF}}$	Total suspended solids in secondary effluent
$\mathbf{TSS_{WAS}}$	Total suspended solids in waste activated sludge
TSU	Total sludge units
TTO	Total toxic organics
TWAS	Total waste activated sludge
TWUA	Texas Water Utilities Association
$\boldsymbol{U}$	Fluid velocity
$\boldsymbol{U_{per}}$	Permissible unbalance
U	Heat transfer coefficient
UCT	University of Capetown
UEL	Upper explosive limit
U.K.	United Kingdom
UL	Underwriters Laboratory
UPSs	Uninterruptible Power Systems
U.S.	United States
USD	United States dollar
USDA	United States Department of Agriculture
U.S.S.R	Union of Soviet Socialist Republics
UV	Ultraviolet
V	Velocity of travel of scrapers
V	Voltage
$\boldsymbol{V}$	Volume of reactor
$\boldsymbol{V_{AX}}$	Anoxic volume
$\boldsymbol{V_{AB}}$	Volume of aeration basin

V_B	Basin volume
vL	Downflow rate
v^2**/2g**	Velocity head
VA/ALK	Volatile acid-to-alkalinity ratio
VAR	Vector attraction reduction
VFA	Volatile fatty acid
VHO	Very high output
VIP	Virginia Initiative Plant
VOC	Volatile organic compound
VFDs	Variable frequency drives
VS	Volatile solids
$\mathbf{VS_{digested\ sludge}}$	Volatile solids concentration of the digested sludge
$\mathbf{VS_{feed}}$	Volatile solids concentration of the feed sludge
VSA	Vacuum swing adsorption
VSR	Volatile solids reduction
VSS	Volatile suspended solids
$\mathbf{VSS_{2INF}}$	Volatile suspended solids in secondary influent
W	Watts
W	Weight
W	Wash water rate
W/WW ITA	Water and Wastewater Instrumentation Testing Association
ω	Rotational speed
WA	Weight alarm
WAN	Wide area network
WAS	Waste activated sludge
WEAO	Water Environment Association of Ontario
WEF	Water Environment Federation
WEFTEC	Water Environment Federation Technical Exposition and Conference
WERF	Water Environment Research Foundation
WPCF	Water Pollution Control Federation
WRFs	Water reclamation facilities
WRRC	Water Resources Research Center
WRS	White data medium reference signal
WS	Weight switch
WWTPs	Wastewater treatment plants
x	Forward distance traveled during exposure
Z_W	Vertical distance

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Glossary

absorption (1) Taking up of matter in bulk by other matter, as in dissolving of a gas by a liquid. (2) Penetration of substances into the bulk of the solid or liquid. See also *adsorption*.

absorption capacity A measure of the quantity of a soluble substance that can be absorbed by a given quantity of a solid substance.

acclimation The dynamic response of a system to the addition or deletion of a substance until equilibrium is reached; adjustment to a change in the environment.

accuracy The absolute nearness to the truth. In physical measurements, it is the degree of agreement between the quantity measured and the actual quantity. It should not be confused with "precision," which denotes the reproducibility of the measurement.

acid (1) A substance that tends to lose a proton. (2) A substance that dissolves in water with the formation of hydrogen ions. (3) A substance containing hydrogen which may be replaced by metals to form salts.

acid-forming bacteria Microorganisms that can metabolize complex organic compounds under anaerobic conditions. This metabolic activity is the first step in the two-step anaerobic fermentation process leading to the production of methane.

acidity The quantitative capacity of aqueous solutions to neutralize a base; measured by titration with a standard solution of a base to a specified end point; usually expressed as milligrams of equivalent calcium carbonate per liter (mg/L $CaCO_3$); not to be confused with pH. Water does not have to have a low pH to have high acidity.

acre-foot (ac-ft) A volume of water 1-ft deep and 1 ac in area, or 43 560 cu ft (1 233.5 m^3).

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activated carbon Adsorptive particles or granules usually obtained by heating carbonaceous material in the absence of air or in steam and possessing a high capacity to selectively remove trace and soluble components from solution.

activated carbon adsorption Removal of soluble components from aqueous solution by contact with highly adsorptive granular or powdered carbon.

activated carbon treatment Treatment process in which water is brought into contact with highly adsorptive granular or powdered carbon to remove soluble components; process may be applied to raw water, primary effluent, or chemically clarified wastewater for nonspecific removal of organics, or to secondary effluent as a polishing process to remove specific organics.

activated sludge Sludge particles produced by the growth of organisms in the aeration tank in the presence of dissolved oxygen.

activated-sludge loading The pounds (kilograms) of BOD in the applied liquid per unit volume of aeration capacity or per pound (kilogram) of activated sludge per day.

activated-sludge process A biological wastewater treatment process that converts nonsettleable (suspended, dissolved, and colloidal solids) organic materials to a settleable product using aerobic and facultative microorganisms.

adsorption The adherence of a gas, liquid, or dissolved material to the surface of a solid or liquid. It should not be confused with *absorption*.

adsorption water Water held on the surface of solid particles by molecular forces with the emission of heat (heat of wetting).

advanced waste treatment Any physical, chemical, or biological treatment process used to accomplish a degree of treatment greater than that achieved by secondary treatment.

aerated contact bed A biological treatment unit consisting of stone, cement-asbestos, or other surfaces supported in an aeration tank, in which air is diffused up and around the surfaces and settled wastewater flows through the tank; also called a *contact aerator*.

aerated pond A natural or artificial wastewater treatment pond in which mechanical or diffused air aeration is used to supplement the oxygen supply.

aeration (1) The bringing about of intimate contact between air and a liquid by one or more of the following methods: (a) spraying the liquid in the air; (b) bubbling air through the liquid; and (c) agitating the liquid to promote surface absorption of air. (2) The supplying of air to confined spaces under nappes, downstream from gates in conduits, and so on, to relieve low pressures and to replenish air entrained and removed from such confined spaces by flowing water. (3) Relief of the effects of cavitation by admitting air to the affected section.

aeration period (1) The theoretical time, usually expressed in hours, during which mixed liquor is subjected to aeration in an aeration tank while undergoing activated-sludge treatment. It is equal to the volume of the tank divided by the volumetric rate of flow of the wastewater and return sludge. (2) The theoretical time during which water is subjected to aeration.

aeration tank A tank in which wastewater or other liquid is aerated.

aerator A device that brings air and a liquid into intimate contact. See *diffuser*.

aerobic Requiring, or not destroyed by, the presence of free or dissolved oxygen in an aqueous environment.

aerobic bacteria Bacteria that require free elemental oxygen to sustain life.

aerobic digestion The breakdown of suspended and dissolved organic matter in the presence of dissolved oxygen. An extension of the activated-sludge process, waste sludge is stored in an aerated tank where aerobic microorganisms break down the material.

aerobic lagoon An oxygen-containing lagoon, often equipped with mechanical aerators, in which wastewater is partially stabilized by the metabolic activities of bacteria and algae. Small lagoons (less than 0.5 ac [0.2 ha] and less than 3-ft [0.9-m] deep) may remain aerobic without mechanical aeration. See also *anaerobic lagoon*.

aerosol Colloidal particles dispersed in a gas, smoke, or fog.

agglomeration Coalescence of dispersed suspended matter into larger flocs or particles.

agitator Mechanical apparatus for mixing or aerating. A device for creating turbulence.

air-bound Obstructed, as to the free flow of water, because of air entrapped in a high point; used to describe a pipeline or pump in such condition.

air chamber A closed pipe chamber installed on the discharge line of a reciprocating pump to take up irregularities in hydraulic conditions, induce a uniform flow in suction and discharge lines, and relieve the pump of shocks caused by pulsating flow.

air-chamber pump A displacement pump equipped with an air chamber in which the air is alternately compressed and expanded by the water displaced by the pump, resulting in the water being discharged at a more even rate.

air diffuser Devices of varied design that transfer oxygen from air into a liquid.

air diffusion The transfer of air into a liquid through an oxygen-transfer device. See *diffusion*.

air gap The unobstructed vertical distance through the free atmosphere between the lowest opening from any pipe or outlet supplying water to a tank, plumbing fixture, or other device, and the flood-level rim of the receptacle.

air lift A device for raising liquid by injecting air in and near the bottom of a riser pipe submerged in the liquid to be raised.

air-lift pump A pump, used largely for lifting water from wells, from which fine pressured air bubbles are discharged into the water at the bottom of the well. The bubbles reduce the density of the water at the bottom, allowing the denser surrounding water to push it up in the discharge pipe to the outlet. Also called an *air lift*.

air stripping A technique for removal of volatile substances from a solution; employs the principles of Henry's Law to transfer volatile pollutants from a solution of high concentration into an air stream of lower concentration. The process ordinarily is designed so that the solution containing the volatile pollutant contacts large volumes of air. The method is used to remove ammonia in advanced waste treatment.

algae Photosynthetic microscopic plants that contain chlorophyll that float or are suspended in water. They may also be attached to structures, rocks, etc. In high concentrations, algae may deplete dissolved oxygen in receiving waters.

algal assay An analytical procedure that uses specified nutrients and algal inoculums to identify the limiting algal nutrient in water bodies.

algal bloom Large masses of microscopic and macroscopic plant life, such as green algae, occurring in bodies of water.

alkali Generally, any substance that has highly basic properties; used particularly with reference to the soluble salts of sodium, potassium, calcium, and magnesium.

alkaline The condition of water, wastewater, or soil that contains a sufficient amount of alkali substances to raise the pH above 7.0.

alkalinity The capacity of water to neutralize acids; a property imparted by carbonates, bicarbonates, hydroxides, and occasionally borates, silicates, and phosphates. It is expressed in milligrams of equivalent calcium carbonate per liter (mg/L $CaCO_3$).

alkyl benzene sulfonate (ABS) A type of surfactant, or surface active agent, present in synthetic detergents in the United States prior to 1965. ABS was troublesome because of its foam-producing characteristics and resistance to breakdown by biological action. ABS has been replaced in detergents by linear alkyl sulfonate, which is biodegradable.

alum, aluminum sulfate [$Al_2(SO_4)_3 \times 18H_2O$] Used as a coagulant in filtration. Dissolved in water, it hydrolyzes into $Al(OH)_2$ and sulfuric acid (H_2SO_4). To precipitate the hydroxide, as needed for coagulation, the water must be alkaline.

ambient Generally refers to the prevailing dynamic environmental conditions in a given area.

ammonia, ammonium (NH_3, NH_4^+) Urea and proteins are degraded into dissolved ammonia and ammonium in raw wastewaters. Typically, raw wastewater contains

30 to 50 mg/L of NH_3. Reactions between chlorine and ammonia are important in disinfection.

ammonia nitrogen The quantity of elemental nitrogen present in the form of ammonia (NH_3).

ammoniator Apparatus used for applying ammonia or ammonium compounds to water.

ammonification Bacterial decomposition of organic nitrogen to ammonia.

amoeba A group of simple protozoans, some of which produce diseases such as dysentery in humans.

ampere The unit of measurement of electrical current. It is proportional to the quantity of electrons flowing through a conductor past a given point in one second and is analogous to cubic feet of water flowing per second. It is the current produced in a circuit by one volt acting through a resistance of one ohm.

amperometric Pertaining to measurement of electric current flowing or generated, rather than by voltage.

anaerobic (1) A condition in which free and dissolved oxygen are unavailable. (2) Requiring or not destroyed by the absence of air or free oxygen.

anaerobic bacteria Bacteria that grow only in the absence of free and dissolved oxygen.

anaerobic digestion The degradation of concentrated wastewater solids, during which anaerobic bacteria break down the organic material into inert solids, water, carbon dioxide, and methane.

anaerobic lagoon A wastewater or sludge treatment process that involves retention under anaerobic conditions.

anion A negatively charged ion attracted to the anode under the influence of electrical potential.

anionic flocculant A polyelectrolyte with a net negative electrical charge.

anoxic Condition in which oxygen is available in the combined form only; there is no free oxygen. Anoxic sections in an activated-sludge plant may be used for denitrification.

antagonism Detrimental interaction between two entities. See also *synergism*.

antichlors Reagents, such as sulfur dioxide, sodium bisulfite, and sodium thiosulfate, that can be used to remove excess chlorine residuals from water or watery wastes by conversion to an inert salt.

anticorrosion treatment Treatment to reduce or eliminate corrosion-producing qualities of a water.

appurtenances Machinery, appliances, or auxiliary structures attached to a main structure enabling it to function, but not considered an integral part of it.

aqueous vapor The gaseous form of water. See *water vapor*.

area drain A drain installed to collect surface or stormwater from an open area of a building.

automatic recording gauge An automatic instrument for measuring and recording graphically and continuously. Also called *register*.

automatic sampling Collecting of samples of prescribed volume over a defined time period by an apparatus designed to operate remotely without direct manual control. See also *composite sample.*

autothermal thermophilic aerobic digestion As part of the aerobic digestion process, heat is evolved. In a contained vessel, the sufficient heat is generated to maintain temperatures in the thermophilic range. At higher temperatures, detention time requirements are reduced for a given solids reduction resulting in an end product that is relatively pathogen free.

autotrophic organisms Organisms including nitrifying bacteria and algae that use carbon dioxide as a source of carbon for cell synthesis. They can consume dissolved nitrates and ammonium salts.

available chlorine A measure of the total oxidizing power of chlorinated lime, hypochlorites, and other materials used as a source of chlorine as compared with that of elemental chlorine.

average An arithmetic mean obtained by adding quantities and dividing the sum by the number of quantities.

average daily flow (1) The total quantity of liquid tributary to a point divided by the number of days of flow measurement. (2) In water and wastewater applications, the total flow past a point over a period of time divided by the number of days in that period.

average flow Arithmetic average of flows measured at a given point.

average velocity The average velocity of a stream flowing in a channel or conduit at a given cross section or in a given reach. It is equal to the discharge divided by the cross-sectional area of the section or the average cross-sectional area of the reach. Also called *mean velocity*.

axis A line about which a figure or a body is symmetrically arranged, or about which such a figure or body rotates.

backflow connection In plumbing, any arrangement whereby backflow can occur. Also called *interconnection*, *cross connection*.

backflow preventer A device on a water supply pipe to prevent the backflow of water into the water supply system from the connections on its outlet end. See also *vacuum breaker* and *air gap*.

backflushing The action of reversing the flow through a conduit for the purpose of cleaning the conduit of deposits.

back-pressure valve A valve provided with a disk hinged on the edge so that it opens in the direction of normal flow and closes with reverse flow; a check valve.

backwashing The operation of cleaning a filter by reversing the flow of liquid through it and washing out matter previously captured in it. Filters include true filters such as sand and diatomaceous earth-types, but not other treatment units such as trickling filters.

bacteria A group of universally distributed, rigid, essentially unicellular microscopic organisms lacking chlorophyll. They perform a variety of biological treatment processes including biological oxidation, sludge digestion, nitrification, and denitrification.

bacterial analysis The examination of water and wastewater to determine the presence, number, and identity of bacteria; more commonly called *bacterial examination*.

bacterial examination The examination of water and wastewater to determine the presence, number, and identity of bacteria. Also called *bacterial analysis*. See also *bacteriological count*.

bacteriological count A means for quantifying numbers of organisms. See also *most probable number*.

baffles Deflector vanes, guides, grids, gratings, or similar devices constructed or placed in flowing water, wastewater, or slurry systems as a check or to produce a more uniform distribution of velocities; absorb energy; divert, guide, or agitate the liquids; and check eddies.

barminutor A bar screen of standard design fitted with an electrically operated shredding device that sweeps vertically up and down the screen cutting up material retained on the screen.

bar screen A screen composed of parallel bars, either vertical or inclined, placed in a waterway to catch debris. The screenings are raked from it either manually or automatically. Also called *bar rack*, *rack*.

base A compound that dissociates in aqueous solution to yield hydroxyl ions.

basic data Records of observations and measurements of physical facts, occurrences, and conditions, as they have occurred, excluding any material or information developed by means of computation or estimate. In the strictest sense, basic data include only the recorded notes of observations and measurements, although in general use it

is taken to include computations or estimates necessary to present a clear statement of facts, occurrences, and conditions.

Beggiatoa A filamentous organism whose growth is stimulated by H_2S.

belt screen A continuous band or belt of wire mesh, bars, plates, or other screening medium that passes around upper and lower rollers and from which the material caught on the screen is usually removed by gravity, brushes, or other means.

bicarbonate alkalinity Alkalinity caused by bicarbonate ions.

bioassay (1) An assay method using a change in biological activity as a qualitative or quantitative means of analyzing a material's response to biological treatment. (2) A method of determining the toxic effects of industrial wastes and other wastewaters by using viable organisms; exposure of fish to various levels of a chemical under controlled conditions to determine safe and toxic levels of that chemical.

biochemical (1) Pertaining to chemical change resulting from biological action. (2) A chemical compound resulting from fermentation. (3) Pertaining to the chemistry of plant and animal life.

biochemical oxidation Oxidation brought about by biological activity resulting in the chemical combination of oxygen with organic matter. See *oxidized wastewater*.

biochemical oxygen demand (BOD) A measure of the quantity of oxygen used in the biochemical oxidation of organic matter in a specified time, at a specific temperature, and under specified conditions.

biochemical oxygen demand (BOD) load The BOD content (usually expressed in mass per unit of time) of wastewater passing into a waste treatment system or to a body of water.

biodegradation The destruction of organic materials by microorganisms, soils, natural bodies of water, or wastewater treatment systems.

biofilm Accumulation of microbial growth on the surface of a support material.

biological contactors Inert surfaces engineered to provide a high specific surface area on which a biofilm can develop; usually designed so that the surface is cyclically moved through the medium to be biologically oxidized and through the open air so that oxygen transfer occurs.

biological denitrification The transformation of nitrate nitrogen to inert nitrogen gas by microorganisms in an anoxic environment in the presence of an electron donor to drive the reaction.

biological filter A bed of sand, gravel, broken stone, or other medium through which wastewater flows or trickles. It depends on biological action for its effectiveness.

biological filtration The process of passing a liquid through a biological filter containing fixed media on the surfaces of which develop zoogleal films that absorb and adsorb fine suspended, colloidal, and dissolved solids and release end products of biochemical action.

biological oxidation The process by which living organisms in the presence of oxygen convert organic matter into a more stable or mineral form.

biological process (1) The process by which metabolic activities of bacteria and other microorganisms break down complex organic materials into simple, more stable substances. Self-purification of polluted streams, sludge digestion, and all the so-called secondary wastewater treatments depend on this process. (2) Process involving living organisms and their life activities. Also called *biochemical process*.

biomass The mass of biological material contained in a system.

biosolids The organic product of municipal wastewater treatment that can be beneficially used.

bleed (1) To drain a liquid or gas, as to vent accumulated air from a water line or to drain a trap or a container of accumulated water. (2) The exuding, percolation, or seeping of a liquid through a surface.

blinding (1) Clogging of the filter cloth of a vacuum filter, belt press, belt thickener, or pressure filter. (2) Obstruction of the fine media of a sand filter.

blowdown (1) The removal of a portion of any process flow to maintain the constituents of the flow within desired levels. The process may be intermittent or continuous. (2) The water discharged from a boiler or cooling tower to dispose of accumulated dissolved solids.

bottom contraction The reduction in the area of overflowing water caused by the crest of a weir contracting the nappe.

bottom ventilation Movement of air through the medium of a wastewater filter facilitated by vent stacks or provisions for the entrance or exit of air at the base of the filter.

bound water (1) Water held strongly on the surface or in the interior of colloidal particles. (2) Water associated with the hydration of crystalline compounds.

branch circuit That portion of the wiring system between the final overcurrent device that protects the circuit and the outlet.

breakpoint chlorination Addition of chlorine to water or wastewater until the chlorine demand has been satisfied, with further additions resulting in a residual that is directly proportional to the amount added beyond the breakpoint.

brush aerator A surface aerator that rotates about a horizontal shaft with metal blades attached to it; commonly used in oxidation ditches.

buffer A substance that resists a change in pH.

bulking Inability of activated-sludge solids to separate from the liquid under quiescent conditions; may be associated with the growth of filamentous organisms, low DO, or high sludge loading rates. Bulking sludge typically has an SVI > 150 mL/g.

bus An electrical conductor that serves as a common connection for two or more electrical circuits. A bus may be in the form of rigid bars, either circular or rectangular in cross section, or in the form of stranded conductor cables held under tension.

butterfly valve A valve in which the disk, as it opens or closes, rotates about a spindle supported by the frame of the valve. The valve is opened at a stem. At full opening, the disk is in a position parallel to the axis of the conduit.

bypass An arrangement of pipes, conduits, gates, and valves by which the flow may be passed around a hydraulic structure appurtenance or treatment process; a controlled diversion.

cake Wastewater solids that have been sufficiently dewatered to form a semisolid mass.

calcium hypochlorite [$Ca(OCl)_2 \cdot 4H_2O$] A solid that, when mixed with water, liberates the hypochlorite ion OCl^- and can be used for disinfection.

calibration (1) The determination, checking, or rectifying of the graduation of any instrument giving quantitative measurements. (2) The process of taking measurements or of making observations to establish the relationship between two quantities.

calorie The amount of heat necessary to raise the temperature of 1 g of water at 15 °C by 1 °C.

capacitor (condenser) A device to provide capacitance, which is the property of a system of conductors and dielectrics that permit the storage of electrically separated charges when potential differences exist between the conductors. A dielectric is an insulator.

capacity (1) The quantity that can be contained exactly, or the rate of flow that can be carried out exactly. (2) The load for which an electrical apparatus is rated either by the user or manufacturer.

carbon (C) (1) A chemical element essential for growth. (2) A solid material used for adsorption of pollutants.

carbonaceous biochemical oxygen demand (CBOD) A quantitative measure of the amount of dissolved oxygen required for the biological oxidation of carbon-containing compounds in a sample. See *BOD*.

carbon adsorption The use of either granular or powdered carbon to remove organic compounds from wastewater or effluents. Organic molecules in solution are drawn to the highly porous surface of the carbon by intermolecular attraction forces.

carbonate hardness Hardness caused by the presence of carbonates and bicarbonates of calcium and magnesium in water. Such hardness may be removed to the limit of solubility by boiling the water. When the hardness is numerically greater than the sum of the carbonate alkalinity and bicarbonate alkalinity, the amount of hardness is equivalent to the total alkalinity and is called *carbonate hardness*. It is expressed in milligrams of equivalent calcium carbonate per liter (mg/L $CaCO_3$). See also *hardness*.

carbonation The diffusion of carbon dioxide gas through a liquid to render the liquid stable with respect to precipitation or dissolution of alkaline constituents. See also *recarbonation*.

carcinogen A material that induces excessive or abnormal cellular growth in an organism.

carrying capacity The maximum rate of flow that a conduit, channel, or other hydraulic structure is capable of passing.

cascade aerator An aerating device built in the form of steps or an inclined plane on which are placed staggered projections arranged to break up the water and bring it into contact with air.

cathodic protection An electrical system for prevention of rust, corrosion, and pitting of steel and iron surfaces in contact with water. A low-voltage current is made to flow through a liquid or a soil in contact with the metal in such a manner that the external electromotive force renders the metal structure cathodic and concentrates corrosion on auxiliary anodic parts used for that purpose.

cation A positively charged ion attracted to the cathode under the influence of electrical potential.

cationic flocculant A polyelectrolyte with a net positive electrical charge.

caustic alkalinity The alkalinity caused by hydroxyl ions. See also *alkalinity*.

cavitation (1) The action, resulting from forcing a flow stream to change direction, in which reduced internal pressure causes dissolved gases to expand, creating negative pressure. Cavitation frequently causes pitting of the hydraulic structure affected. (2) The formation of a cavity between the downstream surface of a moving body (e.g., the blade of a propeller) and a liquid normally in contact with it. (3) Describing the action of an operating centrifugal pump when it is attempting to discharge more water than suction can provide.

Celsius The international name for the centigrade scale of temperature, on which the freezing point and boiling point of water are 0 °C and 100 °C, respectively, at a barometric pressure of 1.013×10^5 Pa (760-mm Hg).

centigrade A thermometer temperature scale in which 0° marks the freezing point and 100° the boiling point of water at 760-mm Hg barometric pressure. Also called *Celsius*. To convert temperature on this scale to Fahrenheit, multiply by 1.8 and add 32.

centrate Liquid removed by a centrifuge; typically contains high concentrations of suspended, nonsettling solids.

centrifugal pump A pump consisting of an impeller fixed on a rotating shaft and enclosed in a casing having an inlet and a discharge connection. The rotating impeller creates pressure in the liquid by the velocity derived from centrifugal force.

centrifugal screw pump A centrifugal pump having a screw-type impeller; may be of axial flow or combined axial and radial flow.

centrifugation Imposition of a centrifugal force to separate solids from liquids based on density differences. In sludge dewatering, the separated solids commonly are called *cake* and the liquid is called *centrate*.

centrifuge A mechanical device in which centrifugal force is used to separate solids from liquids or to separate liquids of different densities.

certification A program to substantiate the capabilities of personnel by documentation of experience and learning in a defined area of endeavor.

cfs (cu ft/sec) The rate of flow of a material in cubic feet per second; used for measurement of water, wastewater, or gas; equals 2.832×10^{-2} m^3/s.

chain bucket A continuous chain equipped with buckets and mounted on a scow. Also called a *ladder dredge*.

chamber Any space enclosed by walls or a compartment; often prefixed by a descriptive word indicating its function, such as *grit* chamber, *screen* chamber, *discharge* chamber, or *flushing* chamber.

change of state The process by which a substance passes from one to another of the solid, the liquid, and the gaseous states, and in which marked changes in its physical properties and molecular structure occur.

channel (1) A perceptible natural or artificial waterway that periodically or continuously contains moving water or forms a connecting link between two bodies of water. It has a definite bed and banks that confine the water. (2) The deep portion of a river or waterway where the main current flows. (3) The part of a body of water deep enough to be used for navigation through an area otherwise too shallow for naviga-

tion. (4) Informally, a more or less linear conduit of substantial size in cavernous limestones or lava rocks. See also *open channel*.

channel roughness That roughness of a channel including the extra roughness owing to local expansion or contraction and obstacles, as well as the roughness of the stream bed proper; that is, friction offered to the flow by the surface of the bed of the channel in contact with the water. It is expressed as the roughness coefficient in velocity formulas.

check valve A valve with a disk hinged on one edge so that it opens in the direction of normal flow and closes with reverse flow. An approved check valve is of substantial construction and suitable materials, is positive in closing, and permits no leakage in a direction opposite to normal flow.

chemical Commonly, any substance used in or produced by a chemical process. Certain chemicals may be added to water or wastewater to improve treatment efficiency; others are pollutants that require removal.

chemical analysis Analysis by chemical methods to show the composition and concentration of substances.

chemical coagulation The destabilization and initial aggregation of colloidal and finely divided suspended matter by the addition of an inorganic coagulant. See also *flocculation*.

chemical conditioning Mixing chemicals with a sludge prior to dewatering to improve the solids separation characteristics. Typical conditioners include polyelectrolytes, iron salts, and lime.

chemical dose A specific quantity of chemical applied to a specific quantity of fluid for a specific purpose.

chemical equilibrium The condition that exists when there is no net transfer of mass or energy between the components of a system. This is the condition in a reversible chemical reaction when the rate of the forward reaction equals the rate of the reverse reaction.

chemical equivalent The weight (in grams) of a substance that combines with or displaces 1 g of hydrogen. It is found by dividing the formula weight by its valence.

chemical feeder A device for dispensing a chemical at a predetermined rate for the treatment of water or wastewater. The change in rate of feed may be effected manually or automatically by flowrate changes. Feeders are designed for solids, liquids, or gases.

chemical gas feeder A feeder for dispensing a chemical in the gaseous state. The rate is usually graduated in gravimetric terms. Such devices may have proprietary names.

chemical oxidation The oxidation of compounds in wastewater or water by chemical means. Typical oxidants include ozone, chlorine, and potassium permanganate.

chemical oxygen demand (COD) A quantitative measure of the amount of oxygen required for the chemical oxidation of carbonaceous (organic) material in wastewater using inorganic dichromate or permanganate salts as oxidants in a 2-hour test.

chemical precipitation (1) Formation of particulates by the addition of chemicals. (2) The process of softening water by the addition of lime or lime and soda to form insoluble compounds; usually followed by sedimentation or filtration to remove the newly created suspended solids.

chemical reaction A transformation of one or more chemical species into other species resulting in the evolution of heat or gas, color formation, or precipitation. It may be initiated by a physical process such as heating, by the addition of a chemical reagent, or it may occur spontaneously.

chemical reagent A chemical added to a system to induce a chemical reaction.

chemical sludge Sludge obtained by treatment of water or wastewater with inorganic coagulants.

chemical solution tank A tank in which chemicals are added in solution before they are used in a water or wastewater treatment process.

chemical tank A tank in which chemicals are stored before they are used in a water or wastewater treatment process.

chemical treatment Any treatment process involving the addition of chemicals to obtain a desired result such as precipitation, coagulation, flocculation, sludge conditioning, disinfection, or odor control.

chloramines Compounds of organic or inorganic nitrogen formed during the addition of chlorine to wastewater. See *breakpoint chlorination*.

chlorination The application of chlorine or chlorine compounds to water or wastewater, generally for the purpose of disinfection, but frequently for chemical oxidation and odor control.

chlorinator Any metering device used to add chlorine to water or wastewater.

chlorine (Cl_2) An element ordinarily existing as a greenish-yellow gas about 2.5 times heavier than air. At atmospheric pressure and a temperature of −30.1 °F (−48 °C), the gas becomes an amber liquid about 1.5 times heavier than water. Its atomic weight is 35.457, and its molecular weight is 70.914.

chlorine contact chamber A detention basin provided to diffuse chlorine through water or wastewater and to provide adequate contact time for disinfection. Also called a *chlorination chamber* or *chlorination basin*.

chlorine demand The difference between the amount of chlorine added to a wastewater and the amount of chlorine remaining after a given contact time. Chlorine

dosage is a function of the substances present in the water, temperature, and contact time.

chlorine dose The amount of chlorine applied to a wastewater, usually expressed in milligrams per liter (mg/L) or pounds per million gallons (lb/mil. gal).

chlorine ice A yellowish ice formed in a chlorinator when chlorine gas comes in contact with water at 49 °F (9 °C) or lower. Chlorine ice is frequently detrimental to the performance of a chlorinator if it is formed in quantities sufficient to interfere with the safe operation of float controls or to cause plugging of openings essential to flow indication, control, or rate of application.

chlorine residual The amount of chlorine in all forms remaining in water after treatment to ensure disinfection for a period of time.

chlorine room A separate room or building for housing chlorine and chlorination equipment, with arrangements for protecting personnel and plant equipment.

chlorine toxicity The detrimental effects on biota caused by the inherent properties of chlorine.

chromatography The generic name of a group of separation processes that depend on the redistribution of the molecules of a mixture between a gas or liquid phase in contact with one or more bulk phases. The types of chromatography are adsorption, column, gas, gel, liquid, thin-layer, and paper.

ciliated protozoa Protozoans with cilia (hair-like appendages) that assist in movement; common in trickling filters and healthy activated sludge. Free-swimming ciliates are present in the bulk liquid, stalked ciliates are commonly attached to solids matter in the liquid.

circuit A conductor or a system of conductors through which an electrical current flows or is intended to flow.

circuit breaker A device designed to open or close a circuit by nonautomatic means and open the circuit automatically on a predetermined overload of current without injury to itself.

clarification Any process or combination of processes whose primary purpose is to reduce the concentration of suspended matter in a liquid; formerly used as a synonym for *settling* or *sedimentation*. In recent years, the latter terms are preferable when describing settling processes.

clarifier Any large circular or rectangular sedimentation tank used to remove settleable solids in water or wastewater. A special type of clarifier, called an *upflow clarifier*, uses flotation rather than sedimentation to remove solids.

clear-water basin A reservoir for the storage of filtered water of sufficient capacity to prevent the necessity of frequent variations in the rate of filtration with variations in demands. Also called *filtered-water reservoir*, *clear-water reservoir*, *clear well*.

closed centrifugal pump A centrifugal pump having its impeller built with the vanes enclosed within circular disks.

closed conduit Any closed artificial or natural duct for conveying fluids.

closed impeller An impeller having the side walls extended from the outer circumference of the suction opening to the vane tips.

coagulant A simple electrolyte, usually an inorganic salt containing a multivalent cation of iron, aluminum, or calcium [for example, $FeCl_3$, $FeCl_2$, $Al_2(SO_4)_3$, and CaO]. Also, an inorganic acid or base that induces coagulation of suspended solids. See also *flocculant*.

coagulant* or *flocculant aid An insoluble particulate used to enhance solid–liquid separation by providing nucleating sites or acting as a weighting agent or sorbent; also used colloquially to describe the action of flocculents in water treatment.

coagulation The conversion of colloidal (<0.001 mm) or dispersed (0.001 to 0.1 mm) particles into small visible coagulated particles (0.1 to 1 mm) by the addition of a coagulant, compressing the electrical double layer surrounding each suspended particle, decreasing the magnitude of repulsive electrostatic interactions between particles, and thereby destabilizing the particle. See also *flocculation*.

coagulation basin A basin used for the coagulation of suspended or colloidal matter, with or without the addition of a coagulant, in which the liquid is mixed gently to induce agglomeration with a consequent increase in the settling velocity of particulates.

coating A material applied to the inside or outside of a pipe, valve, or other fixture to protect it primarily against corrosion. Coatings may be of various materials.

Cocci Sphere-shaped bacteria.

codisposal Joint disposal of wastewater sludge and municipal refuse in one process or facility. Disposal can be intermediate, as with incineration or composting, or final, as with placement in a sanitary landfill.

coefficient A numerical quantity, determined by experimental or analytical methods, interposed in a formula that expresses the relationship between two or more variables to include the effect of special conditions or to correct a theoretical relationship to one found by experiment or actual practice.

coefficient of viscosity A numerical factor that is a measure of the internal resistance of a fluid to flow; the greater the resistance to flow, the larger the coefficient. It is equal to the shearing force in dynes per square centimeter (dyne/cm^2) transmitted from one

fluid plane to another parallel plane 1 cm distant, and is generated by a difference in fluid velocities in the two planes of 1 cm/s in the direction of the force. The coefficient varies with temperature. Also called *absolute viscosity*. The unit of measure is the poise, a force of 1 dyne/cm^2.

cohesion The force of molecular attraction between the particles of any substance that tends to hold them together.

coil A set of windings with or without an iron core, shaped to produce a magnetic force when current flows through the windings. This force is used in relays and other electrical equipment to pull contacts together or to separate them.

coliform-group bacteria A group of bacteria predominantly inhabiting the intestines of man or animal, but also occasionally found elsewhere. It includes all aerobic and facultative anaerobic, Gram-negative, non-spore-forming, rod-shaped bacteria that ferment lactose with the production of gas. Also included are all bacteria that produce a dark, purplish-green metallic sheen by the membrane filter technique used for coliform identification. The two groups are not always identified, but they are generally of equal sanitary significance.

collection system In wastewater, a system of conduits, generally underground pipes, that receives and conveys sanitary wastewater or stormwater; in water supply, a system of conduits or canals used to capture a water supply and convey it to a common point.

colloids Finely divided solids (less than 0.002 mm and greater than 0.000 001 mm) that will not settle but may be removed by coagulation, biochemical action, or membrane filtration; they are intermediate between true solutions and suspensions.

colony A discrete clump of microorganisms on a surface as opposed to dispersed growth throughout a liquid culture medium.

color Any dissolved solids that impart a visible hue to water.

colorimeter An instrument that quantitatively measures the amount of light of a specific wavelength absorbed by a solution.

combined available chlorine The concentration of chlorine that is combined with ammonia as chloramine or as other chloro derivatives, yet is still available to oxidize organic matter.

combined available residual chlorine That portion of the total residual chlorine remaining in water or wastewater at the end of a specified contact period that will react chemically and biologically as chloramines.

combined residual chlorination The application of chlorine to water or wastewater to produce, with natural or added ammonia or with certain organic nitrogen compounds, a combined chlorine residual.

combined sewer A sewer intended to receive both wastewater and storm or surface water.

combustible-gas indicator An explosimeter; a device for measuring the concentration of potentially explosive fumes. The measurement is based on the catalytic oxidation of a combustible gas on a heated platinum filament that is part of a Whetstone bridge.

commercially dry sludge Sludge containing not more than 10% moisture by weight; the limit is 5% in the fertilizer trade.

comminution An in-stream process of cutting and screening solids contained in wastewater flow.

comminutor A shredding or grinding device that reduces the size of gross suspended materials in wastewater without removing them from the liquid.

complete mix Activated sludge process whereby wastewater is rapidly and evenly distributed throughout the aeration tank.

composite sample A combination of individual samples of water or wastewater taken at preselected intervals to minimize the effect of the variability of the individual sample. Individual samples may be of equal volume or may be proportional to the flow at the time of sampling.

compost The product of the thermophilic biological oxidation of sludge or other materials.

concentration (1) The amount of a given substance dissolved in a discrete unit volume of solution or applied to a unit weight of solid. (2) The process of increasing the dissolved solids per unit volume of solution, usually by evaporation of the liquid. (3) The process of increasing the suspended solids per unit volume of sludge as by sedimentation or dewatering.

concentrator A solids contact unit used to decrease the water content of sludge or slurry.

condensate Condensed steam from any heat exchanger.

condensation The process by which a substance changes from the vapor state to the liquid or solid state. Water that falls as precipitation from the atmosphere has condensed from the vapor state to rain or snow. Dew and frost are also forms of condensation.

condenser Any device for reducing gases or vapors to liquid or solid form.

conditioning The chemical, physical, or biological treatment of sludges to improve their dewaterability.

conductor A material that offers very little resistance to the flow of current and is, therefore, used to carry current or conduct electricity.

conduit (duct) bank A length of one or more conduits or ducts (which may be enclosed in concrete) that is designed to contain cables.

contacts Any set of points that may be joined manually or automatically to complete a circuit. Contacts are found in breakers, switches, relays, and starters.

contact stabilization Modification of the activated-sludge process involving a short period of contact between wastewater and sludge for rapid removal of soluble BOD by adsorption, followed by a longer period of aeration in a separate tank where sludge is oxidized and new sludge synthesized.

contact tank A tank used in water or wastewater treatment to promote contact between treatment chemicals or other materials and the liquid treated.

contact time The time that the material processed is exposed to another substance (such as activated sludge or activated carbon) for completion of the desired reaction. See also *detention time*.

contamination The introduction into water of microorganisms, chemicals, wastes, or wastewater in a concentration that makes the water unfit for its intended use.

continuous-flow pump A displacement pump within which the direction of flow of the water is not changed or reversed.

continuous-flow tank A tank through which liquid flows continuously at its normal rate of flow, as distinguished from a fill-and-draw or batch system.

continuous load A load where the maximum current is expected to continue for 3 hours or more.

contracted weir A rectangular notched weir with a crest width narrower than the channel across which it is installed and with vertical sides extending above the upstream water level producing a contraction in the stream of water as it leaves the notch.

controlled discharge Regulation of effluent flowrates to correspond with flow variations in receiving waters to maintain established water quality.

controller A device or group of devices, that serve to govern, in some predetermined measure, the electrical power delivered to the apparatus to which it is connected.

convection (1) In physics, mass motions within a fluid resulting in the transport and mixing of the properties of that fluid, caused by the force of gravity and by differences in density resulting from nonuniform temperature. (2) In meteorology, atmospheric motions that are predominantly vertical, resulting in vertical transport and mixing of atmospheric properties; sometimes caused when large masses of air are heated by contact with a warm land surface.

conventional aeration Process design configuration whereby the aeration tank organic loading is higher at the influent end than at the effluent end. Flow passes through a serpentine tank system, typically side-by-side, before passing on to the secondary clarifier. Also called *plug flow*.

conventional treatment Well-known or well-established water or wastewater treatment processes, excluding advanced or tertiary treatment; it generally consists of primary and secondary treatment.

conversion factor A numerical constant by which a quantity with its value expressed in units of one kind is multiplied to express the value in units of another kind.

cooling coil A coil of pipe or tubing containing a stream of hot fluid that is cooled by heat transfer to a cold fluid outside. Conversely, the coil may contain a cold fluid to cool a hot fluid in which the coil is immersed.

core sampler A long, slender pole with a foot valve at the bottom end that allows the depth of the sludge blanket to be measured. Sometimes called a *sludge judge*.

correlation (1) A mutual relationship or connection. (2) The degree of relative correspondence, as between two sets of data.

corrosion The gradual deterioration or destruction of a substance or material by chemical action, frequently induced by electrochemical processes. The action proceeds inward from the surface.

corrosion control (1) In water treatment, any method that keeps the metallic ions of a conduit from going into solution, such as increasing the pH of the water, removing free oxygen from the water, or controlling the carbonate balance of the water. (2) The sequestration of metallic ions and the formation of protective films on metal surfaces by chemical treatment.

critical depth The depth of water flowing in an open channel or partially filled conduit corresponding to one of the recognized critical velocities.

critical flow (1) A condition of flow in which the mean velocity is at one of the critical values, ordinarily at Belanger's critical depth and velocity; also used in reference to Reynolds' critical velocities, which define the point at which the flow changes from streamline or nonturbulent flows. (2) The maximum discharge of a conduit that has a free outlet and has the water ponded at the inlet.

cross connection (1) A physical connection through which a supply of potable water could be contaminated or polluted. (2) A connection between a supervised potable water supply and an unsupervised supply of unknown potability.

culture Any organic growth that has been developed intentionally by providing suitable nutrients and environment.

culture media Substances used to support the growth of microorganisms in analytical procedures.

cyclone separator A conical unit used for separating particles by centrifugal force.

data Records of observations and measurements of physical facts, occurrences, and conditions reduced to written, graphical, or tabular form.

debris Generally, solid wastes from natural and man-made sources deposited indiscriminately on land and water.

decantation Separation of a liquid from solids or from a liquid of higher density by drawing off the upper layer after the heavier material has settled.

dechlorination The partial or complete reduction of residual chlorine by any chemical or physical process. Sulfur dioxide is frequently used for this purpose.

declining growth phase Period of time between the log-growth phase and the endogenous phase, where the amount of food is in short supply, leading to ever-slowing bacterial growth rates.

decomposition The breakdown of complex material into simpler substances by chemical or biological processes.

decomposition of wastewater (1) The breakdown of organic matter in wastewater by bacterial action, either aerobic or anaerobic. (2) Chemical or biological transformation of the organic or inorganic materials contained in wastewater.

defoamer A material having low compatibility with foam and a low surface tension. Defoamers are used to control, prevent, or destroy various types of foam, the most widely used being silicone defoamers. A droplet of silicone defoamer contacting a bubble of foam will cause the bubble to undergo a local and drastic reduction in film strength, thereby breaking the film. Unchanged, the defoamer continues to contact other bubbles, thus breaking up the foam. A valuable property of most defoamers is their effectiveness in extremely low concentration. In addition to silicones, defoamers for special purposes are based on polyamides, vegetable oils, and stearic acid.

degasification (1) The removal of a gas from a liquid medium. (2) In water treatment, the removal of oxygen from water to inhibit corrosion. It may be accomplished by mechanical methods, chemical methods, or a combination of both.

degreasing (1) The process of removing greases and oils from waste, wastewater, sludge, or solids. (2) The industrial process of removing grease and oils from machine parts or iron products.

degree (1) On the centigrade or Celsius thermometer scale, 1/100 of the interval from the freezing point to the boiling point of water under standard conditions; on the

Fahrenheit scale, 1/180 of this interval. (2) A unit of angular measure; the central angle subtended by 1/360 of the circumference of a circle.

demand The rate at which electrical energy is delivered to a piece of power-consuming equipment or system.

demand average The demand on an electrical system or any of its parts over an interval of time, as determined by dividing the total number of watt-hours by the number of hours (units of time) in the interval.

demand coincident The sum of two or more demands that occurs in the same demand interval.

demand factor The ratio of the maximum demand of the system or part of a system to the total connected load of the system or part of the system under consideration.

demand instantaneous peak The maximum demand at the instant of greatest load.

demand interval The period of time that electrical energy flows is averaged to determine demand, such as 60 minutes, 15 minutes, or instantaneous.

demand maximum The greatest of all demands of the load under consideration that occurs during a specified period of time.

demand noncoincident The sum of two or more individual demands that do not occur in the same demand interval, which is meaningful only when considering demands within a limited period of time, such as a day, week, month, and a heating or cooling season.

denitrification The anaerobic biological reduction of nitrate nitrogen to nitrogen gas; also, removal of total nitrogen from a system. See also *nitrification*.

density current A flow of water through a large body of water that retains its unmixed identity because of a difference in density.

deoxygenation The depletion of the dissolved oxygen in a liquid either under natural conditions associated with the biochemical oxidation of the organic matter present or by addition of chemical reducing agents.

deoxygenation constant A constant that expresses the rate of the biochemical oxidation of organic matter under aerobic conditions. Its value depends on the time unit involved (usually 1 day) and varies with temperature and other test conditions.

departure The difference between any single observation and the normal.

deposition The act or process of settling solid material from a fluid suspension.

depth of blanket Level of sludge in the bottom of a secondary clarifier, typically measured in feet.

design criteria (1) Engineering guidelines specifying construction details and materials. (2) Objectives, results, or limits that must be met by a facility, structure, or process in performance of its intended functions.

design flow Engineering guidelines that typically specify the amount of influent flow that can be expected on a daily basis over the course of a year. Other design flows can be set for monthly or peak flows.

design loadings Flowrates and constituent concentrations that determine the design of a process unit or facility necessary for proper operation.

design voltage The nominal voltage for which a line or piece of equipment is designed. This is a reference level of voltage for identification and not necessarily the precise level at which it operates.

detention time The period of time that a water or wastewater flow is retained in a basin, tank, or reservoir for storage or completion of physical, chemical, or biological reaction. See also *contact time*, *retention time*.

detergent (1) Any of a group of synthetic, organic, liquid, or water-soluble cleaning agents that are inactivated by hard water and have wetting and emulsifying properties but, unlike soap, are not prepared from fats and oils. (2) A substance that reduces the surface tension of water.

detoxification Treatment to modify or remove a toxic material.

dewater (1) To extract a portion of the water present in a sludge or slurry. (2) To drain or remove water from an enclosure. A river bed may be dewatered so that a dam can be built; a structure may be dewatered so that it can be inspected or repaired.

dewatered sludge The solid residue remaining after removal of water from a wet sludge by draining or filtering. Dewatering is distinguished from thickening in that dewatered sludge may be transported by solids handling procedures.

dewatering The process of partially removing water; may refer to removal of water from a basin, tank, reservoir, or other storage unit, or the separation of water from solid material.

dewpoint The temperature to which air with a given concentration of water vapor must be cooled to cause condensation of the vapor.

dialysis The selective separation of dissolved or colloidal solids on the basis of molecular size by diffusion through a semipermeable membrane. See also *reverse osmosis*.

differential plunger pump A reciprocating pump with a plunger so designed that it draws the liquid into the cylinder on the upward stroke but is double-acting on the discharge stroke.

diffused aeration Injection of air under pressure through submerged porous plates, perforated pipes, or other devices to form small air bubbles from which oxygen is transferred to the liquid as the bubbles rise to the water surface.

diffused air Small air bubbles formed below the surface of a liquid to transfer oxygen to the liquid.

diffuser A porous plate, tube, or other device through which air is forced and divided into minute bubbles for diffusion in liquids. In the activated sludge process, it is a device for dissolving air into mixed liquor. It is also used to mix chemicals such as chlorine through perforated holes.

diffusion (1) The transfer of mass from one fluid phase to another across an interface, for example liquid to solid or gas to liquid. (2) The spatial equalization of one material throughout another.

diffusion aerator An aerator that blows air under low pressure through submerged porous plates, perforated pipes, or other devices so that small air bubbles rise continuously through the water or wastewater.

digested solids Solids digested under either aerobic or anaerobic conditions until the volatile content has been reduced to the point at which the solids are relatively nonputrescible and inoffensive.

digester A tank or other vessel for the storage and anaerobic or aerobic decomposition of organic matter present in the sludge. See also *anaerobic digestion*.

digester coils A system of hot water or steam pipes installed in a digestion tank to heat the digester contents.

digestion (1) The biological decomposition of the organic matter in sludge, resulting in partial liquefaction, mineralization, and volume reduction. (2) The process carried out in a digester.

discharge The flow or rate of flow from a canal, conduit, pump, stack, tank, or treatment process. See also *effluent*.

discharge area The cross-sectional area of a waterway. Used to compute the discharge of a stream, pipe, conduit, or other carrying system.

discharge capacity The maximum rate of flow that a conduit, channel, or other hydraulic structure is capable of passing.

discharge head A measure of the pressure exerted by a fluid at the point of discharge, usually from a pump.

discharge rate (1) The determination of the quantity of water flowing per unit of time in a stream channel, conduit, or orifice at a given point by means of a current meter,

rod float, weir, pitot tube, or other measuring device or method. The operation includes not only the measurement of velocity of water and the cross-sectional area of the stream of water, but also the necessary subsequent computations. (2) The numerical results of a measurement of discharge, expressed in appropriate units.

disconnecting means A device, group of devices, or other means whereby the conductors of a circuit can be disconnected from the source of power.

discrete sedimentation Sedimentation in which removal of suspended solids is a function of terminal settling velocity.

disinfectant A substance used for disinfection and in which disinfection has been accomplished.

disinfected wastewater Wastewater to which a disinfecting agent has been added.

disinfection (1) The killing of waterborne fecal and pathogenic bacteria and viruses in potable water supplies or wastewater effluents with a disinfectant; an operational term that must be defined within limits, such as achieving an effluent with no more than 200 colonies fecal coliform/100 mL. (2) The killing of the larger portion of microorganisms, excluding bacterial spores, in or on a substance with the probability that all pathogenic forms are killed, inactivated, or otherwise rendered nonvirulent.

dispersion (1) Scattering and mixing. (2) The mixing of polluted fluids with a large volume of water in a stream or other body of water. (3) The repelling action of an electric potential on fine particles in suspension in water, as in a stream carrying clay. This dispersion usually is ended by contact with ocean water causing flocculation and precipitation of the clay, a common cause of shoaling in harbors. (4) In a continuous-flow treatment unit, the phenomenon of short-circuiting.

displacement pump A type of pump in which the water is induced to flow from the source of supply through an inlet pipe and valve and into the pump chamber by a vacuum created therein by the withdrawal of a piston or piston-like device which, on its return, displaces a certain volume of the water contained in the chamber and forces it to flow through the discharge valves and discharge pipes.

disposal Release to the environment. See also *ultimate disposal*.

dissolved air flotation (DAF) A separation process in which air bubbles emerging from a supersaturated solution become attached to suspended solids in the liquid undergoing treatment and float them up to the surface. See also *diffused air*.

dissolved oxygen (DO) The oxygen dissolved in liquid, usually expressed in milligrams per liter (mg/L) or percent saturation.

dissolved solids Solids in solution that cannot be removed by filtration; for example, NaCl and other salts that must be removed by evaporation. See also *total dissolved solids.*

distributor A device used to apply liquid to the surface of a filter or contact bed. Distributors are of two general types: fixed and movable. The fixed type consists of perforated pipes, notched troughs, sloping boards, or sprinkler nozzles. The movable type consists of rotating, reciprocating, or traveling perforated pipes or troughs applying a spray or a thin sheet of liquid.

diurnal (1) Occurring during a 24-hour period; diurnal variation. (2) Occurring during the day (as opposed to night). (3) In tidal hydraulics, having a period or cycle of approximately 1 tidal day.

diversity The characteristic or variety of electrical loads whereby individual maximum demands usually occur at different times. Diversity among equipment loads results in diversity among the loads of transformers, feeders, and substations.

diversity factor The ratio of the sum of the coincident demands of two or more loads to their maximum demands for the same period.

domestic wastewater Wastewater derived principally from dwellings, business buildings, institutions, and the like. It may or may not contain groundwater, surface water, or stormwater.

dosing tank Any tank used in applying a dose; specifically used for intermittent application of wastewater to subsequent processes.

double-suction impeller An impeller with two suction inlets, one on each side of the impeller.

double-suction pump A centrifugal pump with suction pipes connected to the casing from both sides.

DPD method An analytical method for determining chlorine residual using the reagent DPD (n-diethyl-p-phenylenediamine). This is the most commonly and officially recognized test for free chlorine residual.

drag The resistance offered by a liquid to the settlement or deposition of a suspended particle.

drag coefficient A measure of the resistance to sedimentation or flotation of a suspended particle as influenced by its size, shape, density, and terminal velocity. It is the ratio of the force per unit area to the stagnation pressure and is dimensionless. See also *friction factor*.

drain (1) A conduit or channel constructed to carry off, by gravity, liquids other than wastewater, including surplus underground, storm, or surface water. It may be an open ditch, lined or unlined, or a buried pipe. (2) In plumbing, any pipe that carries water or wastewater in a building drainage system.

drawdown (1) The magnitude of the change in surface elevation of a body of water as a result of the withdrawal of water. (2) The magnitude of the lowering of the water surface in a well, and of the water table or piezometric surface adjacent to the well, resulting from the withdrawal of water from the well by pumping. (3) In a continuous water surface with accelerating flow, the difference in elevation between downstream and upstream points.

drum screen A screen in the form of a cylinder or truncated cone that rotates on its axis.

dry-bulb temperature The temperature of air measured by a conventional thermometer.

dry feeder A feeder for dispensing a chemical or other fine material to water or wastewater at a rate controlled manually or automatically by the rate of flow. The constant rate may be either volumetric or gravimetric.

drying beds Confined, shallow layers of sand or gravel on which wet sludge is distributed for draining and air drying; also applied to underdrained, shallow, dyked, earthen structures used for drying sludge.

dry suspended solids The weight of the suspended matter in a sample after drying for a specified time at a specific temperature.

dry weather flow (1) The flow of wastewater in a combined sewer during dry weather. Such flow consists mainly of wastewater, with no stormwater included. (2) The flow of water in a stream during dry weather, usually contributed entirely by groundwater.

dual-media filters Deep-bed filters using discrete layers of dissimilar media, such as anthracite and sand, placed one on top of the other.

duplex pump A reciprocating pump consisting of two cylinders placed side by side and connected to the same suction and discharge pipe; the pistons move so that one exerts suction while the other exerts pressure resulting in continuous discharge from the pump.

dynamic equilibrium See *population dynamics*.

dynamic head (1) When there is flow, (a) the head at the top of a waterwheel; (b) the height of the hydraulic grade line above the top of a waterwheel; and (c) the head against which a pump works. (2) That head of fluid that would produce statically the pressure of a moving fluid.

dynamic suction head The reading of a gauge on the suction line of a pump corrected for the distance of the pump below the free surface of the body of liquid being pumped; exists only when the pump is below the free surface. When pumping proceeds at the required capacity, the vertical distance from the source of supply to the center of the pump minus velocity head and entrance and friction losses. Internal pump losses are not subtracted.

dynamic suction lift When pumping proceeds at the required capacity, the vertical distance from the source of supply to the center of the suction end of a pump, plus velocity head and entrance and friction losses. Internal pump losses are not added.

E. coli See *Escherichia coli*.

eductor A device for mixing air with water; a liquid pump operating under a jet principle, using liquid under pressure as the operating medium to entrain air in the liquid. See also *ejector*.

effective size The diameter of the particles, spherical in shape, equal in size, and arranged in a given manner, of a hypothetical sample of granular material that would have the same transmission constant as the actual material under consideration. There are a number of methods for determining effective size, the most common being that developed by Allen Hazen, which consists of passing the granular material through sieves with varying dimensions of mesh. In this method, the effective size is determined from the dimensions of that mesh, which permits 10% of the sample to pass and will retain the remaining 90%; in other words, the effective size is that for which 10% of the grains are smaller and 90% larger.

effervescence The vigorous escape of small gas bubbles from a liquid, especially as a result of chemical action.

efficiency The relative results obtained in any operation in relation to the energy or effort required to achieve such results. It is the ratio of the total output to the total input, expressed as a percentage.

effluent Wastewater or other liquid, partially or completely treated or in its natural state, flowing out of a reservoir, basin, treatment plant, or industrial treatment plant, or part thereof.

effluent quality The physical, biological, and chemical characteristics of a wastewater or other liquid flowing out of a basin, reservoir, pipe, or treatment plant.

ejector A device for moving a fluid or solid by entraining it in a high-velocity stream or air or water jet.

elbow A pipe fitting that connects two pipes at an angle. The angle is always 90 deg unless another angle is stated. Also called an *ell*.

electromotive force The property of a physical device that tends to produce an electrical current in a circuit. It is the moving force that causes current to flow (see *volt*).

elevation head The energy possessed per unit weight of a fluid because of its elevation above some point. Also called *position head* or *potential head*.

elutriation A process of sludge conditioning whereby the sludge is washed with either fresh water or plant effluent to reduce the demand for conditioning chemicals

and to improve the settling or filtering characteristics of the solids. Excessive alkalinity is removed in this process.

emission Discharge of a liquid, solid, or gaseous material.

emulsifying agent An agent capable of modifying the surface tension of emulsion droplets to prevent coalescence. Examples are soap and other surface-active agents, certain proteins and gums, water-soluble cellulose derivatives, and polyhydric alcohol esters and ethers.

emulsion A heterogeneous liquid mixture of two or more liquids not normally dissolved in one another, but held in suspension one in the other by forceful agitation or by emulsifiers that modify the surface tension of the droplets to prevent coalescence.

endogenous respiration Autooxidation by organisms in biological processes.

energy (electrical) As commonly used in the utility industry, electrical energy means kilowatt-hours.

Enterococci A group of Cocci that normally inhabit the intestines of man and animals. Incorrectly used interchangeably with *fecal Streptococci*.

entrainment The carryover of drops of liquid during processes such as distillation. The trapping of bubbles in a liquid produced either mechanically through turbulence or chemically through a reaction.

enzyme A catalyst produced by living cells. All enzymes are proteins, but not all proteins are enzymes.

epidemic A disease that occurs simultaneously in a large fraction of the community.

equalization In wastewater systems, the storage and controlled release of wastewaters to treatment processes at a controlled rate determined by the capacity of the processes, or at a rate proportional to the flow in the receiving stream; used to smooth out variations in temperature and composition as well as flow.

equalizing basin A holding basin in which variations in flow and composition of a liquid are averaged. Such basins are used to provide a flow of reasonably uniform volume and composition to a treatment unit. Also called *balancing reservoir*.

equilibrium A condition of balance in which the rate of formation and the rate of consumption or degradation of various constituents are equal. See also *chemical equilibrium*.

equilibrium constant A value that describes the quantitative relationship between chemical species in a system at equilibrium.

equivalent calcium carbonate A common form of expressing hardness, the acidity, or the carbon dioxide, carbonate, bicarbonate, noncarbonate, hydroxide, or total alkalinity

of water; expressed in milligrams per liter (mg/L). It is calculated by multiplying the number of chemical equivalents of any of these constituents present in 1 L by 50, the equivalent weight of calcium carbonate. See also *chemical equivalent*.

Escherichia coli (E. coli) One of the species of bacteria in the fecal coliform group. It is found in large numbers in the gastrointestinal tract and feces of warm-blooded animals and man. Its presence is considered indicative of fresh fecal contamination, and it is used as an indicator organism for the presence of less easily detected pathogenic bacteria.

eutrophication Nutrient enrichment of a lake or other water body, typically characterized by increased growth of planktonic algae and rooted plants. It can be accelerated by wastewater discharges and polluted runoff.

evaporation (1) The process by which water becomes a vapor. (2) The quantity of water that is evaporated; the rate is expressed in depth of water, measured as liquid water removed from a specified surface per unit of time, generally in inches or centimeters per day, month, or year. (3) The concentration of dissolved solids by driving off water through the application of heat.

evaporation opportunity The ratio of the rate of evaporation from a land or water surface in contact with the atmosphere to evaporation under existing atmospheric conditions; that is, the ratio of the actual to the potential rate of evaporation. Also called *relative evaporation*.

evaporation rate The quantity of water, expressed in terms of depth of liquid water, evaporated from a given water surface per unit of time. It is usually expressed in inches or millimeters per day, month, or year.

evapotranspiration Water withdrawn from soil by evaporation or plant transpiration; considered synonymous with consumptive use.

evapotranspiration potential Water loss that would occur if there was never a deficiency of water in the soil for use by vegetation.

explosimeter A device for measuring the concentration of potentially explosive fumes. Also called a *combustible-gas indicator*.

extended aeration A modification of the activated-sludge process using long aeration periods to promote aerobic digestion of the biological mass by endogenous respiration. The process includes stabilization of organic matter under aerobic conditions and disposal of the gaseous end products into the air. Effluent contains finely divided suspended matter and soluble matter.

extended aeration process A modification of the activated-sludge process. See *extended aeration*.

extraction The process of dissolving and separating out particular constituents of a liquid by treatment with solvents specific for those constituents. Extraction may be liquid–solid or liquid–liquid.

facultative Having the ability to live under different conditions; for example, with or without free oxygen.

facultative bacteria Bacteria that can grow and metabolize in the presence, as well as in the absence, of dissolved oxygen.

facultative lagoon A lagoon or treatment pond with an aerobic upper section and an anaerobic bottom section so that both aerobic and anaerobic biological processes occur simultaneously.

Fahrenheit A temperature scale in which 32° marks the freezing point and 212° the boiling point of water at 760-mm Hg. To convert to centigrade (Celsius), subtract 32 and multiply by 0.5556.

false filter bottom A type of underdrainage system consisting of a porous or perforated floor suspended above the true bottom of the filter. See also *underdrain*.

fats (wastes) Triglyceride esters of fatty acids; erroneously used as a synonym for *grease*.

fecal coliform Aerobic and facultative, Gram-negative, non-spore-forming, rod-shaped bacteria capable of growth at 44.5 °C (112 °F), and associated with fecal matter of warm-blooded animals.

fecal indicators Fecal coliform, fecal Streptococci, and other bacterial groups originating in human or other warm-blooded animals, indicating contamination by fecal matter.

fecal Streptococci The subgroup of enterococci that is of particular concern in water and wastewater. See also *Enterococci*.

feeder A circuit conductor between the service equipment or switchboard and the branch circuit overcurrent device.

fermentation Changes in organic matter or organic wastes brought about by anaerobic microorganisms and leading to the formation of carbon dioxide, organic acids, or other simple products. See also *biological oxidation*.

ferric chloride ($FeCl_3$) A soluble iron salt often used as a sludge conditioner to enhance precipitation or bind up sulfur compounds in wastewater treatment. See also *coagulant*.

ferric sulfate [$Fe_2(SO_4)_3$] A water-soluble iron salt formed by reaction of ferric hydroxide and sulfuric acid or by reaction of iron and hot concentrated sulfuric acid; also obtainable in solution by reaction of chlorine and ferrous sulfate; used in conjunction with lime as a sludge conditioner to enhance precipitation.

ferrous chloride ($FeCl_2$) A soluble iron salt used as a sludge conditioner to enhance precipitation or bind up sulfur. See also *coagulant*.

ferrous sulfate ($FeSO_4 \cdot 7H_2O$) A water-soluble iron salt, sometimes called *copperas*; used in conjunction with lime as a sludge conditioner to enhance precipitation.

field groundwater velocity The actual or field velocity of groundwater percolating through water-bearing material. It is measured by the volume of groundwater passing through a unit cross-sectional area in unit time divided by the effective porosity. Also called *effective groundwater velocity*, *true groundwater velocity*, *actual groundwater velocity*.

field moisture capacity The approximate quantity of water that can be permanently retained in the soil in opposition to the downward pull of gravity. It may be expressed as a percentage of dry weight or in inches for a given depth of soil. The length of time required for a soil to reach field moisture capacity varies considerably with various soils, being approximately 24 to 48 hours for sandy soils, 5 to 10 days for silt clay soils, and longer for clays. Also called *capillary capacity*, *field carrying capacity*, *maximum water-holding capacity*, *moisture-holding capacity*, *normal moisture capacity*.

field permeability coefficient The rate of flow of water, in gallons per day (gpd) or liters per second (L/s), under prevailing conditions, through each 1 ft (0.3 m) of thickness of a given aquifer in a width of 1 mile (1.6 km), for each 1 ft/mile (0.19 m/km) of hydraulic gradient. Also called *hydraulic conductivity*.

filamentous growth Intertwined, thread-like biological growths characteristic of some species of bacteria, fungi, and algae. Such growths reduce sludge settleability and dewaterability.

filamentous organisms Bacterial, fungal, and algal species that grow in thread-like colonies resulting in a biological mass that will not settle and may interfere with drainage through a filter.

filter A device or structure for removing solid or colloidal material, usually of a type that cannot be removed by sedimentation, from water, wastewater, or other liquid. The liquid is passed through a filtering medium, usually a granular material but sometimes finely woven cloth, unglazed porcelain, or specially prepared paper. There are many types of filters used in water and wastewater treatment. See also *pressure filter*.

filter aid Solid particulate media (for example, diatomaceous earth) added to a filter to improve the rate of filtration; also used colloquially to describe flocculents in water treatment; same as filtration aid. See also *coagulant* or *flocculent aid*.

filter bed (1) A type of bank revetment consisting of layers of filtering medium of which the particles gradually increase in size from the bottom upward. Such a filter

allows the groundwater to flow freely, but it prevents even the smallest soil particles from being washed out. (2) A tank for water filtration that has a false bottom covered with sand, such as a rapid sand filter. (3) A pond with sand bedding, as a sand filter or slow sand filter. (4) The media that comprise a trickling filter.

filter bottom (1) The underdrainage system for collecting the water that has passed through a rapid sand filter and for distributing the wash water that cleans the filtering medium. (2) The underdrainage system supporting the graded gravel of a biological bed. It may consist of specially fabricated tile or concrete blocks containing waterways and slots in the top for conveying the underdrainage, or it may consist of inverted half tile.

filter cake The solids collected on the surface of a mechanical filter. It also applies to spent cake removed from a diatomaceous earth filter.

filter clogging The effect occurring when fine particles fill the voids of a sand filter or biological bed, or when growths form surface mats that retard the normal passage of liquid through the filter.

filter cloth A fabric stretched around the drum of a vacuum filter.

filtered wastewater Wastewater that has passed through a mechanical filtering process but not through a trickling filter bed.

filter efficiency The operating results of a filter as measured by various criteria such as percentage reduction in suspended matter, total solids, BOD, bacteria, or color.

filter flooding The filling of a trickling filter to an elevation above the top of the medium by closing all outlets in order to reduce or control filter flies.

filter gallery A gallery provided in a treatment plant for the installation of conduits and valves and used as a passageway to provide access to them. See also *pipe gallery*.

filter loading Organically, the pounds (kilograms) of BOD in the applied liquid per unit of filter bed area or volume per day. Hydraulically, the quantity of liquid applied per unit of filter bed area or volume per day.

filter media (1) Material through which water, wastewater, or other liquid is passed for the purpose of purification, treatment, or conditioning. (2) A cloth or metal material of some appropriate design used to intercept sludge solids in sludge filtration. (3) Particulate (sand, gravel, or diatomaceous earth) or fibrous (cloth) material placed within a filter to collect suspended particles.

filter ponding The formation of ponds on the surface of trickling filters, caused by excessive biofilm growth, media degradation, or inadequate ventilation. Sometimes called *filter pooling*.

filter press A plate and frame press operated mechanically to produce a semisolid cake from a slurry. See also *plate press*.

filter rate The rate of application of material to some process involving filtration, for example, application of wastewater sludge to a vacuum filter, wastewater flow to a trickling filter, or water flow to a rapid sand filter.

filter run (1) The interval between the cleaning and washing operation of a rapid sand filter. (2) The interval between the changes of the filter medium on a sludge dewatering filter.

filter strainer A perforated device inserted in the underdrain of a rapid sand filter through which the filtered water is collected and through which the wash water is distributed when the filter is washed. Also called a strainer head.

filter underdrain A system of subsurface drains to collect water that passes through a sand filter or biological bed. See also *filter bottom*.

filter wash The reversal of flow through a rapid sand filter to wash clogged material out of the filtering medium and relieve conditions causing loss of head. Also called *backwash*.

filtrate The liquid that has passed through a filter.

filtration The process of contacting a dilute liquid suspension with filter media for the removal of suspended or colloidal matter, or for the dewatering of concentrated sludge.

final effluent The effluent from the final treatment unit of a wastewater treatment plant.

final sedimentation The separation of solids from wastewater in the last settling tank of a treatment plant.

fire flow The rate of flow, usually expressed in gallons per minute (gpm) or cubic meters per second (m^3/s), that can be delivered from a water distribution system at a specified residual pressure for fire fighting. When delivery is to fire department pumpers, the specified residual pressure is generally 20 psi (138 kPa).

fire pressure The pressure necessary in water mains when water is used for fire fighting; applied to cases in which the pressure for fire fighting is increased above that normally maintained for general use.

fire-service connection A pipe extending from a main to supply a sprinkler, standpipe, yard main, or other fire protection system.

fire system A separate system of water pipes or mains and their appurtenances installed solely to furnish water for extinguishing fires.

first-stage BOD That part of oxygen demand associated with biochemical oxidation of carbonaceous material. Usually, the greater part of the carbonaceous material is oxidized before the second stage (active oxidation of the nitrogenous material) takes place.

five-day biochemical oxygen demand (BOD_5) A standard test to assess wastewater pollution due to organic substances, measuring the oxygen used under controlled conditions of temperature (20 °C) and time (5 days).

fixed distributor A distributor consisting of perforated pipes or notched troughs, sloping boards, or sprinkler nozzles that remain stationary when the distributor is operating. See also *distributor*.

fixed solids The residue remaining after ignition of suspended or dissolved matter.

flame arrester (1) A device incorporating a fine-mesh wire screen or tube bundle inserted in a vent or pipe and designed to resist the flashback of flame. (2) Device consisting of a multiple number of corrugated stamped sheets in a gas-tight housing. As a flame passes through the sheets, it is cooled below the ignition point.

flange A projecting rim, edge, lip, or rib.

flap gate A gate that opens and closes by rotation around a hinge or hinges at the top side of the gate.

flap valve A valve that is hinged at one edge and opens and shuts by rotating about the hinges. See also *check valve*.

flash dryer A device for vaporizing water from partly dewatered and finely divided sludge through contact with a current of hot gas or superheated vapor. It includes a squirrel-cage mill for separating the sludge cake into fine particles.

flash mixer A device for uniform, quick dispersal of chemicals throughout a liquid.

flash point The temperature at which a gas, volatile liquid, or other substance ignites.

flat-crested weir A weir with a horizontal crest in the direction of flow and of appreciable length when compared with the depth of water passing over it.

flight A scraper in a rectangular sedimentation tank with blades that move sludge along the bottom of the tank to a collection point. As the flights return, scum is collected on the surface of the tank and pushed to an outlet point.

float control A float device that is triggered by changing liquid levels that activates, deactivates, or alternates process equipment operation.

float gauge A device for measuring the elevation of the liquid, the actuating element of which is a buoyant float that rests on the surface of the liquid and rises or falls with it. The elevation of the surface is measured by a chain or tape attached to the float.

floating cover A gas-tight metal cover floating on the sludge in a digestion tank, with guides to assist in smooth vertical travel as the sludge level changes.

float switch An electrical switch operated by a float in a tank or reservoir and usually controlling the motor of a pump.

float valve A valve, such as a plug or gate, that is actuated by a float to control the flow into a tank.

floc Collections of smaller particles agglomerated into larger, more easily settleable particles through chemical, physical, or biological treatment. See also *flocculation*.

flocculant Water-soluble organic polyelectrolytes that are used alone or in conjunction with inorganic coagulants, such as aluminum or iron salts, to agglomerate the solids present to form large, dense floc particles that settle rapidly.

flocculating tank A tank used for the formation of floc by the gentle agitation of liquid suspensions, with or without the aid of chemicals.

flocculation In water and wastewater treatment, the agglomeration of colloidal and finely divided suspended matter after coagulation by gentle stirring by either mechanical or hydraulic means. For biological wastewater treatment in which coagulation is not used, agglomeration may be accomplished biologically.

flocculation agent A coagulating substance that, when added to water, forms a flocculent precipitate that will entrain suspended matter and expedite sedimentation; examples are alum, ferrous sulfate, and lime.

flocculator (1) A mechanical device to enhance the formation of floc in a liquid. (2) An apparatus for the formation of floc in water and wastewater.

flood flow The discharge of a stream during periods of flood.

flood frequency The frequency with which the maximum flood may be expected to occur at a site in any average interval of years. Frequency analysis defines the "n-year flood" as being the flood that will, over a long period of time, be equaled or exceeded on the average once every n years. Thus, the 10-year flood would be expected to occur approximately 100 times in a period of 1 000 years, and of these, 10 would be expected to reach the 100-year magnitude. Sometimes expressed in terms of percentage of probability; for example, a probability of 1% would be 100-year flood; a probability of 10% would be a 10-year flood.

flood-protection works Structures built to protect lands and property from damage by floods.

flotation (1) Separation of suspended particles, or oil and grease, from solution by naturally or artificially raising them to the surface, usually with air. (2) Thickening of

waste activated sludge by injecting air into it and introducing the mixture into a tank where the air buoys the sludge to the surface.

flow (1) The movement of a stream of water or other fluid from place to place; the movement of silt, water, sand, or other material. (2) The fluid that is in motion. (3) The quantity or rate of movement of a fluid discharge; the total quantity carried by a stream. (4) To issue forth or discharge. (5) The liquid or amount of liquid per unit time passing a given point.

flow-control valve A device that controls the rate of flow of a fluid.

flow equalization Transient storage of wastewater for release to a sewer system or wastewater treatment plant at a controlled rate to provide a reasonably uniform flow for treatment.

flowrate The volume or mass of a gas, liquid, or solid material that passes through a cross section of conduit in a given time; measured in such units as kilograms per hour (kg/h), cubic meters per second (m^3/s), liters per day (L/d), or gallons per day (gpd).

flow recording Documentation of the rate of flow of a fluid past a given point. The recording is normally accomplished automatically.

flow regulator A structure installed in a canal, conduit, or channel to control the flow of water or wastewater at the intake or to control the water level in a canal, channel, or treatment unit. See also *rate-of-flow controller*.

flow sheet A diagrammatic representation of the progression of steps in a process showing their sequence and interdependence.

fluidized bed reactor A pressure vessel or tank that is designed for liquid–solid or gas–solid reaction. The liquid or gas moves upward through the solids particles at a velocity sufficient to suspend the individual particles in the fluid. Applications include ion exchange, granular activated carbon adsorbers, and some types of furnaces, kilns, and biological contactors.

flushing The flow of water under pressure in a conduit or well to remove clogged material.

foam (1) A collection of minute bubbles formed on the surface of a liquid by agitation, fermentation, and so on. (2) The frothy substance composed of an aggregation of bubbles on the surface of liquids and created by violent agitation or by the admission of air bubbles to liquid containing surface-active materials, solid particles, or both. Also called *froth*.

food-to-microorganism (F:M) ratio In the activated-sludge process, the loading rate expressed as pounds of BOD_5 per pound of mixed liquor or mixed liquor volatile suspended solids per day (lb BOD_5/d/lb MLSS or MLVSS).

foot valve (1) A valve placed at the bottom of the suction pipe of a pump that opens to allow water to enter the suction pipe, but closes to prevent water from passing out of it at the bottom end. (2) A valve with the reverse action attached to the drainage pipe of a vacuum chamber. It allows water to drain out, but closes to hold the vacuum.

forced aeration The bringing about of intimate contact between air and liquid where the air, under pressure, is applied below the surface of the liquid through diffusers or other devices that promote the formation of small bubbles.

force main A pressure pipe joining the pump discharge at a water or wastewater pumping station with a point of gravity flow.

formazine turbidity unit (FTU) A standard unit of turbidity based on a known chemical reaction that produces insoluble particulates of uniform size. The FTU has largely replaced the JTU. Also known as *nephelometric turbidity unit*.

fouling A gelatinous, slimy accumulation resulting from the activity of organisms in the water. Fouling may be found on concrete, masonry, or metal surfaces, but tuberculation is found only on metal surfaces.

Francis turbine A reaction turbine of the radial inward-flow type.

free available chlorine The amount of chlorine available as dissolved gas, hypochlorous acid, or hypochlorite ion that is not combined with an amine or other organic compound.

free available residual chlorine That portion of the total residual chlorine remaining in water or wastewater at the end of a specified contact period that will react chemically and biologically as hypochlorous acid or hypochlorite ion.

freeboard The vertical distance between the normal maximum level of the surface of the liquid in a conduit, reservoir, tank, or canal and the top of the sides of an open conduit or the top of a dam or levee, which is provided so that waves and other movements of the liquid will not overflow the confining structure.

free flow A condition of flow through or over a structure where such flow is not affected by submergence or the existence of tailwater.

free oxygen Elemental oxygen (O_2).

free-swimming ciliate Mobile, one-celled organisms using cilia (hair-like projections) for movement.

free water Suspended water constituting films covering the surface of solid particles or the walls of fractures, but in excess of pellicular water; mobile water is free to move in any direction under the pull of the force of gravity and unbalanced film pressure.

frequency (1) The time rate of vibration or the number of complex cycles per unit time. (2) The number of occurrences of a certain phenomenon in a given time. (3) The

number of occasions on which the same numerical measure of a particular quantity has occurred between definite limits. (4) The number of cycles through which an alternating current passes per second. Frequency has been generally standardized in the electrical utility industry in the United States at 60 cycles per second (60 Hz).

fresh-air inlet A specially constructed opening usually provided with a perforated cover to facilitate ventilation of a wastewater line.

fresh sludge Sludge in which decomposition is little advanced.

fresh wastewater Wastewater of recent origin containing dissolved oxygen.

friction factor A measure of the resistance to flow of fluid in a conduit as influenced by wall roughness.

friction head The head loss resulting from water flowing in a stream or conduit as the result of the disturbances set up by the contact between the moving water and its containing conduit and by intermolecular friction. In laminar flow, the head loss is approximately proportional to the first power of the velocity; in turbulent flow to a higher power, approximately the square of the velocity. While, strictly speaking, head losses such as those caused by bends, expansions, obstructions, and impact are not included in this term, the usual practice is to include all such head losses under this term.

friction loss The head loss resulting from water flowing in a stream or conduit as the result of the disturbances set up by the contact between the moving water and its containing conduit and by intermolecular friction. See also *friction head*.

fungi Small, nonchlorophyll-bearing plants that lack roots, stems, or leaves; occur (among other places) in water, wastewater, or wastewater effluents; and grow best in the absence of light. Their decomposition may cause disagreeable tastes and odors in water; in some wastewater treatment processes they are helpful and in others they are detrimental.

fuse A protective device that carries the full current of a circuit. If the current is higher than the fuse rating, it contains a substance that will melt and break the current. Fuses cannot be reset but must be replaced.

gas chromatography A method of separating a mixture of compounds into its constituents so they can be identified. The sample is vaporized into a gas-filled column, fractionated by being swept over a solid adsorbent, selectively eluted, and identified.

gas chromatography-mass spectrometry (GC-MS) An analytical technique involving the use of both gas chromatography and mass spectrometry, the former to separate a complex mixture into its components and the latter to deduce the atomic and molecular weights of those components. It is particularly useful in identifying organic compounds.

gas dome In sludge digestion tanks, usually a steel cover floating entirely or in part on the liquid sludge.

gasification The transformation of soluble and suspended organic materials into gas during waste decomposition.

gas production The creation of a gas by chemical or biological means.

gate valve A valve in which the closing element consists of a disk that slides over the opening or cross-sectional area through which water passes.

gauge (1) A device for indicating the magnitude or position of an element in specific units when such magnitude or position is subject to change; examples of such elements are the elevation of a water surface, the velocity of flowing water, the pressure of water, the amount or intensity of precipitation, and the depth of snowfall. (2) The act or operation of registering or measuring the magnitude or position of a thing when these characteristics are subject to change. (3) The operation of determining the discharge in a waterway by using both discharge measurements and a record of stage.

globe valve A valve having a round, ball-like shell and horizontal disk.

gpcd The rate of water, wastewater, or other flow measured in U.S. gallons (liters) per capita of served population per day.

gpd The rate of water, wastewater, or other flow measured in U.S. gallons (liters) per day.

gpm The rate of water, wastewater, or other flow measured in U.S. gallons (liters) per minute.

grab sample A sample taken at a given place and time. It may be representative of the flow. See also *composite sample*.

gradient The rate of change of any characteristic per unit of length or slope. The term is usually applied to such things as elevation, velocity, or pressure. See *slope*.

grease and oil In wastewater, a group of substances including fats, waxes, free fatty acids, calcium and magnesium soaps, mineral oils, and certain other nonfatty materials; water-insoluble organic compounds of plant and animal origins or industrial wastes that can be removed by natural flotation skimming.

grease skimmer A device for removing floating grease or scum from the surface of wastewater in a tank.

grit The heavy suspended mineral matter present in water or wastewater, such as sand, gravel, or cinders. It is removed in a pretreatment unit called a *grit chamber* to avoid abrasion and wearing of subsequent treatment devices.

grit chamber A detention chamber or an enlargement of a sewer designed to reduce the velocity of flow of the liquid to permit the separation of mineral (grit) from organic solids by differential sedimentation.

grit collector A device placed in a grit chamber to convey deposited grit to a point of collection.

grit separator Any process or device designed to separate grit from a water or wastewater stream.

grit washer A device for washing organic matter out of grit.

ground A conducting connection, whether intentional or accidental, between an electrical circuit or equipment and earth, or to some conducting body that serves in place of earth.

grounded Connected to earth or to some conducting body that serves in place of the earth.

hardness A characteristic of water imparted primarily by salts of calcium and magnesium, such as bicarbonates, carbonates, sulfates, chlorides, and nitrates, that causes curdling and increased consumption of soap, deposition of scale in boilers, damage in some industrial processes, and sometimes objectionable taste. It may be determined by a standard laboratory titration procedure or computed from the amounts of calcium and magnesium expressed as equivalent calcium carbonate. See also *carbonate hardness*.

hazardous waste Any waste that is potentially damaging to environmental health because of toxicity, ignitability, corrosivity, chemical reactivity, or other reasons.

head (1) The height of the free surface of fluid above any point in a hydraulic system; a measure of the pressure or force exerted by the fluid. (2) The energy, either kinetic or potential, possessed by each unit weight of a liquid, expressed as the vertical height through which a unit weight would have to fall to release the average energy possessed. It is used in various compound terms such as *pressure head*, *velocity head*, and *loss of head*. (3) The upper end of anything, such as a headworks. (4) The source of anything, such as a head-water. (5) A comparatively high promontory with either a cliff or steep face extending into a large body of water, such as a sea or lake. An unnamed head is usually called a *headland*.

header (1) A structure installed at the head or upper end of a gully to prevent overfall cutting. (2) A supply ditch for the irrigation of a field. (3) A large pipe installed to intercept the ends of a series of pipes; a manifold. (4) The closing plate on the end of a sewer lateral that will not be used immediately.

head gate A gate at the entrance to a conduit such as a pipeline, penstock, or canal.

head loss Energy losses resulting from the resistance of flow of fluids; may be classified into conduit surface and conduit form losses.

headworks (1) All the structures and devices located at the head or diversion point of a conduit or canal. The term as used is practically synonymous with *diversion works*; an intake heading. (2) The initial structures and devices of a water or wastewater treatment plant.

heat exchanger A device providing for the transfer of heat between two fluids.

heat treatment A sludge conditioning process combining high temperature, time, and pressure to improve the dewaterability of organic sludge.

heavy metals Metals that can be precipitated by hydrogen sulfide in acid solution, for example, lead, silver, gold, mercury, bismuth, and copper.

high-purity oxygen A modification of the activated-sludge process using relatively pure oxygen and covered aeration tanks in a conventional flow arrangement.

high-rate aeration A modification of the activated-sludge process whereby the mixed liquor suspended solids loadings are kept high, allowing high food-to-microorganism (F:M) ratios and shorter detention times.

humus sludge Sloughed particles of biomass from trickling media that are removed in the secondary clarifier.

hydrated lime Limestone that has been "burned" and treated with water under controlled conditions until the calcium oxide portion has been converted to calcium hydroxide.

hydraulic loading The amount of water applied to a given treatment process, usually expressed as volume per unit time, or volume per unit time per unit surface area.

hydraulic radius The cross-sectional area of a stream of water divided by the length of that part of its periphery in contact with its containing conduit; the ratio of area to wetted perimeter. Also called *hydraulic mean depth*.

hydrocarbon Any of the class of compounds consisting solely of carbon and hydrogen. Usually derived from petroleum.

hydrogen-ion concentration The concentration of hydrogen ions in moles per liter of solution (moles/L). Commonly expressed as the pH value, which is the logarithm of the reciprocal of the hydrogen-ion concentration. See also *pH*.

hydrogen sulfide (H_2S) A toxic and lethal gas produced in sewers and digesters by anaerobic decomposition. Detectable in low concentrations (%) by its characteristic "rotten egg" odor. It deadens the sense of smell in higher concentrations or after pro-

longed exposure. Respiratory paralysis and death may occur quickly at concentrations as low as 0.07% by volume in air.

hydrostatic level The level or elevation to which the top of a column of water would rise from an artesian aquifer or basin, or from a conduit under pressure.

hypochlorination The use of sodium hypochlorite ($NaOCl_2$) for disinfection.

hypochlorite Calcium, sodium, or lithium hypochlorite.

Imhoff cone A cone-shaped graduated vessel used to measure the volume of settleable solids in various liquids of wastewater origin during various settling times.

impedance, resistance, and reactance The relationship between impedance, resistance, and reactance is given by the following equation:

$$Z = R + jX$$

Where

Z = impedance (Ω),
R = resistance (Ω),
X = reactance (Ω), and
j is the imaginary unit $\sqrt{-1}$.

impeller A rotating set of vanes designed to impel rotation of a mass of fluid.

incineration Combustion or controlled burning of volatile organic matter in sludge and solid waste reducing the volume of the material while producing heat, dry inorganic ash, and gaseous emissions.

incinerator A furnace or apparatus for incineration.

index (1) An indicator, usually numerically expressed, of the relation of one phenomenon to another. (2) An indicating part of an instrument.

indicator (1) A device that shows by an index, pointer, or dial the instantaneous value of such quantities as depth, pressure, velocity, stage, or the movements or positions of water-controlling devices; a gauge. See also *recorder*. (2) A substance giving a visible change, usually of color, at a desired point in a chemical reaction, generally at a prescribed end point.

indicator gauge A gauge that shows, by means of an index, pointer, or dial the instantaneous value of such characteristics as depth, pressure, velocity, stage, discharge, or the movements or positions of waste-controlling devices. See also *indicator*, *recorder*.

industrial wastewater Wastewater derived from industrial sources or processes.

infectious hepatitis An acute viral inflammation of the liver characterized by jaundice, fever, nausea, vomiting, and abdominal discomfort; may be waterborne.

infiltration (1) The flow or movement of water through the interstices or pores of a soil or other porous medium. (2) The quantity of groundwater that leaks into a pipe through joints, porous walls, or breaks. (3) The entrance of water from the ground into a gallery. (4) The absorption of liquid by the soil, either as it falls as precipitation or from a stream flowing over the surface.

inflow In relation to sanitary sewers, the extraneous flow that enters a sanitary sewer from sources other than infiltration, such as roof leaders, basement drains, land drains, and manhole covers. See also *infiltration*.

influent Water, wastewater, or other liquid flowing into a reservoir, basin, treatment plant, or treatment process. See also *effluent*.

inlet (1) A surface connection to a drain pipe. (2) A structure at the diversion end of a conduit. (3) The upstream end of any structure through which water may flow. (4) A form of connection between the surface of the ground and a drain or sewer for the admission of surface or stormwater. (5) An intake.

inlet control Control of the relationship between headwater elevation and discharge by the inlet or upstream end of any structure through which water may flow.

inorganic All those combinations of elements that do not include organic carbon.

inorganic matter Mineral-type compounds that are generally nonvolatile, not combustible, and not biodegradable. Most inorganic-type compounds or reactions are ionic in nature; therefore, rapid reactions are characteristic.

instrumentation Use of technology to control, monitor, or analyze physical, chemical, or biological parameters.

interlock A means of tying one or more circuits to another. It may be mechanical in nature but more likely involves the use of relays or solid state components.

intermittent chlorination A technique of noncontinuous chlorination used to control biological fouling of surfaces in freshwater circuits, particularly those used for heat transfer.

intermittent filter A natural or artificial bed of sand or other fine-grained material to the surface of which wastewater is applied intermittently in flooding doses and through which it passes; filtration is accomplished under aerobic conditions.

inventory A detailed list showing quantities, descriptions, and values of property. It may also include units of measure and unit prices. The term is often confined to consumable materials but may also cover fixed assets. When an inventory covers all property of the enterprise and is priced as of a certain date, it is known as an appraisal.

ion A charged atom, molecule, or radical that affects the transport of electricity through an electrolyte or, to a certain extent, through a gas. An atom or molecule that has lost or gained one or more electrons.

ion exchange (1) A chemical process involving reversible interchange of ions between a liquid and a solid, but no radical change in structure of the solid. (2) A chemical process in which ions from two different molecules are exchanged. (3) The reversible transfer or sorption of ions from a liquid to a solid phase by replacement with other ions from the solid to the liquid. See also *regeneration*.

irrigation The artificial application of water to lands to meet the water needs of growing plants not met by rainfall.

irrigation requirement The quantity of water, exclusive of precipitation, that is required for crop production. It includes surface evaporation and other economically unavoidable water waste.

irrigation return water Drainage water from irrigated farmlands, generally containing high concentrations of dissolved salts and other materials that have been leached out of the upper layers of the soil.

jacketed pump A pump equipped with jackets around the cylinders, heads, and stuffing boxes through which steam or other heat may be forced to permit the handling of such materials as pitch, resin, and asphalt that are solid when cold but melt on heating; when the pump handles materials at high temperatures, cold water may be substituted for steam or heat.

Jackson turbidity unit (JTU) A standard unit of turbidity based on the visual extinction of a candle flame when viewed through a column of turbid water containing suspended solids. It varies with the solids composition (barium sulfate, diatomaceous earth, and so on). The JTU has largely been replaced by the more reproducible nephelometric turbidity unit.

jar test A laboratory procedure for evaluating coagulation, flocculation, and sedimentation processes in a series of parallel comparisons.

jet The stream of water under pressure issuing from an orifice, nozzle, or tube.

joint (1) A surface of contact between two bodies or masses of material of like or different character or composition. (2) A connection between two lengths of pipe, made either with or without the use of a third part. (3) A length or piece of pipe.

kinematic viscosity Ratio of absolute viscosity, expressed in poises (grams per centimeter per second [g/cm·s]), and the density, in grams per cubic centimeter (g/cm^3), at room temperature.

kinetics The study of the rates at which changes occur in chemical, physical, and biological treatment processes.

Kjeldahl nitrogen (TKN) The combined amount of organic and ammonia nitrogen.

Kraus process A modification of the activated-sludge process in which aerobically conditioned supernatant liquor from anaerobic digesters is added to activated sludge aeration tanks to improve the settling characteristics of the sludge and to add an oxygen resource in the form of nitrates.

kilovar One thousand reactive volt amps (see *power*).

kilovolt One thousand volts.

kilowatt One thousand watts.

kilowatt-hour The units of electrical energy equal to one kilowatt of electrical power in an electrical circuit for 1 hour.

laboratory procedures Modes of conducting laboratory processes and analytical tests consistent with validated standard testing techniques.

lag growth phase The initial period following bacterial introduction during which the population grows slowly as the bacteria acclimates to the new environment.

lagoon Any large holding or detention pond, usually with earthen dikes, used to contain wastewater while sedimentation and biological oxidation occur. See also *anaerobic lagoon*.

laminar flow The flow of a viscous fluid in which particles of the fluid move in parallel layers, each of which has a constant velocity but is in motion relative to its neighboring layers. Also called *streamline flow*, *viscous flow*.

land application The recycling, treatment, or disposal of wastewater or wastewater solids to the land under controlled conditions.

landfill The disposal of solid wastes or sludges by placing on land, compacting, and covering with a thin layer of soil.

leachate Liquid that has percolated through solid waste or other permeable material and extracted soluble dissolved or suspended materials from it.

leakage Uncontrolled loss of water from artificial structures as a result of hydrostatic pressure.

leakage detector A device or appliance, the principle of which is the audibility of water flowing through a leak. Most of these devices are marketed under descriptive trade names.

lethal concentration The concentration of a test material that causes death of a specified percentage of a population, usually expressed as the median or 50% level (L_{50}).

lift station A structure that contains pumps and appurtenant piping, valves, and other mechanical and electrical equipment for pumping water, wastewater, or other liquid. Also called a *pumping station*.

lighting panel An enclosure carrying numerous low-voltage breakers, switches, and fuses servings lights or receptacles in an area.

lime Any of a family of chemicals consisting essentially of calcium hydroxide made from limestone (calcite) composed almost wholly of calcium carbonate or a mixture of calcium and magnesium carbonate; used to increase pH to promote precipitation reactions or for lime stabilization to kill parthenogenic organisms.

lining A protective covering over all or a portion of the perimeter of a conduit or reservoir intended to prevent seepage losses, withstand pressure, or resist erosion. In the case of conduits, lining is also sometimes installed to reduce friction losses.

lipids A group of organic compounds that make up the fats and other esters with analogous properties.

liquefaction (1) Act or process of liquefying or of rendering or becoming liquid; reduction to a liquid state. (2) Act or process of converting a solid or a gas to a liquid by changes in temperature or pressure, or the changing of the organic matter in wastewater from a solid to a soluble state.

liquid A substance that flows freely; characterized by free movement of the constituent molecules among themselves, but without the tendency to separate from one another, which is characteristic of gases. Liquid and fluid are often used synonymously, but fluid has the broader significance of including both liquids and gases.

liquid chlorine Elemental chlorine converted to a liquid state by compression and refrigeration of the dry, purified gas. Liquid chlorine is shipped under pressure in steel containers.

load The amount of electrical power required at any specified point or points on an electrical system. Load originates at the power-consuming equipment (see *demand*).

load center A point at which the load of a given area is assumed to be concentrated.

load diversity The difference between the sum of the individual maximum demands of two or more individual loads and the coincident maximum demand of those loads.

load factor The ratio of the average load in kilowatts supplied during a designated period to the peak or maximum load in kilowatts occurring in that period. Load factor, in percent, may be derived by multiplying the kilowatt-hours used in the period by

100 and then dividing by the product of the maximum demand in kilowatts and the number of hours in the period.

log growth phase Initial stage of bacterial growth, during which there is an ample food supply, causing bacteria to grow at their maximum rate.

loss of head (1) The decrease in energy between two points resulting from friction, bend, obstruction, expansion, or any other cause. It does not include changes in the elevation of the hydraulic grade unless the hydraulic and energy grades parallel each other. (2) The difference between the total heads at two points in a hydraulic system.

low-rate filter A trickling filter designed to receive a small load of BOD per unit volume of filtering material and to have a low dosage rate per unit of surface area, usually 2 to 5 mgd/ac (2.2×10^{-5} to 5.4×10^{-5} $m^3/m^2 \cdot s$) generally without recirculation. The organic loading (BOD) rate is usually in the range of 5 to 25 lb/1 000 cu ft (80 to 400 g/m^3). Also called a *standard rate filter*.

Manning formula A formula for open-channel flow published by Manning in 1890. It gives the value of *c* in the Chezy formula. See also *Manning roughness coefficient*.

Manning roughness coefficient The roughness coefficient in the Manning formula for determination of the discharge coefficient in the Chezy formula.

manometer An instrument for measuring pressure. It usually consists of a U-shaped tube containing a liquid, the surface of which moves proportionally in one end of the tube with changes in pressure in the liquid in the other end; also, a tube-type of differential pressure gauge.

mass spectrometer A device that permits observation of the masses of molecular fragments produced by destructible bombardment of the molecule with electrons in a vacuum; coupled with gas chromatography (GC-MS), mass spectrometry can yield very specific compound identification.

mass spectrometry A means of sorting ions by separating them according to their masses.

mean (1) The arithmetic average of a group of data. (2) The statistical average (50% point) determined by probability analysis.

mean cell residence time (MCRT) The average time that a given unit of cell mass stays in the activated-sludge aeration tank. It is usually calculated as the total mixed liquor suspended solids in the aeration tank divided by the combination of solids in the effluent and solids wasted.

mechanical aeration (1) The mixing, by mechanical means, of wastewater and activated sludge in the aeration tank of the activated-sludge process to bring fresh surfaces of liquid into contact with the atmosphere. (2) The introduction of atmospheric

oxygen into a liquid by the mechanical action of paddle, paddle wheel, spray, or turbine mechanisms.

mechanical aerator A mechanical device for the introduction of atmospheric oxygen into a liquid. See also *mechanical aeration*.

mechanically cleaned screen A screen equipped with a mechanical cleaning apparatus for removal of retained solids.

mechanical rake A machine-operated mechanism used for cleaning debris from racks located at the intakes of conduits supplying water to hydroelectric power plants, water supply systems, or for other uses, and conveying wastewater to pumps or treatment processes.

median In a statistical array, the value having as many cases larger in value as cases smaller in value.

membrane filter test A sample of water is passed through a sterile filter membrane. The filter is removed and placed on a culture medium and then incubated for a preset period of time. Coliform colonies, which have a pink to dark-red color with a metallic sheen, are then counted using the aid of a low-power binocular wide-field dissecting microscope. The membrane filter test is used to test for the presence and relative number of coliform organisms.

mercaptans Aliphatic organic compounds that contain sulfur. They are noted for their disagreeable odor and are found in certain industrial wastes.

mercury gauge A gauge in which the pressure of a fluid is measured by the height the fluid pressure will sustain a column of mercury.

mesh One of the openings or spaces in a screen. The value of the mesh is usually given as the number of openings per linear inch. This gives no recognition to the diameter of the wire; thus, the mesh number does not always have a definite relationship to the size of the hole.

mesophilic That group of bacteria that grow best within the temperature range of 20 to 40 °C (68 to 104 °F).

mesophilic digestion Digestion by biological action at 27 to 38 °C (80 to 100 °F).

mesophilic range Operationally, that temperature range most conducive to the maintenance of optimum digestion by mesophilic bacteria, generally accepted as between 27 and 38 °C (80 and 100 °F).

metabolism (1) The biochemical processes in which food is utilized and wastes formed by living organisms. (2) All biochemical reactions involved in cell synthesis and growth.

metazoan A group of animals having bodies composed of cells differentiated into tissues and organs and usually having a digestive cavity lined with specialized cells.

meter An instrument for measuring some quantity such as the rate of flow of liquids, gases, or electric currents.

methane (CH_4) A colorless, odorless, flammable, gaseous hydrocarbon present in natural gas and formed by the anaerobic decomposition of organic matter, or produced artificially by heating carbon monoxide and hydrogen over a nickel catalyst. See also *anaerobic digestion*.

methane bacteria A specialized group of obligate anaerobic bacteria that decompose organic matter to form methane.

methane fermentation A reaction sequence that produces methane during the anaerobic decomposition or organic waste. In the first phase, acid-forming bacteria produce acetic acid; in the second, the methane bacteria use this acid and carbon dioxide to produce methane. Fermentation results in the conversion of organic matter into methane gas.

mgd Million gallons per day; a measure of flow equal to 1.547 cu ft/sec, 681 gpm, or 3 785 m^3/d.

mg/L Milligrams per liter; a measure of concentration equal to and replacing ppm in the case of dilute concentrations.

microbial activity The activities of microorganisms resulting in chemical or physical changes.

microbial film A gelatinous film of microbial growth attached to or spanning the interstices of a support medium. Also called *biological slime*.

microorganisms Very small organisms, either plant or animal, invisible or barely visible to the naked eye. Examples are algae, bacteria, fungi, protozoa, and viruses.

microscopic Very small, generally between 0.5 and 100 mm, and visible only by magnification with an optical microscope.

microscopic examination (1) The examination of water to determine the presence and amounts of plant and animal life, such as bacteria, algae, diatoms, protozoa, and crustacea. (2) The examination of water to determine the presence of microscopic solids. (3) The examination of microbiota in process water, such as the mixed liquor in an activated-sludge plant.

mist Fine liquid droplets of such small size that gravity separation is hindered. Fog is a water mist.

mixed-flow pump A centrifugal pump in which the head is developed partly by centrifugal force and partly by the lift of the vanes on the liquid. This type of pump has a single inlet impeller; the flow enters axially and leaves axially and radially.

mixed liquor A mixture of raw or settled wastewater and activated sludge contained in an aeration tank in the activated-sludge process. See also *mixed liquor suspended solids*.

mixed liquor suspended solids (MLSS) The concentration of suspended solids in activated-sludge mixed liquor, expressed in milligrams per liter (mg/L). Commonly used in connection with activated-sludge aeration units.

mixed liquor volatile suspended solids (MLVSS) That fraction of the suspended solids in activated-sludge mixed liquor that can be driven off by combustion at 550 °C (1022 °F); it indicates the concentration of microorganisms available for biological oxidation.

mixed-media filter A filter containing filtering media of different particle size or density.

mixing basin A basin or tank in which agitation is applied to water, wastewater, or sludge to increase the dispersion rate of applied chemicals; also, tanks used for general mixing purposes.

mixing chamber A chamber used to facilitate the mixing of chemicals with liquid or the mixing of two or more liquids of different characteristics. It may be equipped with a mechanical device that accomplishes the mixing.

mixing channel A channel provided in a water or wastewater treatment plant; the hydraulic characteristics of the waterway or its construction features are such that chemicals or liquids are thoroughly mixed.

modified aeration A modification of the activated-sludge process in which a shortened period of aeration (1.5 to 3 hours) is used with a reduced quantity of suspended solids (200 to 500 mg/L MLSS) in the mixed liquor. Sludge settling is usually poor; high suspended solids concentration may be expected in effluent.

moisture Condensed or diffused water collected on or excluded to a surface.

moisture content The quantity of water present in soil, wastewater sludge, industrial waste sludge, and screenings, usually expressed in percentage of wet weight.

mole (1) Molecular weight of a substance, normally expressed in grams. (2) A device to clear sewers and pipelines. (3) A massive harbor work, with a core of earth or stone, extending from shore into deep water. It serves as a breakwater, a berthing facility, or a combination of the two.

monitoring (1) Routine observation, sampling, and testing of designated locations or parameters to determine the efficiency of treatment or compliance with standards or requirements. (2) The procedure or operation of locating and measuring radioactive contamination by means of survey instruments that can detect and measure, as dose rate, ionizing radiations.

Monod equation A mathematical expression first used by Monod in describing the relationship between the microbial growth rate and concentration of growth-limiting substrate.

most probable number (MPN) That number of organisms per unit volume which, in accordance with statistical theory, would be more likely than any other number to yield the observed test result or would yield the observed test result with the greatest frequency. Expressed as density of organisms/100 mL. Results are computed from the number of positive findings of coliform group organisms resulting from multiple portion decimal dilution plantings. Used commonly for coliform bacteria.

motor controller A specialized type of controller whose typical functions performed by a motor controller include starting, accelerating, stopping, reversing, and protecting motors.

moving average Trend analysis tool for determining patterns or changes in treatment process. For example, a 7-day moving average would be the sum of the datum points for 7 days divided by 7.

mudballs (1) Accretions of siliceous incrustations on the exterior surface of sand grains. From these incrustations grow numerous filamentous organisms over which there is a gelatinous coating. Mudballs are approximately spherical in shape and vary in size from that of a pea up to 1 or 2 in. (2.5 to 5.1 cm) or more in diameter. They are formed principally by the retention and gradual building up of growths that are not completely removed by the washing process. (2) Balls of sediment sometimes found in debris-laden flow and channel deposits.

mud blanket A layer of flocculant material that forms on the surface of a sand filter.

multimedia filter beds A filtration apparatus consisting of two or more media, such as anthracite and sand, through which wastewater flows and by which it is cleansed. Media may be intermixed or segregated.

multiple-hearth incinerator A countercurrent-type of incinerator frequently used to dry and burn partially dried sludges. Heated air and products of combustion pass by finely pulverized sludge that is continuously raked to expose fresh surfaces.

multiple-stage sludge digestion The progressive digestion of waste sludge in two or more tanks arranged in series.

multistage pump A centrifugal pump with two or more sets of vanes or impellers connected in series in the same casing. Such a pump may be designated as two-stage, three-stage, or more, according to the number of sets of vanes used. The purpose is to increase the head of the discharging fluid.

municipal wastewater treatment Generally includes the treatment of domestic, commercial, and industrial wastes.

nappe The sheet or curtain of water overflowing a weir or dam. When freely overflowing any given structure, it has a well-defined upper and lower surface.

National Pollutant Discharge Elimination System (NPDES) A permit that is the basis for the monthly monitoring reports required by most states in the United States.

negative head (1) The loss of head in excess of the static head (a partial vacuum). (2) A condition of negative pressure produced by clogging of rapid sand filters near the end of a filter run.

negative pressure A pressure less than the local atmospheric pressure at a given point.

nematode Member of the phylum (Nematoda) of elongated cylindrical worms parasitic in animals or plants or free-living in soil or water.

nephelometer An instrument for comparing turbidities of solutions by passing a beam of light through a transparent tube and measuring the ratio of the intensity of the shattered light to that of the incident light.

nephelometric turbidity unit (NTU) Units of a turbidity measurement using a nephelometer.

net available head The difference in pressure between the water in a power conduit before it enters the water wheel and the first free water surface in the conduit below the water wheel.

n factor Values of the roughness coefficient used in Manning formula or Kutter formula. See also *roughness coefficient*, *Manning formula*.

nitrate (NO_3) An oxygenated form of nitrogen.

nitrification The oxidation of ammonia nitrogen to nitrate nitrogen in wastewater by biological or chemical reactions. See also *denitrification*.

nitrifying bacteria Bacteria capable of oxidizing nitrogenous material.

nitrite (NO_2) An intermediate oxygenated form of nitrogen.

nitrogen (N) An essential nutrient that is often present in wastewater as ammonia, nitrate, nitrite, and organic nitrogen. The concentrations of each form and the sum (total nitrogen) are expressed as milligrams per liter (mg/L) elemental nitrogen. Also

present in some groundwater as nitrate and in some polluted groundwater in other forms. See also *nutrient*.

nitrogen cycle A graphical presentation of the conservation of matter in nature showing the chemical transformation of nitrogen through various stages of decomposition and assimilation. The various chemical forms of nitrogen as it moves among living and nonliving matter are used to illustrate general biological principles that are applicable to wastewater and sludge treatment.

nitrogenous oxygen demand (NOD) A quantitative measure of the amount of oxygen required for the biological oxidation of nitrogenous material, such as ammonia nitrogen and organic nitrogen, in wastewater; usually measured after the carbonaceous oxygen demand has been satisfied. See also *biochemical oxygen demand*, *nitrification*, *second-stage BOD*.

nitrogen removal The removal of nitrogen from wastewater through physical, chemical, or biological processes, or by some combination of these.

Nitrosomonas A genus of bacteria that oxidize ammonia to nitrate.

Nocardia Irregularly bent, short filamentous organisms that are characterized in an activated-sludge system when a dark chocolate mousse foam is present.

nonclogging impeller An impeller of the open, closed, or semiclosed type designed with large passages for passing large solids.

nonsettleable solids Suspended matter that will stay in suspension for an extended period of time. Such a period may be arbitrarily taken for testing purposes as 1 hour. See also *suspended solids*.

nonuniform flow A flow in which the slope, cross-sectional area, and velocity change from section to section in the channel.

nozzle (1) A short, cone-shaped tube used as an outlet for a hose or pipe. The velocity of the emerging stream of water is increased by the reduction in cross-sectional area of the nozzle. (2) A short piece of pipe with a flange on one end and a saddle flange on the other end. (3) A side outlet attached to a pipe by riveting, brazing, or welding.

nozzle aerator An aerator consisting of a pressure nozzle through which water is propelled into the air in a fine spray. Also called *spray aerator*.

nutrient Any substance that is assimilated by organisms and promotes growth; generally applied to nitrogen and phosphorus in wastewater, but also to other essential and trace elements.

odor control Prevention or reduction of objectionable odors by chlorination, aeration, or other processes, or by masking with chemical aerosols.

odor threshold The point at which, after successive dilutions with odorless water or air, the odor of a sample can barely be detected. The threshold odor is expressed quantitatively by the number of times the sample is diluted with odorless water or air.

off-peak power That part of the available load or energy that can be produced at off-peak hours outside the load curve when the combined primary and secondary load has fallen below plant capacity.

ohm The unit of measurement of electrical resistance. It is that resistance through which an electromotive force of one volt will produce a current of one ampere.

oil separation (1) Removal of insoluble oils and floating grease from municipal wastewater. (2) Removal of soluble or emulsified oils from industrial wastewater.

open centrifugal pump A centrifugal pump in which the impeller is built with a set of independent vanes.

open channel Any natural or artificial water conduit in which water flows with a free surface.

open-channel flow Flow of a fluid with its surface exposed to the atmosphere. The conduit may be an open channel or a closed conduit flowing partly full.

open impeller An impeller without attached side walls.

operators (1) Persons employed to operate a treatment facility. (2) Mechanism used to manipulate valve positions.

organic Refers to volatile, combustible, and sometimes biodegradable chemical compounds containing carbon atoms (carbonaceous) bonded together with other elements. The principal groups of organic substances found in wastewater are proteins, carbohydrates, and fats and oils. See also *inorganic*.

organic loading The amount of organic material, usually measured as BOD_5, applied to a given treatment process; expressed as weight per unit time per unit surface area or per unit weight.

organic nitrogen Nitrogen chemically bound in organic molecules such as proteins, amines, and amino acids.

orifice (1) An opening with a closed perimeter, usually of regular form, in a plate, wall, or partition through which water may flow; generally used for the purpose of measurement or control of such water. The edge may be sharp or of another configuration. (2) The end of a small tube such as a pitot tube or piezometer.

orifice plate A plate containing an orifice. In pipes, the plate is usually inserted between a pair of flanges and the orifice is smaller in area than the cross section of the pipe.

orthophosphate (1) A salt that contains phosphorus as $(PO_4)^{-3}$. (2) A product of hydrolysis of condensed (polymeric) phosphates. (3) A nutrient required for plant and animal growth. See also *nutrient*, *phosphorus removal*.

osmosis The process of diffusion of a solvent through a semipermeable membrane from a solution of lower concentration to one of higher concentration.

outfall (1) The point, location, or structure where wastewater or drainage discharges from a sewer, drain, or other conduit. (2) The conduit leading to the ultimate disposal area.

outlet A point on the wiring system at which the current is taken to supply utilization equipment.

overflow rate One of the criteria in the design of settling tanks for treatment plants; expressed as the settling velocity of particles that are removed in an ideal basin if they enter at the surface. It is expressed as a volume of flow per unit water surface area.

overflow weir Any device or structure over which any excess water or wastewater beyond the capacity of the conduit or container is allowed to flow or waste.

overland flow (1) The flow of water over the ground before it enters some defined channel. (2) A type of wastewater irrigation.

overturn The phenomenon of vertical circulation that occurs in large bodies of water because of the increase in density of water above and below 39.2 °F (4 °C). In the spring, as the surface of the water warms above the freezing point, the water increases in density and tends to sink, producing vertical currents; in the fall, as the surface water becomes colder, it also tends to sink. Wind may also create such vertical currents.

oxidant A chemical substance capable of promoting oxidation, for example, O_2, O_3, and Cl_2. See also *oxidation*, *reduction*.

oxidation (1) A chemical reaction in which the oxidation number (valence) of an element increases because of the loss of one or more electrons by that element. Oxidation of an element is accompanied by simultaneous reduction of the other reactant. See also *reduction*. (2) The conversion or organic materials to simpler, more stable forms with the release of energy. This may be accomplished by chemical or biological means. (3) The addition of oxygen to a compound.

oxidation ditch A secondary wastewater treatment facility that uses an oval channel with a rotor placed across it to provide aeration and circulation. The screened wastewater in the ditch is aerated by the rotor and circulated at approximately 1 to 2 ft/sec (0.3 m/s). See also *secondary treatment*.

oxidation pond A relatively shallow body of wastewater contained in an earthen basin of controlled shape in which biological oxidation of organic matter is effected by natural or artificially accelerated transfer of oxygen.

oxidation process Any method of wastewater treatment for the oxidation of the putrescible organic matter.

oxidation–reduction potential (ORP) The potential required to transfer electrons from the oxidant to the reductant and used as a qualitative measure of the state of oxidation in wastewater treatment systems.

oxidized sludge Sludge in which the organic matter has been stabilized by chemical or biological oxidation.

oxidized wastewater Wastewater in which the organic matter has been stabilized.

oxygen (O) A necessary chemical element. Typically found as O_2 and used in biological oxidation. It constitutes approximately 20% of the atmosphere.

oxygenation capacity In treatment processes, a measure of the ability of an aerator to supply oxygen to a liquid.

oxygen consumed A measure of the oxygen-consuming capability of inorganic and organic matter present in water or wastewater. See also *chemical oxygen demand*.

oxygen deficiency (1) The additional quantity of oxygen required to satisfy the oxygen requirement in a given liquid; usually expressed in milligrams per liter (mg/L). (2) Lack of oxygen.

oxygen transfer (1) Exchange of oxygen between a gaseous and a liquid phase. (2) The amount of oxygen absorbed by a liquid compared to the amount fed into the liquid through an aeration or oxygenation device; usually expressed as percent.

oxygen uptake rate The oxygen used during biochemical oxidation, typically expressed as mg O_2/L/h in the activated sludge process.

oxygen utilization (1) The portion of oxygen effectively used to support aerobic treatment processes. (2) The oxygen used to support combustion in the degradation of sludge by incineration or wet-air oxidation.

ozonation The process of contacting water, wastewater, or air with ozone for purposes of disinfection, oxidation, or odor control.

ozone (O_3) Oxygen in a molecular form with three atoms of oxygen forming each molecule.

paddle aerator A device, similar in form to a paddle wheel, that is used in the aeration of water.

panel board One or more panel units designed for assembly into a single panel, including buses, and with or without switched and/or automatic overcurrent devices. Panel boards are used to control light, heat, or power circuits of small individual or grouped loads. They are designed to be set in a cabinet box or in or against a wall or partition and are accessible from the front only (see *switchboard*).

Parshall flume A calibrated device developed by Parshall for measuring the flow of liquid in an open conduit consisting essentially of a contracting length, a throat, and an expanding length. At the throat is a sill over which the flow passes at Belanger's critical depth. The upper and lower heads are each measured at a definite distance from the sill. The lower head need not be measured unless the sill is submerged more than about 67%.

partial pressure The pressure exerted by each gas independently of the others in a mixture of gases. The partial pressure of each gas is proportional to the amount (percent by volume) of that gas in the mixture.

particles Generally, discrete solids suspended in water or wastewater that can vary widely in size, shape, density, and charge.

parts per million (ppm) The number of weight or volume units of a minor constituent present with each 1 million units of a solution or mixture. The more specific term, milligrams per liter (mg/L), is preferred.

pathogenic bacteria Bacteria that cause disease in the host organism by their parasitic growth.

pathogens Pathogenic or disease-producing organisms.

peak (1) The maximum quantity that occurs over a relatively short period of time. Also called *peak demand*, *peak load*. (2) The highest load carried by an electric generating system during any specific period. It is usually expressed in kilowatts (kW).

peak load (1) The maximum average load carried by an electric generating plant or system for a short time period such as 1 hour or less. (2) The maximum demand for water placed on a pumping station, treatment plant, or distribution system; expressed as a rate. (3) The maximum rate of flow of wastewater to a pumping station or treatment plant. Also called *peak demand*.

period (1) The interval required for the completion of a recurring event. (2) Any specified duration of time.

peripheral weir The outlet weir extending around the inside of the circumference of a circular settling tank over which the effluent discharges.

permeability (1) The property of a material that permits appreciable movement of water through it when it is saturated; the movement is actuated by hydrostatic pres-

sure of the magnitude normally encountered in natural subsurface water. Perviousness is sometimes used in the same sense as permeability. (2) The capacity of a rock or rock material to transmit a fluid. See also *permeability coefficient*.

permeability coefficient A coefficient expressing the rate of flow of a fluid through a cross section of permeable material under a hydraulic or pressure gradient. The standard coefficient of permeability used in the hydrologic work of the U.S. Geological Survey (USGS), known also as the *Meinzer unit*, is defined as the rate of flow of water in gallons per day (gpd) at 60 °F through a cross section of 1 ft (0.3 m) under a hydraulic gradient of 100%. See also *field permeability coefficient*.

pervious Possessing a texture that permits water to move through perceptibly under the head differences ordinarily found in subsurface water. See also *permeability*.

pH A measure of the hydrogen-ion concentration in a solution, expressed as the logarithm (base 10) of the reciprocal of the hydrogen-ion concentration in gram moles per liter (g/mole/L). On the pH scale (0 to 14), a value of 7 at 25 °C (77 °F) represents a neutral condition. Decreasing values indicate increasing hydrogen-ion concentration (acidity); increasing values indicate decreasing hydrogen-ion concentration (alkalinity).

phase Any portion of a physical system separated by a definite physical boundary from the rest of the system. The three physical phases are solid, liquid, and gas; colloids are the dispersed phase and liquids are the continuous phase.

phenolic compounds Hydroxyl derivatives of benzene. The simplest phenolic compound is hydroxyl benzene (C_6H_5OH).

phosphate A salt or ester of phosphoric acid. See also *orthophosphate*, *phosphorus*.

phosphorus An essential chemical element and nutrient for all life forms. Occurs in orthophosphate, pyrophosphate, tripolyphosphate, and organic phosphate forms. Each of these forms and their sum (total phosphorus) is expressed as milligrams per liter (mg/L) elemental phosphorus. See also *nutrient*.

phosphorus removal The precipitation of soluble phosphorus by coagulation and subsequent flocculation and sedimentation.

photosynthesis The synthesis of complex organic materials, especially carbohydrates, from carbon dioxide, water, and inorganic salts with sunlight as the source of energy and with the aid of a catalyst, such as chlorophyll.

photosynthetic bacteria Bacteria that obtain their energy for growth from light by photosynthesis.

physical analysis The examination of water and wastewater to determine physical characteristics such as temperature, turbidity, color, odors, and taste.

physical-chemical treatment Treatment of wastewater by unit processes other than those based on microbiological activity. Unit processes commonly included are precipitation with coagulants, flocculation with or without chemical flocculents, filtration, adsorption, chemical oxidation, air stripping, ion exchange, reverse osmosis, and several others.

physical treatment Any treatment process involving only physical means of solid–liquid separation, for example, screens, racks, clarification, and comminutors. Chemical and biological reactions do not play an important role in treatment.

phytoplankton Plankton consisting of plants, such as algae.

pin floc Small floc particles that settle poorly.

pipe A closed conduit that diverts or conducts water or wastewater from one location to another.

pipe diameter The nominal or commercially designated inside diameter of a pipe, unless otherwise stated.

pipe fittings Connections, appliances, and adjuncts designed to be used in connection with pipes; examples are elbows and bends to alter the direction of a pipe; tees and crosses to connect a branch with a main; plugs and caps to close an end; and bushings, diminishers, or reducing sockets to couple two pipes of different dimensions.

pipe gallery (1) Any conduit for pipe, usually of a size to allow a person to walk through. (2) A gallery provided in a treatment plant for the installation of conduits and valves and used as a passageway to provide access to them.

piping system A system of pipes, fittings, and appurtenances within which a fluid flows.

piston pump A reciprocating pump in which the cylinder is tightly fitted with a reciprocating piston.

plant hydraulic capacity The level of flow into a plant above which the system is hydraulically overloaded.

plastic media Honeycomb-like products, manufactured from plastics of various compositions, with high surface area : volume ratios that are used in trickling filters in place of crushed stone. The product is available in large modules fabricated from sheets that may be cut to size on-site, and small discrete pieces to be loosely packed in the filter bed. See also *trickling filter*.

plate press A filter press consisting of a number of parallel plate units lined with filter cloth that rests on drainage channels in the plates. Pressure is exerted by the pumping of solids into chambers created between the cloths. The operation is carried out in batches.

plug flow Flow in which fluid particles are discharged from a tank or pipe in the same order in which they entered it. The particles retain their discrete identities and remain in the tank for a time equal to the theoretical detention time.

plumbing (1) The pipes, fixtures, and other apparatus inside a building for bringing in the water supply and removing the liquid and waterborne wastes. (2) The installation of the foregoing pipes, fixtures, and other apparatus.

plumbing fixtures Receptacles that receive liquid, water, or wastewater and discharge them into a drainage system.

plunger pump A reciprocating pump with a plunger that does not come in contact with the cylinder walls, but enters and withdraws from it through packing glands. Such packing may be inside or outside the center, according to the design of the pump.

pneumatic ejector A device for raising wastewater, sludge, or other liquid by alternately admitting it through an inward swinging check valve into the bottom of an airtight pot and then discharging it through an outward swinging check value by admitting compressed air to the pot above the liquid.

point gauge A sharp-pointed rod attached to a graduated staff or vernier scale used for measuring the elevation of the surface of water. The point is lowered until the tip barely touches the water and forms a streak in flowing water and a meniscus jump in still water. It can also be used in a still well and can operate on an electric current with a buzzer or light that will operate when contact with the water is made.

polishing A general term for those treatment processes that are applied after conventional ones. See also *advanced waste treatment*, *tertiary treatment*.

pollution (1) Specific impairment of water quality by agricultural, domestic, or industrial wastes (including thermal and atomic wastes) to a degree that has an adverse effect on any beneficial use of the water. (2) The addition to a natural body of water any material that diminishes the optimal economic use of a water body by the population it serves and has an adverse effect on the surrounding environment.

polychlorinated biphenyls (PCBs) A class of aromatic organic compounds with two six-carbon unsaturated rings, with chlorine atoms substituted on each ring and more than two such chlorine atoms per molecule of PCB. They are typically stable, resist both chemical and biological degradation, and are toxic to many biological species.

polyelectrolyte flocculants Polymeric organic compounds used to induce or enhance the flocculation of suspended and colloidal solids and thereby facilitate sedimentation or the dewatering of sludges.

polyelectrolytes Complex polymeric compounds, usually composed of synthetic macromolecules that form charged species (ions) in solution; water-soluble polyelec-

trolytes are used as flocculants; insoluble polyelectrolytes are used as ion exchange resins. See also *polymers*.

polymers Synthetic organic compounds with high molecular weights and composed of repeating chemical units (monomers); they may be polyelectrolytes, such as water-soluble flocculents or water-insoluble ion exchange resins, or insoluble uncharged materials, such as those used for plastic or plastic-lined pipe and plastic trickling filter media.

polyvinyl chloride (PVC) An artificial polymer made from vinyl chloride monomer (CH_2:CHCl); frequently used in pipes, sheets, and vessels for transport, containment, and treatment in water and wastewater facilities. See also *polymers*.

population dynamics The ever-changing numbers of microscopic organisms within the activated sludge process.

population equivalent The estimated population that would contribute a given amount of a specific waste parameter (BOD_5, suspended solids, or flow); usually applied to industrial waste. Domestic wastewater contains material that consumes, on the average, 0.17 lb of oxygen/cap/d (0.08 kg/cap·d), as measured by the standard BOD test. For example, if an industry discharges 1 000 lb of BOD/d (454 kg/d), its waste is equivalent to the domestic wastewater from 6 000 persons (1 000/0.17 = approximately 6 000).

pore As applied to stone, soil, or other material, any small interstice or open space, generally one that allows the passage or adsorption of liquid or gas.

pore space Open space in rock or granular material.

porosity (1) The quality of being porous or containing interstices. (2) The ratio of the aggregate volume of interstices in a rock or soil to its total volume; usually stated as a percentage.

positive-displacement pump Pump type in which liquid is induced to flow from the supply source through an inlet pipe and inlet valve. Water is brought into the pump chamber by a vacuum created by the withdrawal of a piston or pistonlike device, which, on its return, displaces a certain volume of water contained in the chamber and forces it to flow through the discharge valve and pipe.

postaeration The addition of air to plant effluent to increase the oxygen concentration of treated wastewater.

postchlorination The application of chlorine to wastewater following treatment.

power (apparent) The mathematical product of the volts and amps of a circuit. The product generally is divided by 1000 and designated as kilovolt amperes (kVA).

power (electric) The time rate of transferring or using electrical energy, usually expressed in kilowatts (kW).

power (reactive) That portion of *apparent power* that does no work. It is usually measured in kilovars. Reactive power must be supplied to most types of magnetic equipment, such as motors, ballasts, transformers, and relays. Typically, it is supplied by generators or by electrostatic equipment such as capacitors.

power requirements The rate of energy input needed to operate a piece of equipment, a treatment plant, or other facility or system. The form of energy may be electrical, fossil fuel, other types, or a combination.

preaeration A preparatory treatment of wastewater consisting of aeration to remove gases, add oxygen, promote flotation of grease, and aid coagulation.

prechlorination The application of chlorine to wastewater at or near the treatment plant entrance. Often used after bar screens and grit chambers to control odors in primary settling tanks.

precipitate (1) To condense and cause to fall as precipitation, as water vapor condenses and falls as rain. (2) The separation from solution as a precipitate. (3) The substance that is precipitated.

preliminary treatment Unit operations, such as screening, comminution, and grit removal, that prepare the wastewater for subsequent major treatment.

press filter A press operated mechanically for partially dewatering sludge. See also *filter press*, *plate press*.

pressure (1) The total load or force acting on a surface. (2) In hydraulics, unless otherwise stated, the pressure per unit area or intensity of pressure above local atmospheric pressure expressed in pounds per square inch (psi) or kilograms per square centimeter (kg/cm^2).

pressure filter (1) An enclosed vessel having a vertical or horizontal cylinder of iron, steel, wood, or other material containing granular media through which liquid is forced under pressure. (2) A mechanical filter for partially dewatering sludge. See also *filter press*, *plate press*.

pressure gauge A device for registering the pressure of solids, liquids, or gases. It may be graduated to register pressure in any units desired.

pressure-relief valve Valve that opens automatically when the pressure reaches a preset limit to relieve stress on a pipeline.

pressure tank A tank used in connection with a water distribution system for a single household, for several houses, or for a portion of a larger water system that is airtight

and holds both air and water and in which air is compressed and the pressure so created is transmitted to the water.

pretreatment Treatment of industrial wastewater at its source before discharge to municipal collection systems.

primary effluent The liquid portion of wastewater leaving the primary treatment process.

primary sedimentation tank The first settling tank for the removal of settleable solids through which wastewater is passed in a treatment works. Sometimes called a *primary clarifier*.

primary sludge Sludge obtained from a primary sedimentation tank.

primary treatment (1) The first major treatment in a wastewater treatment facility, used for the purpose of sedimentation. (2) The removal of a substantial amount of suspended matter, but little or no colloidal and dissolved matter. (3) Wastewater treatment processes usually consisting of clarification with or without chemical treatment to accomplish solid–liquid separation.

primary voltage The voltage of the circuit supplying power to a transformer, as opposed to the output voltage or load-supplied voltage, which is called *secondary voltage*. In power supply practice, the primary is almost always the high-voltage side and the secondary the low-voltage side of the transformer.

propeller pump A centrifugal pump that develops most of its head by the propelling or lifting action of the vanes on the liquid. Also called an *axial-flow pump*.

propeller-type impeller An impeller of the straight axial-flow type.

proportional weir A special type of weir in which the discharge through the weir is directly proportional to the head.

protozoa Small one-celled animals including amoebae, ciliates, and flagellates.

publicly owned treatment works Wastewater treatment plant.

pump A mechanical device for causing flow, for raising or lifting water or other fluid, or for applying pressure to fluids.

pump curve A curve or curves showing the interrelation of speed, dynamic head, capacity, brake horsepower, and efficiency of a pump.

pump efficiency The ratio of energy converted into useful work to the energy applied to the pump shaft, or the energy difference in the water at the discharge and suction nozzles divided by the power input at the pump shaft.

pumping head The sum of the static head and friction head on a pump discharging a given quantity of water.

pumping station (1) A facility housing relatively large pumps and their appurtenances. *Pump house* is the usual term for shelters for small water pumps. (2) A facility containing lift pumps to facilitate wastewater collection or reclaimed water distribution.

pump pit A dry well or chamber, below ground level, in which a pump is located.

pump stage The number of impellers in a centrifugal pump; for example, a single-stage pump has one impeller; a two-stage pump has two impellers.

putrefaction Biological decomposition, usually of organic matter, with the production of foul-smelling products associated with anaerobic conditions.

putrescibility (1) The relative tendency of organic matter to undergo decomposition in the absence of oxygen. (2) The susceptibility of wastewaters, effluent, or sludge to putrefaction. (3) The stability of a polluted, raw, or partially treated wastewater.

quicklime A calcined material, the major part of which is calcium oxide, or calcium oxide in natural association with a lesser amount of magnesium oxide. It is capable of combining with water, that is, being slaked.

raceway Any channel for holding wires, cables, or bus bars that is designed expressly and solely for that purpose. Raceways may be of metal or insulating materials and the term includes rigid metal conduit, nonmetallic conduit, flexible metal conduit, and electrical metallic tubing. Raceways may be located beneath the floor or on or above the surface (refer to the National Electric Code for approved raceways).

rack A device fixed in place and used to remove suspended or floating solids from wastewater. It is composed of parallel bars that are evenly spaced. See also *screen*.

radial flow The direction of flow across a tank from center to periphery or vice versa.

radiation (1) The emission and propagation of energy through space or through a material medium; also the energy so propagated. (2) The dispersion of energy by electromagnetic waves rather than by conduction and convection.

range A measure of the variability of a quantity; the difference between the largest and smallest values in the sequence of values of the quantity.

rate (1) The speed at which a chemical reaction occurs. (2) Flow volume per unit time. See also *kinetics*.

rate-of-flow controller An automatic device that controls the rate of flow of a fluid.

rate-of-flow recorder A recorder for registering the rate of flow of water; generally, used with a rapid sand filter.

raw sludge Settled sludge promptly removed from sedimentation tanks before decomposition has much advanced.

raw wastewater Wastewater before it receives any treatment.

reaction rate The rate at which a chemical reaction progresses. See also *kinetics*, *rate*.

reactor The container, vessel, or tank in which a chemical or biological reaction is carried out.

recalcining Recovery of lime from water and wastewater treatment sludge.

recarbonation (1) The process of introducing carbon dioxide as a final stage in the lime-soda ash softening process to convert carbonates to bicarbonates and thereby stabilize the solution against precipitation of carbonates. (2) The addition of carbon dioxide to the effluent of an advanced wastewater treatment ammonia air stripping process to lower the pH. (3) The diffusion of carbon dioxide gas through a liquid to replace the carbon dioxide removed by the addition of lime. (4) The diffusion of carbon dioxide gas through a liquid to render the liquid stable with respect to precipitation or dissolution of alkaline constituents.

receiving water A river, lake, ocean, or other watercourse into which wastewater or treated effluent is discharged.

receptacle A contact device installed at the outlet for connection of a single attachment plug. A single receptacle is a single contact device with no other contact device on the same yoke. A multiple receptacle is a single device containing two or more receptacles.

reciprocating pump A type of displacement pump consisting essentially of a closed cylinder containing a piston or plunger as the displacing mechanism. Liquid is drawn into the cylinder through an inlet valve and forced out through an outlet valve. When the piston acts on the liquid in one end of the cylinder, the pump is termed *single-action*; when it acts in both ends, it is termed *double-action*.

recirculation (1) In the wastewater field, the return of all or a portion of the effluent in a trickling filter to maintain a uniform high rate through the filter. Return of a portion of the effluent to maintain minimum flow is sometimes called *recycling*. (2) The return of effluent to the incoming flow. (3) The return of the effluent from a process, factory, or operation to the incoming flow to reduce the water intake. The incoming flow is called *makeup water*.

reclaimed wastewater Wastewater used for some beneficial purpose usually after some degree of treatment.

recorder (1) A device that makes a graph or other record of the stage, pressure, depth, velocity, or the movement or position of water-controlling devices, usually as a function of time. See also *indicator*. (2) The person who records the observational data.

recording gauge An automatic instrument for measuring and recording graphically and continuously. Also called a *register*.

rectangular weir A weir having a notch that is rectangular in shape.

recycle (1) To return water after some type of treatment for further use; generally implies a closed system. (2) To recover useful values from segregated solid waste.

recycling (1) An operation in which a substance is passed through the same series of processes, pipes, or vessels more than once. (2) The conversion of solid waste into usable materials or energy.

reduce The opposite of oxidize. The action of a substance to decrease the positive valence of an ion.

reduction The addition of electrons to a chemical entity decreasing its valence. See also *oxidation*.

refractory Brick or similar material that lines a furnace or incinerator.

regeneration (1) In ion exchange, the process of restoring an ion exchange material to the state used for adsorption. (2) The periodic restoration of exchange capacity of ion exchange media used in water treatment.

relative humidity (1) The amount of water vapor in the air; expressed as a percentage of the maximum amount that the air could hold at the given temperature. (2) The ratio of the actual water vapor pressure to the saturation vapor pressure.

relay An electrical device that is designed to interpret input conditions in a prescribed manner and, after specified conditions are met, to respond to cause electrical operation or similar abrupt change in associated control circuits. The most common form of relay uses a coil and set of contacts. When current flows in the coil, contacts are opened or closed, depending on their arrangement. Relays are said to be normally open or normally closed.

relief valve A valve that releases air from a pipeline automatically without loss of water, or introduces air into a line automatically if the internal pressure becomes less than that of the atmosphere.

removal efficiency A measure of the effectiveness of a process in removing a constituent, such as BOD or TSS. Removal efficiency is calculated by subtracting the effluent value from the influent value and dividing it by the influent value. Multiply the answer by 100 to convert to a percentage.

repair An element of maintenance, as distinguished from replacement or retirement.

replacement Installation of new or alternate equipment in place of existing equipment for a variety of reasons, such as obsolescence, total disrepair, improvement, or modification.

replacement cost (1) The actual or estimated cost of duplication with a property of equal utility and desirability. (2) The cost of replacing property.

residue (1) The equilibrium quantity of a compound or element remaining in an organism after uptake and clearance. (2) The dry solid remaining after evaporation.

resistance The property of an electrical circuit or device that opposes current flow, thereby causing conversion of electrical energy to heat or radiant energy.

respiration Intake of oxygen and discharge of carbon dioxide as a result of biological oxidation.

retention time The theoretical time required to displace the contents of a tank or unit at a given rate of discharge (volume divided by the rate of discharge). Also called *detention time*.

return sludge Settled activated sludge returned to mix with incoming raw or primary settled wastewater. More commonly called *return activated sludge*.

reverse osmosis An advanced method used in water and wastewater treatment that relies on a semipermeable membrane to separate the water from its impurities. An external force is used to reverse the normal osmotic flow resulting in movement of the water from a solution of higher solute concentration to one of lower concentration. Also called *hyperfiltration*.

revolving screen A screen or rack in the form of a cylinder or a continuous belt that is revolved mechanically. The screenings are removed by water jets, automatic scrapers, or manually.

Reynolds' number A dimensionless quantity used to characterize the type of flow in a hydraulic structure where resistance to motion depends on the viscosity of the liquid in conjunction with inertia. It is equal to the ratio of inertial forces to viscous forces. The number is chiefly applicable to closed systems of flow, such as pipes or conduits where there is no free water surface, or to bodies fully immersed in the fluid so the free surface need not be considered.

riprap Broken stone or boulders placed compactly or irregularly on dams, levees, dikes, or similar embankments for protection of earth surfaces against the action of waves or currents.

rising time The time necessary for removal, by flotation, of suspended or aggregated colloidal substances.

rotary distributor A movable distributor made up of horizontal arms that extend to the edge of the circular trickling filter bed, revolve about a central post, and distribute liquid over the bed through orifices in the arms. The jet action of the discharging liquid normally supplies the motive power. See also *distributor*.

rotary dryer A long, slowly revolving, steel cylinder with its long axis slightly inclined, through which passes the material to be dried in hot air. The material passes through from inlet to outlet, tumbling about.

rotary pump A type of displacement pump consisting essentially of elements rotating in a pump case that is closely fit. The rotation of these elements alternately draws in and discharges the water being pumped. Such pumps act with neither suction nor discharge valves, operate at almost any speed, and do not depend on centrifugal forces to lift the water.

rotary valve A valve consisting of a casing more or less spherical in shape and a gate that turns on trunnions through 90 deg when opening or closing and having a cylindrical opening of the same diameter as that of the pipe it serves.

rotating biological contactor (RBC) A device for wastewater treatment composed of large, closely spaced plastic discs that are rotated about a horizontal shaft. The discs alternately move through the wastewater and the air and develop a biological growth on their surfaces.

rotating distributor A distributor consisting of rotating or reciprocating perforated pipes or troughs from which liquid is discharged in the form of a spray or in a thin sheet at uniform rates over the surface area to be wetted.

rotifer Minute, multicellular aquatic animals with rotating cilia on the head and forked tails. Rotifers help stimulate microfloral activity and decomposition, enhance oxygen penetration, and recycle mineral nutrients.

roughing filter A trickling filter used to remove an initial portion of the soluble BOD, usually about 50%, but not to provide complete removal.

roughness coefficient A factor in many engineering equations for computing the average velocity of flow of water in a conduit or channel. It represents the effect of the roughness of the confining material on the energy losses in the flowing water.

safety valve A valve that automatically opens when prescribed conditions, usually pressure, are exceeded in a pipeline or other closed receptacle containing liquids or gases. It prevents such conditions from being exceeded and causing damage.

Salmonella A genus of aerobic, rod-shaped, usually motile bacteria that are pathogenic for man and other warm-blooded animals.

sampler A device used with or without flow measurement to obtain a portion of liquid for analytical purposes. May be designed for taking single samples (grab), composite samples, continuous samples, or periodic samples.

sand filter A bed of sand through which water is passed to remove fine suspended particles. Commonly used in tertiary wastewater treatment plants and sludge drying beds.

sanitary sewer A sewer that carries liquid and waterborne wastes from residences, commercial buildings, industrial plants, and institutions together with minor quantities of ground, storm, and surface water that are not admitted intentionally. See also *wastewater*.

Sarcadina Species of amoeba found in wastewater. Does not play a significant role in the activated-sludge process other than as an indication of start up or the passing of a toxic influence.

saturated air Air containing all the water vapor that it is capable of holding at a given temperature and pressure.

saturated liquid Liquid that contains at a given temperature as much of a solute as it can retain in the presence of an excess of that solute.

scraper (1) Device used to remove solids from a clarifier to a sump. (2) Mechanism to remove dewatered solids from a belt filter press or conveyor.

screen A device with openings, generally of uniform size, used to retain or remove suspended or floating solids in flow stream preventing them from passing a given point in a conduit. The screening element may consist of parallel bars, rods, wires, grating, wire mesh, or perforated plate.

screening A preliminary treatment process that removes large suspended or floating solids from raw wastewater to prevent subsequent plugging of pipes or damage to pumps.

screenings (1) Material removed from liquids by screens. (2) Broken rock, including the dust, of a size that will pass through a given screen depending on the character of the stone.

screenings grinder A device for grinding, shredding, or macerating material removed from wastewater by screens.

screw-feed pump A pump with either a horizontal or vertical cylindrical casing in which operates a runner with radial blades like those of a ship's propeller. See also *vertical screw pump*.

scrubbing Removal of suspended solids and undesirable gases from gaseous emissions.

scum (1) The extraneous or foreign matter that rises to the surface of a liquid and forms a layer or film there. (2) A residue deposited on a container or channel at the water surface. (3) A mass of solid matter that floats on the surface.

scum baffle A vertical baffle dipping below the surface of wastewater in a tank to prevent the passage of floating matter.

scum breaker A device installed in a sludge digestion tank to break up scum.

scum chamber A space provided in a sludge digestion tank for accumulated scum rising from the digestion unit.

scum collector A mechanical device for skimming and removing scum from the surface of settling tanks.

scum removal Separation of floating grease and oil from wastewater usually during preliminary or primary treatment.

scum trough A trough placed in a primary sedimentation tank to intercept scum and convey it out of the tank.

Secchi disk Tool to measure the clarity of the water.

secondary effluent (1) The liquid portion of wastewater leaving secondary treatment. (2) An effluent that, with some exceptions, contains not more than 30 mg/L each (on a 30-day average basis) of BOD_5 and suspended solids.

secondary sedimentation tank A settling tank following secondary treatment designed to remove by gravity part of the suspended matter. Also called a *secondary clarifier*.

secondary treatment (1) Generally, a level of treatment that produces secondary effluent. (2) Sometimes used interchangeably with the concept of biological wastewater treatment, particularly the activated-sludge process. Commonly applied to treatment that consists chiefly of clarification followed by a biological process with separate sludge collection and handling.

secondary voltage The output or load-supplied voltage of a transformer or substation (see *primary voltage*).

second-stage BOD That part of the oxygen demand associated with the biochemical oxidation of nitrogenous material. As the term implies, the oxidation of the nitrogenous materials usually does not start until a portion of the carbonaceous material has been oxidized during the first stage.

sedimentation (1) The process of subsidence and decomposition of suspended matter or other liquids by gravity. It is usually accomplished by reducing the velocity of the liquid below the point at which it can transport the suspended material. Also called settling. It may be enhanced by coagulation and flocculation. (2) Solid–liquid separation resulting from the application of an external force, usually settling in a clarifier under the force of gravity. It can be variously classed as discrete, flocculent, hindered, and zone sedimentation.

sedimentation tank A basin or tank in which wastewater containing settleable solids is retained for removal of the suspended matter by gravity. Also called a *sedimentation basin*, *settling basin*, *settling tank*, or *clarifier*.

seed sludge In biological treatment, the inoculation of the unit process with biologically active sludge resulting in acceleration of the initial stage of the process.

self-cleansing velocity The minimum velocity necessary to keep solids in suspension in sewers, thus preventing their deposition and subsequent nuisance from stoppages and odors of decomposition.

separate sewer system A sewer system carrying sanitary wastewater and other water-carried wastes from residences, commercial buildings, industrial plants, and institutions, as well as minor quantities of ground, storm, and surface water that are not intentionally admitted. See also *combined sewer*, *wastewater*.

septage The sludge produced in individual on-site wastewater disposal systems such as septic tanks and cesspools.

septic (1) Anaerobic. (2) Putrid, rotten, foul smelling; anaerobic.

septicity A condition produced by growth of anaerobic organisms.

septic wastewater Wastewater undergoing anaerobic decomposition.

service Conductors and equipment for delivering energy from the electrical supply system to the wiring system of the premises served.

service charge The rate charged by the utility for rendering service, usually used as a ready-to-serve charge.

service conductors Supply conductors that extend from the street main or from transformers to the service equipment of the premises served.

service equipment Necessary equipment usually consisting of a circuit breaker or switch and fuses and their accessories that is located near the point of entrance of the supply conductors to a building or other structure and intended to constitute the main control and means of cut-off of the electrical supply.

settleability The tendency of suspended solids to settle.

settleability test A determination of the settleability of solids in a suspension by measuring the volume of solids settled out of a measured volume of sample in a specified interval of time, usually reported in milliliters per liter (mL/L). Also called the *Imhoff cone test*.

settleable solids (1) That matter in wastewater that will not stay in suspension during a preselected settling period, such as 1 hour, but settles to the bottom. (2) In the Imhoff cone test, the volume of matter that settles to the bottom of the cone in 1 hour. (3) Suspended solids that can be removed by conventional sedimentation.

settleometer A 2-L or larger beaker used to conduct the settleability test.

settling The process of subsidence and deposition of suspended matter carried by a liquid. It is usually accomplished by reducing the velocity of the liquid below the point at which it can transport the suspended material. Also called *sedimentation*.

settling tank A tank or basin in which water, wastewater, or other liquid containing settleable solids is retained for a sufficient time, and in which the velocity of flow is sufficiently low to remove by gravity a part of the suspended matter. See also *sedimentation tank*.

settling time Time necessary for the removal of suspended or colloidal substances by gravitational settling, aggregation, or precipitation.

settling velocity Velocity at which subsidence and deposition of settleable suspended solids in wastewater will occur.

sheet flow Flow in a relatively thin sheet of generally uniform thickness.

short-circuiting A hydraulic condition occurring in parts of a tank where the time of travel is less than the flow-through time.

side contraction The contraction of the nappe or reduction in width of water overflowing a weir brought about by the detachment of the sides of the nappe or jet of water passing over the sides of the weir.

side-water depth The depth of water measured along a vertical exterior wall.

single-action pump A reciprocating pump in which the suction inlet admits water to only one side of the plunger or piston and the discharge is intermittent.

single-stage digestion Digestion limited to a single tank for the entire digestion period.

single-suction impeller An impeller with one suction inlet.

skimming (1) The process of diverting water from the surface of a stream or conduit by means of a shallow overflow. (2) The process of diverting water from any elevation in a reservoir by means of an outlet at a different elevation or by any other skimming device in order to obtain the most palatable drinking water. (3) The process of removing grease or scum from the surface of wastewater in a tank.

skimmings Grease, solids, liquids, and scum skimmed from wastewater settling tanks.

slake To become mixed with water so that a true chemical combination takes place, as in the slaking of lime.

slimes (1) Substances of a viscous organic nature, usually formed from microbiological growth, that attach themselves to other objects forming a coating. (2) The coating of biomass (humus, schmutzdecke, sluff) that accumulates in trickling filters or sand filters and periodically sloughs away to be collected in clarifiers. See also *biofilm*.

slope (1) The inclination of gradient from the horizontal of a line or surface. The degree of inclination is usually expressed as a ratio such as 1:25, indicating unit rise in 25 units of horizontal distance; or in a decimal fraction (0.04); degrees (2 deg 18 min); or percent (4%). (2) Inclination of the invert of a conduit expressed as a decimal or as feet (meters) per stated length measured horizontally in feet. (3) In plumbing, the inclination of a conduit, usually expressed in inches per foot (meter) length of pipe.

sloughing The disattachment of slime and solids accumulated on the media of trickling filters and RBCs in contact areas. Sloughed material usually is removed subsequently in clarifiers. See also *slimes*.

slow sand filter A filter for the purification of water in which water without previous treatment is passed downward through a filtering medium consisting of a layer of sand from 24- to 40-in. (0.6- to 1-m) thick. The filtrate is removed by an underdrainage system and the filter is cleaned by scraping off the clogged sand and eventually replacing it. It is characterized by a slow rate of filtration, commonly 3 to 6 mgd/ac (28 to 56 ML/ha·d) of filter area. Its effectiveness depends on the biological mat (or schmutzdecke) that forms in the top few millimeters.

sludge (1) The accumulated solids separated from liquids during the treatment process that have not undegone a stabilization process. (2) The removed material resulting from chemical treatment, coagulation, flocculation, sedimentation, flotation, or biological oxidation of water or wastewater. (3) Any solid material containing large amounts of entrained water collected during water or wastewater treatment. See also *activated sludge*, *settleable solids*.

sludge age Average residence time of suspended solids in a biological treatment system equal to the total weight of suspended solids in the system divided by the total weight of suspended solids leaving the systems.

sludge blanket Accumulation of sludge hydrodynamically suspended within an enclosed body of water or wastewater.

sludge boil An upwelling of water and sludge deposits caused by release of decomposition gases in the sludge deposits.

sludge circulation The overturning of sludge in sludge digestion tanks by mechanical or hydraulic means or by the use of gas recirculation to disperse scum layers and promote digestion.

sludge collector A mechanical device for scraping the sludge on the bottom of a settling tank to a sump from which it can be drawn.

sludge concentration Any process of reducing the water content of sludge leaving the sludge in a fluid condition.

sludge density index (SDI) A measure of the degree of compaction of a sludge after settling in a graduated container, expressed as mL/g. The sludge volume index (SVI) is the reciprocal of the sludge density index.

sludge dryer A device for removing a large percentage of moisture from sludge or screenings by heat.

sludge drying The process of removing a large percentage of moisture from sludge by drainage or evaporation by any method.

sludge-gas holder A tank used to store gas collected from sludge digestion tanks for the purpose of stabilizing the flow of gas to the burners, maintaining a nearly constant pressure, and supplying gas during periods when the digestion tanks are temporarily out-of-service or when gas production is low.

sludge-gas utilization Using the gas produced by the anaerobic digestion of sludge for beneficial purposes such as heating sludge, mixing sludge, drying sludge, heating buildings, incineration, or fueling engines.

sludge pressing The process of dewatering sludge by subjecting it to pressure, usually within a cloth fabric through which the water passes and in which the solids are retained.

sludge reaeration The continuous aeration of sludge after its initial aeration for the purpose of improving or maintaining its condition.

sludge reduction The reduction in quantity and change in character of sludge as the result of digestion.

sludge solids Dissolved and suspended solids in sludge.

sludge thickener A tank or other equipment designed to concentrate wastewater sludges.

sludge thickening The increase in solids concentration of sludge in a sedimentation tank, DAF, gravity thickener, centrifuge or gravity belt thickener.

sludge utilization The use of sludges resulting from industrial wastewater treatment as soil builders and fertilizer admixtures.

sludge volume index (SVI) The ratio of the volume (in milliliters) of sludge settled from a 1000-mL sample in 30 minutes to the concentration of mixed liquor (in milligrams per liter [mg/L]) multiplied by 1000.

slurry A thick, watery mud or any substance resembling it, such as lime slurry.

soda ash A common name for commercial sodium carbonate (Na_2CO_3).

sodium bisulfite ($NaHSO_3$) A salt used for reducing chlorine residuals; a strong reducing agent; typically found in white powder or granular form in strengths up to 44%. At a strength of 38%, 1.46 parts will consume 1 part of chlorine residual.

sodium carbonate (Na_2CO_3) A salt used in water treatment to increase the alkalinity or pH of water or to neutralize acidity. Also called *soda ash*.

sodium hydroxide (NaOH) A strong caustic chemical used in treatment processes to neutralize acidity, increase alkalinity, or raise the pH value. Also known as *caustic soda*, *sodium hydrate*, *lye*, and *white caustic*.

sodium hypochlorite (NaOCl) A water solution of sodium hydroxide and chlorine in which sodium hypochlorite is the essential ingredient.

sodium metabisulfite ($Na_2S_2O_5$) A cream-colored powder used to conserve chlorine residual; 1.34 parts of $Na_2S_2O_5$ will consume 1 part of chlorine residual.

soil absorption capacity In subsurface effluent disposal, the ability of the soil to absorb water. See *soil absorption test*.

soil absorption test A test for determining the suitability of an area for subsoil effluent disposal by measuring the rate at which the undisturbed soil will absorb water per unit of surface.

soil horizon A layer or section of the soil profile, more or less well defined, occupying a position approximately parallel to the soil surface, and having characteristics that have been produced through the operation of soil-building processes.

soil infiltration rate The maximum rate at which a soil, in a given condition at a given time, can absorb water.

soil porosity The percentage of the soil (or rock) volume that is not occupied by solid particles, including all pore space filled with air and water. The total porosity may be calculated from the following formula: percent pore space = (1 − volume weight/specific gravity) × 100.

solids disposal Any process for the ultimate disposal of solid wastes or sludges by incineration, landfilling, soil conditioning, or other means.

solids inventory Amount of sludge in the treatment system typically expressed as kilogram (tons). Inventory of plant solids should be tracked through the use of a mass balance set of calculations.

solids loading Amount of solids applied to a treatment process per unit time per unit volume.

solids retention time (SRT) The average time of retention of suspended solids in a biological waste treatment system, equal to the total weight of suspended solids leaving the system, per unit time.

sparger An air diffuser designed to give large bubbles, used singly or in combination with mechanical aeration devices.

species A subdivision of a genus having members differing from other members of the same genus in minor details.

specific gravity The ratio of the mass of a body to the mass of an equal volume of water at a specific temperature, typically 20 °C (68 °F).

specific oxygen uptake rate Measures the microbial activity in a biological system expressed in mg O_2/g·h of VSS. Also called *respiration rate*.

specific resistance The relative resistence a sludge offers to the draining of its liquid component.

specific speed A speed or velocity of revolution, expressed in revolutions per minute (rpm), at which the runner of a given type or turbine would operate if it were so reduced in size and proportion that it would develop 1 hp under a 1-ft head. The quantity is used in determining the proper type and character of turbine to install at a hydroelectric power plant under given conditions.

spiral-air flow diffusion A method of diffusing air in the grit chamber or aeration tank of the activated-sludge process where, by means of properly designed baffles and the proper location of diffusers, a spiral helical movement is given to the air and the tank liquor.

splitter box (1) A division box that splits the incoming flow into two or more streams. (2) A device for splitting and directing discharge from the head box to two separate points of application.

spray aerator An aerator consisting of a pressure nozzle through which water is propelled into the air in a fine spray.

spray irrigation A method of land treatment for disposing of some organic wastewaters by spraying them, usually from pipes equipped with fixed or moving spray nozzles. See also *land application*.

stabilization pond A type of oxidation pond in which biological oxidation of organic matter is effected by natural or artificially accelerated transfer of oxygen to the water from air.

staged digestion The progressive digestion of waste in two or more tanks arranged in series, usually divided into primary digestion with mixed contents and secondary digestion where quiescent conditions prevail and supernatant liquor is collected.

staged treatment (1) Any treatment in which similar processes are used in series or stages. (2) In the activated-sludge process, two or more stages consisting of a clarifying stage and a biological stage, or two biological stages. (3) In anaerobic digestion, an operation in which sludge is completely mixed in the first tank and pumped to a second tank for separation of the supernatant liquor from the solids.

staged trickling filter A series of trickling filters through which wastewater passes successively with or without intermediate sedimentation.

stale wastewater Wastewater containing little or no oxygen, but as yet free from putrefaction. See also *septic wastewater*.

stalked ciliates Small, one-celled organisms possessing cilia (hair-like projections used for feeding) that are not motile. They develop at lower prey densities, long SRTs, and low F:M ratios.

Standard Methods (1) An assembly of analytical techniques and descriptions commonly accepted in water and wastewater treatment (*Standard Methods for the Examination of Water and Wastewater*) published jointly by the American Public Health Association, the American Water Works Association, and the Water Environment Federation. (2) Validated methods published by professional organizations and agencies covering specific fields or procedures. These include, among others, the American Public Health Association, American Public Works Association, American Society of Civil Engineers, American Society of Mechanical Engineers, American Society for Testing and Materials, American Water Works Association, U.S. Bureau of Standards, U.S. Standards Institute (formerly American Standards Association), U.S. Public Health Service, Water Environment Federation, and U.S. Environmental Protection Agency.

standard pressure Atmospheric pressure at sea level under standard conditions.

static head Vertical distance between the free level of the source of supply and the point of free discharge or the level of the free surface.

static level (1) The elevation of the water table or pressure surface when it is not influenced by pumping or other forms of extraction from the groundwater. (2) The level of elevation to which the top of a column of water would rise, if afforded the opportunity to do so, from an artesian aquifer, basin, or conduit under pressure. Also called *hydrostatic level.*

static suction head The vertical distance from the source of supply, when its level is above the pump, to the center line of the pump.

static suction lift The vertical distance between the center of the suction end of a pump and the free surface of the liquid being pumped. Static lift does not include friction losses in the suction pipes. Static suction head includes lift and friction losses.

steady flow (1) A flow in which the rate, or quantity of water passing a given point per unit of time, remains constant. (2) Flow in which the velocity vector does not change in either magnitude or direction with respect to time at any point or section.

steady nonuniform flow A flow in which the quantity of water flowing per unit of time remains constant at every point along the conduit, but the velocity varies along the conduit because of a change in the hydraulic characteristics.

step aeration A procedure for adding increments of settled wastewater along the line of flow in the aeration tanks of an activated-sludge plant. Also called *step feed*.

stoichiometric Pertaining to or involving substances that are in the exact proportions required for a given reaction.

straggler floc Large (6-mm or larger) floc particles that have poor settling characteristics.

submerged weir A weir that, when in use, has a water level on the downstream side at an elevation equal to, or higher than, the weir crest. The rate of discharge is affected by the tailwater. Also called a *drowned weir*.

submergence (1) The condition of a weir when the elevation of the water surface on the downstream side is equal to or higher than that of the weir crest. (2) The ratio, expressed as a percentage, of the height of the water surface downstream from a weir above the weir crest to the height of the water surface upstream above the weir crest. The distances upstream or downstream from the crest at which such elevations are measured are important, but have not been standardized. (3) In water power engineering, the ratio of tailwater elevation to the headwater elevation when both are higher than the crest. The overflow crest of the structure is the datum of reference. The distances upstream or downstream from the crest at which headwater and tailwater elevations are measured are important, but have not been standardized. (4) The depth of flooding over a pump suction inlet.

substation An assembly of equipment for switching and/or changing or regulating the voltage electrical supply.

substrate (1) Substances used by organisms in liquid suspension. (2) The liquor in which activated sludge or other matter is kept in suspension.

suction head (1) The head at the inlet to a pump. (2) The head below atmospheric pressure in a piping system.

suction lift The vertical distance from the liquid surface in an open tank or reservoir to the center line of a pump drawing from the tank or reservoir and set higher than the liquid surface.

suctoreans Ciliates that are stalked in the adult stage and have rigid tentacles to catch prey.

sulfate-reducing bacteria Bacteria capable of assimilating oxygen from sulfate compounds, reducing them to sulfides. See also *sulfur bacteria*.

sulfur bacteria Bacteria capable of using dissolved sulfur compounds in their growth; bacteria deriving energy from sulfur or sulfur compounds.

sulfur cycle A graphical presentation of the conservation of matter in nature showing the chemical transformation of sulfur through various stages of decomposition and assimilation. The various chemical forms of sulfur as it moves among living and nonliving matter is used to illustrate general biological principles that are applicable to wastewater and sludge treatment.

sump A tank or pit that receives drainage and stores it temporarily, and from which the discharge is pumped or ejected.

sump pump A mechanism used for removing water or wastewater from a sump or wet well; it may be energized by air, water, steam, or electric motor. Ejectors and submerged centrifugal pumps, either float or manually controlled, are often used for the purpose.

supernatant (1) The liquid remaining above a sediment or precipitate after sedimentation. (2) The most liquid stratum in a sludge digester.

supersaturation (1) An unstable condition of a vapor in which its density is greater than that normally in equilibrium under the given conditions. (2) The condition existing in a given space when it contains more water vapor than is needed to cause saturation; that is, when its temperature is below that required for condensation to take place. This condition probably can occur only when water or ice is immediately present, and when the space contains no dust or condensation nuclei. (3) An unstable condition of a solution in which it contains a solute at a concentration exceeding saturation.

suppressed weir A weir with one or both sides flush with the channel of approach. This prevents contraction of the nappe adjacent to the flush side. The suppression may occur on one end or both ends.

surface aeration The absorption of air through the surface of a liquid.

surface overflow rate A design criterion used for sizing clarifiers; typically expressed as the flow volume per unit amount of clarifier space ($m^3/m^2 \cdot s$ [gpd/sq ft]).

surfactant A surface-active agent, such as ABS or LAS, that concentrates at interfaces, forms micelles, increases solution, lowers surface tension, increases adsorption, and may decrease flocculation.

surge (1) A momentary increase in flow (in an open conduit) or pressure (in a closed conduit) that passes longitudinally along the conduit, usually because of sudden changes in velocity or quantity. (2) Any periodic, usually abrupt, change in flow, temperature, pH, concentration, or similar factor.

surge suppressor A device used in connection with automatic control of pumps to minimize surges in a pipeline.

surge tank A tank or chamber located at or near a hydroelectric powerhouse and connected with the penstock above the turbine. When the flow of water delivered to the turbine is suddenly decreased, the tank absorbs the water that is held back and cushions the increased pressure on the penstock caused by the rapid deceleration of the water flowing in it; also, when the flow delivered to the turbine is suddenly increased, the tank supplies the increased quantity of water required until the flow in the penstock has been accelerated sufficiently. Also used in connection with pumping systems.

suspended matter (1) Solids in suspension in water, wastewater, or effluent. (2) Solids in suspension that can be readily removed by standard filtering procedures in a laboratory.

suspended solids (1) Insoluble solids that either float on the surface of, or are in suspension in, water, wastewater, or other liquids. (2) Solid organic or inorganic particles (colloidal, dispersed, coagulated, or flocculated) physically held in suspension by agitation or flow. (3) The quantity of material removed from wastewater in a laboratory test, as prescribed in *Standard Methods* and referred to as *nonfilterable residue*.

switchboard A large panel or assembly of panels on which switches, overcurrent, and/or other protective devices such as buses and instruments are mounted. Switchboards are generally accessible from the rear as well as from the front and are not intended to be installed in cabinets.

synergism Interaction between two entities producing an effect greater than a simple additive one. See also *antagonism*.

tapered aeration The method of supplying varying quantities of air into the different parts of an aeration tank in the activated-sludge process, more at the inlet, less near the outlet, in approximate proportion to the oxygen demand of the mixed liquor under aeration.

tee A pipe fitting, either cast or wrought, that has one side outlet at right angles to the run. A single-outlet branch pipe.

temperature (1) The thermal state of a substance with respect to its ability to transmit heat to its environment. (2) The measure of the thermal state on some arbitrarily chosen numerical scale. See also *Celsius*, *centigrade*, *Fahrenheit*.

temporary hardness Hardness that can be removed by boiling; more properly called *carbonate hardness*. See also *carbonate hardness*, *hardness*.

tertiary effluent The liquid portion of wastewater leaving tertiary treatment.

tertiary treatment The treatment of wastewater beyond the secondary or biological stage; term normally implies the removal of nutrients, such as phosphorus and nitrogen, and a high percentage of suspended solids; term now being replaced by *advanced waste treatment*. See also *advanced waste treatment*.

thermal stratification The formation of layers of different temperatures in bodies of water.

thermophilic digestion Digestion occurring at a temperature approaching or within the thermophilic range, generally between 43 and 60 °C (110 and 140 °F).

thermophilic range That temperature range most conducive to maintenance of optimum digestion by thermophilic bacteria, generally accepted as between 49 and 57 °C (120 and 135 °F). See also *thermophilic digestion*.

thickeners Any equipment or process, after gravity sedimentation, that increases the concentration of solids in sludges with or without the use of chemical flocculents.

threshold odor The minimum odor of the water sample that can barely be detected after successive dilutions with odorless water. Also called *odor threshold*.

threshold odor number The greatest dilution of a sample with odor-free water that yields a definitely perceptible odor.

titration The determination of a constituent in a known volume of solution by the measured addition of a solution of known strength to completion of the reaction as signalled by observation of an end point.

tolerance The ability of an organism to withstand exposure to a specific compound; a tolerance level may be defined as a period of exposure or a level of exposure (concentration) that is withstood.

total carbon (TC) A quantitative measure of both total inorganic and total organic carbon as determined instrumentally by chemical oxidation to carbon dioxide and subsequent infrared detection in a carbon analyzer. See also *total organic carbon*.

total dissolved solids (TDS) The sum of all dissolved solids (volatile and nonvolatile).

total dynamic discharge head Total dynamic head plus the dynamic suction head or minus the dynamic suction lift.

total dynamic head (TDH) The difference between the elevation corresponding to the pressure at the discharge flange of a pump and the elevation corresponding to the vacuum or pressure at the suction flange of the pump, corrected to the same datum plane, plus the velocity head at the discharge flange of the pump minus the velocity head at the suction flange of the pump.

total head (1) The sum of the pressure, velocity, and position heads above a datum. The height of the energy line above a datum. (2) The difference in elevation between the surface of the water at the source of supply and the elevation of the water at the outlet, plus velocity head and lost head. (3) The high distance of the energy line above the datum; energy head. (4) In open channel flow, the depth plus the velocity head.

total organic carbon (TOC) The amount of carbon bound in organic compounds in a sample. Because all organic compounds have carbon as the common element, total organic carbon measurements provide a fundamental means of assessing the degree of organic pollution.

total oxygen demand (TOD) A quantitative measure of all oxidizable material in a sample water or wastewater as determined instrumentally by measuring the depletion of oxygen after high-temperature combustion. See also *chemical oxygen demand*, *total organic carbon*.

total pumping head The measure of the energy increase imparted to each pound of liquid as it is pumped, and therefore, the algebraic difference between the total discharge head and the total suction head.

total solids (TS) The sum of dissolved and suspended solid constituents in water or wastewater.

total suspended solids (TSS) The amount of insoluble solids floating and in suspension in the wastewater. Also referred to as *total nonfilterable residue*.

toxicant A substance that kills or injures an organism through chemical, physical, or biological action; examples include cyanides, pesticides, and heavy metals.

toxicity The adverse effect that a biologically active substance has, at some concentration, on a living entity.

toxic wastes Wastes that can cause an adverse response when they come in contact with a biological entity.

trace nutrients Substances vital to bacterial growth. Trace nutrients are defined in this text as nitrogen, phosphorus, and iron.

transformer An electromagnetic device for changing the voltage of alternating current electricity.

trap (1) A device used to prevent a material flowing or carried through a conduit from reversing its direction of flow or movement, or from passing a given point. (2) A device to prevent the escape of air from sewers through a plumbing fixture or catch basin.

trash Debris that may be removed from reservoirs, combined sewers, and storm sewers by coarse racks.

trash rack A grid or screen placed across a waterway to catch floating debris.

trickling filter Secondary treatment process where wastewater trickles over rock or honeycombed-shaped plastic media. Biomass and slimes containing microorganisms form on the media and utilize the organic matter for growth and energy.

tri-halomethanes (THM) Derivatives of methane (CH_4) in which three halogen atoms (chlorine, bromine, or iodine) are substituted for three of the hydrogen atoms.

trough A structure, usually with a length several times its transverse dimensions, used to hold or transport water or other liquids.

tube settler A series of tubes, about 2 in. in diameter or 2-in. square, placed in a sedimentation tank to improve the solids removal efficiency.

tubing (1) Flexible pipe of small diameter, usually less than 2 in. (2) A special grade of high-test pipe fitted with couplings and fittings of special design.

turbidimeter An instrument for measurement of turbidity in which a standard suspension is used for reference.

turbidity (1) A condition in water or wastewater caused by the presence of suspended matter and resulting in the scattering and absorption of light. (2) Any suspended solids imparting a visible haze or cloudiness to water that can be removed by filtration. (3) An analytical quantity usually reported in turbidity units determined by measurements of light scattering. See also *formazine turbidity unit*, *nephelometric turbidity unit*.

turbine pump A centrifugal pump in which fixed guide vanes partially convert the velocity energy of the water to pressure head as the water leaves the impeller.

turbulence (1) The fluid property that is characterized by irregular variation in the speed and direction of movement of individual particles or elements of the flow. (2) A state of flow of water in which the water is agitated by cross currents and eddies, as opposed to laminar, streamline, or viscous flow. See also *turbulent flow*.

turbulent flow (1) The flow of a liquid past an object such that the velocity at any fixed point in the fluid varies irregularly. (2) A type of fluid flow in which there is an unsteady motion of the particles and the motion at a fixed point varies in no definite manner. Also called *eddy flow* or *sinuous flow*.

turnover The phenomenon of vertical circulation that occurs in large bodies of water. It results from the increase in density of water above and below 39.2 °F (4 °C), the temperature of minimum density. In the spring, as the surface of the water warms above

the freezing point, the water increases in density and tends to sink, producing vertical currents; in the fall, as the surface water becomes colder, it also tends to sink. Wind may also create such vertical currents. Also called *overturn*.

two-staged digestion The biological decomposition of organic matter in sludge followed by solids–liquid separation of the digested sludge. Two-stage digestion uses two compartments or two tanks to separate the violent initial digestion period from the slower final period to enhance both the digestion and the solids–liquid separation after digestion.

ultimate biochemical oxygen demand (BOD_u) (1) Commonly, the total quantity of oxygen required to completely satisfy the first-stage BOD. (2) More strictly, the quantity of oxygen required to completely satisfy both the first-stage and second-stage BOD.

ultimate disposal The final release of a biologically and chemically stable wastewater or sludge into the environment.

ultraviolet radiation (UV) Light waves shorter than the visible blue-violet waves of the spectrum.

ultraviolet ray Light rays beyond the violet of the spectrum; these are invisible to humans.

underdrain A drain that carries away groundwater or the drainage from prepared beds to which water or wastewater has been applied.

unsteady nonuniform flow Flow in which the velocity and the quantity of water flowing per unit time at every point along the conduit varies with respect to time and position.

upflow Term used to describe treatment units in which flow enters at the bottom and exits at the top.

upflow clarifier A treatment unit in which liquid containing suspended solids is passed upward through a blanket of settling sludge; mixing, flocculation, and solids removal are all accomplished in the same unit.

upflow coagulation Coagulation achieved by passing liquid, to which coagulating chemicals may have been added, upward through a blanket of settling sludge.

upflow filter A gravity or pressure filtration system in which the wastewater flows upward, generally first through a coarse medium and then through a fine medium, before discharging.

upflow tank A sedimentation tank in which water or wastewater enters near the bottom and rises vertically, usually through a blanket of previously settled solids. The clarified liquid flows out at the top and settled sludge flows out the bottom; a vertical-flow tank.

user The party who is billed, usually for sewer service from a single connection; has no reference to the number of persons served. Also called a *customer*.

user charge Charge made to users of wastewater services supplied.

utilization equipment Equipment that uses electrical energy for mechanical, chemical, heating, lighting, or similar useful purposes.

vacuum breaker A device for relieving a vacuum or partial vacuum formed in a pipeline, thereby preventing backsiphoning.

vacuum filter (1) A filter used to accomplish sludge dewatering and consisting of a cylindrical drum mounted on a horizontal axis, covered with filter media, and revolving partially submerged in a dilute sludge mixture. A vacuum is maintained under the media for the larger part of a revolution to extract moisture. The dewatered cake that is formed is scraped off mechanically for disposal. See also *vacuum filtration*. (2) A diatomaceous earth filter open to the atmosphere and on the inlet side of a pump.

vacuum filtration A usually continuous filtration operation that is generally accomplished on a rotating cylindrical drum. As the drum rotates, part of its circumference is subject to an internal vacuum that draws sludge to the filter medium and removes water for subsequent treatment. The dewatered sludge cake is released by a scraper.

vacuum pump (1) A pump for creating a partial vacuum in a closed space. (2) A pump in which water is forced up a pipe by the difference in pressure between the atmosphere and a partial vacuum. (3) An air compressor used in connection with steam condensers and for improving the suction head on other pumps. The compressor takes its suction at low absolute pressure, performs a large number of compressions, and generally discharges at atmospheric pressure.

valence An integer representing the number of hydrogen atoms with which one atom of an element (or one radical) can combine (negative valence), or the number of hydrogen atoms the atom or radical can displace (positive valence).

valve (1) A device installed in a pipeline to control the magnitude and direction of the flow. It consists essentially of a shell and a disk or plug fitted to the shell. (2) In a pump, a waterway, passage through which is controlled by a mechanism.

vapor (1) The gaseous form of any substance. (2) A visible condensation such as fog, mist, or steam that is suspended in air.

vaporization The process by which a substance such as water changes from the liquid or solid state to the gaseous state.

vapor pressure (1) Pressure exerted by a vapor in a confined space. It is a function of the temperature. (2) The partial pressure of water vapor in the atmosphere. See also *relative humidity*. (3) The partial pressure of any liquid.

velocity head (1) The vertical distance or height through which a body would have to fall freely, under the force of gravity, to acquire the velocity it possesses. It is equal to the square of the velocity divided by twice the acceleration of gravity. (2) The theoretical vertical height through which a liquid body may be raised by its kinetic energy. It is equal to the share of the velocity divided by twice the acceleration caused by gravity.

velocity meter A vaned water meter that operates on the principle that the vanes of the wheel move at approximately the same velocity as the flowing water.

Venturi meter A differential meter for measuring the flow of water or other fluid through closed conduits or pipes. It consists of a Venturi tube and one of several proprietary forms of flow-registering devices. The difference in velocity heads between the entrance and the contracted throat is an indication of the rate of flow.

vertical pump (1) A reciprocating pump in which the piston or plunger moves in a vertical direction. (2) A centrifugal pump in which the pump shaft is in a vertical position.

vertical screw pump A pump, similar in shape, characteristics, and use to a horizontal screw pump, but which has the axis of its runner in a vertical position.

virus The smallest (10 to 300 mm in diameter) life form capable of producing infection and diseases in man and animals.

viscosity The molecular attractions within a fluid that make it resist a tendency to deform under applied forces.

V-notch weir A triangular weir.

void A pore or open space in rock or granular material not occupied by solid matter. It may be occupied by air, water, or other gaseous or liquid material. Also called *interstice* or *void space*.

volatile Capable of being evaporated at relatively low temperatures.

volatile acids Fatty acids containing six or fewer carbon atoms. They are soluble in water and can be steam-distilled at atmospheric pressure. They have pungent odors and are often produced during anaerobic decomposition.

volatile solids (VS) Materials, generally organic, that can be driven off from a sample by heating, usually to 550 °C (1022 °F); nonvolatile inorganic solids (ash) remain.

volatile suspended solids (VSS) That fraction of suspended solids, including organic matter and volatile inorganic salts, that will ignite and burn when placed in an electric muffle furnace at 550 °C (1022 °F) for 60 minutes.

volt The unit of electromotive force or electrical pressure (analogous to water pressure). It is the electromotive force that, if steadily applied to a circuit having a resistance of one ohm, will produce a current of one ampere.

voltage (of a circuit) The root mean square (effective) difference in potential between any two points of the circuit concerned. On various systems such as a three-phase, 4-wire and a single-phase, 3-wire, there may be various circuits of varying voltages.

volumetric Pertaining to measurement by volume.

volute pump A centrifugal pump with a casing made in the form of a spiral or volute as an aid to the partial conversion of the velocity energy into pressure head as the water leaves the impellers.

vortex A revolving mass of water in which the stream lines are concentric circles and in which the total head for each stream line is the same.

washout Condition whereby excessive influent flows (typically at peak flow conditions) cause the solids in the aeration basins and/or clarifiers to be carried over into downstream processes or discharged to the receiving stream.

waste activated sludge (WAS) Solids removed from the activated-sludge process to prevent an excessive buildup in the system.

wastewater The spent or used water of a community or industry containing dissolved and suspended matter.

water column (1) The water above the valve in a set of pumps. (2) A measure of head or pressure in a closed pipe or conduit.

water vapor The gaseous form of water; molecules of water present as a gas in an atmosphere of other gases. Movement takes place from higher to lower vapor pressure regions to maintain vapor pressure equilibrium. Also called *aqueous vapor*.

watt The electrical unit of power. Power is the measure of the rate of doing work. A watt is the rate of energy transfer from one ampere flowing under a pressure of one volt at a unity power factor. It is analogous to horsepower or foot-pounds per minute of mechanical power. One horsepower is equivalent to approximately 746 W.

weir A device that has a crest and some side containment of known geometric shape, such as a V, trapezoid, or rectangle, and is used to measure flow of liquid. The liquid surface is exposed to the atmosphere. Flow is related to the upstream height of water

above the crest, position of crest with respect to downstream water surface, and geometry of the weir opening.

weir overflow rate The amount of flow applied to a treatment process (typically a clarifier) per linear measure of weir (gpd/lin ft).

wet-air oxidation A method of sludge disposal that involves the oxidation of sludge solids in water suspension under high pressure and temperature. Also called the *wet oxidation process*.

wire-to-water efficiency The ratio of mechanical output of a pump to the electrical input at the meter.

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Conversion Factors

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Table 1. Conversion from customary to metric units (in alphabetical order).

Multiply Customary Unit	Abbreviation	By	To Obtain Metric Unit
acre	ac	4.047×10^3	m^2
		0.404 7	ha (hectare)
acre-foot	ac-ft	1233	m^3
atmosphere	atm	101.3	kPa (kilopascal)
bar	bar	100.0	kPa
British thermal unit	Btu	1.055	kJ (kilojoule)
British thermal units per cubic foot	Btu/cu ft	37.26	kJ/m^3
British thermal units per gallon	Btu/gal	278.7	kJ/m^3
		0.278 7	kJ/L
British thermal units per hour	Btu/hr	0.2931	W (watt)
British thermal units per hour per square foot	Btu/hr/sq ft	3.155	$J/m^2 \cdot s$
British thermal units per pound	Btu/lb	2.326	kJ/kg
British thermal units per ton	Btu/ton	1.163	J/kg
calorie international	cal	4.187	J (joule)
15°C		4.186	J
20°C		4.182	J
calories per second	cal/sec	4.187	W
centipoise	cP	1.000×10^{-3}	Pa·s
cubic feet per gallon	cu ft/gal	7.482	m^3/m^3
		7.482×10^{-3}	m^3/L
cubic feet per hour	cfh or cu ft/hr	7.867×10^{-6}	m^3/s
		7.867×10^{-3}	L/s
cubic feet per hour per square foot	cfh/sq ft	8.467×10^{-5}	$m^3/m^2 \cdot s$
		304.8	$L/m^2 \cdot h$
cubic feet per million gallons	cu ft/mil. gal	7.482	mL/m^3
cubic feet per minute	cfm or cu ft/min	$4.719\ 10^{-4}$	m^3/s
		0.471 9	L/s
cubic feet per minute per foot	cfm/ft	1.549	L/m ·s
cubic feet per minute per thousand cubic feet	cfm/1000 cu ft	1.667×10^{-2}	$L/m^3 \cdot s$
cubic feet per minute per thousand gallons	cfm/1000 gal	0.124 7	$L/m^3 \cdot s$

cubic feet per pound	cu ft/lb	6.243×10^{-2}	m^3/kg
cubic feet per second	cfs	2.832×10^{-2}	m^3/s
		28.32	L/s
cubic feet per second per acre	cfs/ac	6.997×10^{-6}	$m^3/m^2 \cdot s$
		69.97	L/ha·s
cubic feet per second per square mile	cfs/sq mile	1.093×10^{-8}	$m^3/m^2 \cdot s$
		0.109 3	L/ha·s
cubic foot	cu ft	2.832×10^{-2}	m^3
		28.32	L
cubic inch	cu in.	16.39×10^{-6}	m^3
		16.39	mL
cubic yard	cu yd	0.764 6	m^3
degrees Fahrenheit	°F	0.555 6(°F − 32)	°C (degrees Celsius)
Rankine	°R	0.555 6	K (Kelvin)
feet of head	ft	0.304 8	m
feet per hour	ft/hr	8.467×10^{-5}	m/s
feet per minute	ft/min or fpm	5.080	mm/s
feet per second	ft/sec or fps	0.304 8	m/s
feet per second squared	ft/sec^2	0.304 8	m/s^2
feet per year	ft/yr	0.304 8	m/a (meters per annum)
foot	ft	0.304 8	m
foot-head	ft-head	2989	Pa
foot-pound	ft-lb	1.356	N·m
foot-pounds per inch	ft-lb/in.	53.38	J/m
foot-pounds per minute	ft-lb/min	2.259×10^{-2}	W
foot-pounds per second	ft-lb/sec	1.355	W
gallon	gal	3.785×10^{-3}	m^3
		3.785	L
gallons per day	gpd	4.381×10^{-5}	L/s
		3.785×10^{-3}	m^3/d
gallons per day per acre	gpd/ac	1.083×10^{-11}	$m^3/m^2 \cdot s$
		1.083×10^{-8}	$L/m^2 \cdot s$
		9.353	L/ha·d
gallons per day per capita	gpd/cap	3.785	L/cap·d

Table 1. Conversion from customary to metric units (in alphabetical order) (*continued*).

Multiply Customary Unit	Abbreviation	By	To Obtain Metric Unit
gallons per day per linear foot	gpd/ft	1.437×10^{-7}	$m^3/m{\cdot}s$
		1.437×10^{-4}	$L/m{\cdot}s$
		1.242×10^{-2}	$m^3/m{\cdot}d$
gallons per day per foot of manhole diameter per foot-head	gpd/ft/ft-head	4.074×10^{4}	$(mL/m{\cdot}d)/m$
gallons per day per inch of diameter per mile	gpd/in. dia/mile	92.60	$(mL/m{\cdot}d)/m$
gallons per day per mile	gpd/mile	2.720×10^{-11}	$m^3/m{\cdot}s$
		2.352	$mL/m{\cdot}d$
gallons per day per square foot	gpd/sq ft	4.715×10^{-7}	$m^3/m^2{\cdot}s$ or m/s
		4.074×10^{-2}	$m^3/m^2{\cdot}d$ or m/d
		40.74	$L/m^2{\cdot}d$
gallons per day per thousand square feet	gpd/1000 sq ft	4.074×10^{-2}	$L/m^2{\cdot}d$
gallons per hour	gph	1.051×10^{-6}	m^3/s
		1.051	mL/s
gallons per hour per foot of diameter per foot-head	gph/ft dia/ft-head	11.32	$(mL/m{\cdot}s)/m$
gallons per hour per inch diameter per thousand feet	gph/in. dia/1000 ft	488.9	$(mL/m{\cdot}h)/m$
gallons per million gallons	gal/mil. gal	1.000	mL/m^3
gallons per minute	gpm	6.308×10^{-5}	m^3/s
		6.308×10^{-2}	L/s
		5.451	m^3/d
gallons per minute per acre	gpm/ac	0.155 8	$L/ha{\cdot}s$
gallons per minute per cubic foot	gpm/cu ft	2.228	$L/m^3{\cdot}s$
gallons per minute per foot	gpm/ft	2.070×10^{-4}	$m^3/m{\cdot}s$
		0.207 0	$L/m{\cdot}s$
gallons per minute per square foot	gpm/sq ft	6.791×10^{-4}	$m/m{\cdot}s$
		0.679 1	$L/m^2{\cdot}s$
		58.67	$m^3/m^2{\cdot}d$
gallons per pound	gal/lb	8344	mL/kg
gallons per ton	gal/ton	4.173	mL/kg
grain	gr	64.80	mg

grains per gallon	gr/gal	17.12	g/m^3
		17.12	mg/L
hectare	ha	1.000×10^4	m^2
horsepower	hp	0.745 7	kW
horsepower-hour	hp-hr	2.685	MJ
horsepower-hours per pound	hp-hr/lb	5.919	MJ/kg
horsepower-hours per thousand cubic feet	hp-hr/1000 cu ft	26.34	W/m^3
horsepower-hours per thousand gallons	hp-hr/1000 gal	0.710 3	kJ/L
horsepower-hours per thousand pounds	hp-hr/1000 lb	5.919	kJ/kg
horsepower per gallon per minute	hp/gpm	11.82	MJ/m^3
		11.82	kJ/L
horsepower per million gallons	hp/mil. gal	0.197	W/m^3
		1.970×10^{-4}	W/L
horsepower per thousand gallons	hp/1000 gal	0.197	kW/m^3
inch	in.	25.40	mm
inches of water	in. H_2O	0.248 8	kPa
inches of mercury	in. Hg	3.377	kPa
inches per foot	in./ft	8.333	%
inches per hour	in./hr	25.40	mm/h
inches per year	in./yr	25.40	mm/a (millimeters per annum)
kilowatt-hour	kWh	3.600	MJ
kilowatt-hours per day	kWh/d	41.67	W
kilowatt-hours per gallon	kWh/gal	951.1	MJ/m^3
		0.951 1	MJ/L
kilowatt-hours per million gallons	kWh/mil. gal	951.1	J/m^3
		0.951 1	J/L
kilowatt-hours per pound	kWh/lb	7.936	MJ/kg
kilowatt-hours per thousand pounds	kWh/1000 lb	7.936	kJ/kg
kilowatt-hours per ton	kWh/ton	3.969	kJ/kg
kip	kip	4.448	kN (kilonewton)
kip-feet	kip-ft	1.356	kN·m
kip-feet per second	kip-ft/sec	1.356	kN·m/s
kips per foot	kip/ft	14.59	kN/m
kips per square foot	kip/sq ft	47.88	kPa

Table 1. Conversion from customary to metric units (in alphabetical order) (*continued*).

Multiply Customary Unit	Abbreviation	By	To Obtain Metric Unit
micron	μ	1.000	μm
mil	mil	25.40	μm
mile	mile	1.609	km
miles per hour	mph	0.446 9	m/s
		1.609	km/h
million gallons	mil. gal	3.785×10^3	m^3
		3.785	ML
million gallons per day	mgd	4.383×10^{-2}	m^3/s
		43.83	L/s
		3.785×10^3	m^3/d
		3.785	ML/d
million gallons per day per acre	mgd/ac	1.083×10^{-5}	$m^3/m^2 \cdot s$
		9.353×10^3	$m^3/ha \cdot d$
		9.353	ML/ha·d
most probable number per hundred milliliters	MPN/100 mL	10.00	MPN/L
parts per billion	ppb	1.00 (app.)	μg/L
		1.000	μg/kg
parts per million	ppm	1.00 (app.)	mg/L
		1.000	mg/kg
pound (force)	lbf	4.448	N
pound (mass)	lb	0.453 6	kg
pound-foot	lb-ft	1.356	N·m
pound-feet per second	lb-ft/sec	1.356	N·m/s
pounds per day per capita	lb/d/cap	0.453 6	kg/cap·d
pounds per cubic foot	lb/cu ft	16.02	kg/m^3
pounds per thousand cubic feet	lb/1000 cu ft	16.02	g/m^3
pounds per cubic yard	lb/cu yd	0.593 3	kg/m^3
pounds per day	lb/d	5.250	mg/s
		0.453 6	kg/d

pounds per day per acre	lb/d/ac	0.112 1	$g/m^2 \cdot d$
pounds per day per acre-foot	lb/d/ac-ft	0.367 7	$g/m^3 \cdot d$
pounds per day per cubic foot	lb/d/cu ft	16.02	$kg/m^3 \cdot d$
pounds per day per pound	lb/d/lb	11.57	mg/kg·s
pounds per day per square foot	lb/d/sq ft	56.51	$mg/m^2 \cdot s$
		4.882	$kg/m^2 \cdot d$
pounds per day per thousand cubic feet	lb/d/1000 cu ft	1.602×10^{-2}	$kg/m^3 \cdot d$
pounds per day per thousand square feet	lb/d/1000 sq ft	4.882	$g/m^2 \cdot d$
pounds per foot	lb/ft	1.488	kg/m
pounds per foot per foot of diameter	lb/ft/ft dia	47.88	(N/m)/m
pounds per gallon	lb/gal	0.119 8	kg/L
pounds per hour	lb/hr	1.260×10^{-4}	kg/s
		0.453 6	kg/h
pounds per hour per square foot	lb/hr/sq ft	4.882	$kg/m^2 \cdot h$
		1.356	$g/m^2 \cdot s$
pounds per hour per cubic foot	lb/hr/cu ft	4.450×10^{-6}	kg/L·s
		16.02	$kg/m^3 \cdot h$
pounds per million gallons	lb/mil. gal	0.119 8	g/m^3
		0.119 8	mg/L
pounds per pound	lb/lb	1000	g/kg
pounds per square foot (mass dose)	lb/sq ft	4.883	kg/m^2
pounds per square foot (force)	lb/sq ft	47.88	Pa
pounds per square inch (force)	psi	6895	Pa
pounds per thousand cubic feet	lb/1000 cu ft	16.02	g/m^3
pounds per thousand gallons	lb/1000 gal	0.119 8	g/m^3
pounds per ton	lb/ton	0.500	g/kg
pounds per year per acre	lb/yr/ac	1.121	kg/ha·a
pounds per year per cubic foot	lb/yr/cu ft	16.02	$kg/m^3 \cdot a$
pounds per year per square foot	lb/yr/sq ft	4.882	$kg/m^2 \cdot a$
pound-seconds per square foot	lb-sec/sq ft	47.88	Pa·s
pound-square feet per second	lb-sq ft/sec	4.883	$kg \cdot m^2/s$
revolutions per minute	rpm	1.000	r/min
revolutions per second	rps	1.000	r/s
slug	slug	14.59	kg

Table 1. Conversion from customary to metric units (in alphabetical order) (*continued*).

Multiply Customary Unit	Abbreviation	By	To Obtain Metric Unit
square foot	sq ft	9.290×10^{-2}	m^2
square feet per capita	sq ft/cap	9.290×10^{-2}	m^2/cap
square feet per cubic foot	sq ft/cu ft	3.281	m^2/m^3
square feet per foot	sq ft/ft	0.304 8	m^2/m
square feet per second	sq ft/sec	9.290×10^{-2}	m^2/s
square inch	sq in.	645.2	mm^2
square mile	sq mile	2.590	km^2
square yard	sq yd	0.836 1	m^2
ton (long)	ton	1.016	Mg
ton (short)	ton	0.907 2	Mg
		907.2	kg
tons per acre	ton/ac	0.224 2	kg/m^2
		2.242	Mg/ha
tons per cubic yard	ton/cu yd	1.187	Mg/m^3
watt-hour	W-hr	3.600	J
watts per square foot	W/sq ft	10.76	W/m^2
yard	yd	0.914 4	m

Table 2. Conversion from metric to customary units (in alphabetical order).

Multiply Metric Unit	Abbreviation	By	To Obtain Customary Unit
capita per hectare	cap/ha	0.404 7	cap/ac
capita per square kilometer	cap/km^2	2.590	cap/sq mile
cubic meter	m^3	8.107×10^{-4}	ac-ft
		6.290	barrel (oil)
		8.386	barrel (water)
		28.38	bushel (U.S. dry)
		35.31	cu ft
		1.308	cu yd
		264.2	gal
		2.642×10^{-4}	mil. gal
cubic meters per cubic meter	m^3/m^3	0.133 7	cu ft/gal
		1.337×10^5	cu ft/mil. gal
cubic meters per cubic meter per second	$m^3/m^3 \cdot s$	5.999×10^4	cfm/1000 cu ft
		8.019×10^3	cfm/1000 gal
cubic meters per day	m^3/d	0.183 5	gpm
		2.642×10^{-4}	mgd
		264.2	gpd
cubic meters per hectare per day	$m^3/ha \cdot d$	106.9	gpd/ac
		1.069×10^{-4}	mgd/ac
cubic meters per hectare per second	$m^3/ha \cdot s$	14.29	cfs/ac
		9.147×10^3	cfs/sq mile
cubic meters per kilogram	m^3/kg	16.02	cu ft/lb
cubic meters per meter per day	$m^3/m \cdot d$	80.53	gpd/ft
cubic meters per meter per second	$m^3/m \cdot s$	646.0	cfm/ft
		6.959×10^6	gpd/ft
		3.676×10^{10}	gpd/mile

Table 2. Conversion from metric to customary units (in alphabetical order) (*continued*).

Multiply Metric Unit	Abbreviation	By	To Obtain Customary Unit
cubic meters per second	m^3/s	1.271×10^5	cfh or cu ft/hr
		2.119×10^3	cfm
		35.32	cfs
		9.515×10^5	gph
		1.585×10^4	gpm
		22.83	mgd
cubic meters per square meter per day	$m^3/m^2 \cdot d$	24.55	gpd/sq ft
		1.704×10^{-2}	gpm/sq ft
cubic meters per square meter per hour	$m^3/m^2 \cdot h$	3.281	cfh/sq ft
cubic meters per square meter per second	$m^3/m^2 \cdot s$	1.429×10^3	cfs/ac
		9.149×10^7	cfs/sq mile
		9.238×10^{10}	gpd/ac
		2.121×10^6	gpd/sq ft
		1.473×10^3	gpm/sq ft
		9.238×10^4	mgd/ac
		1.181×10^4	cfh/sq ft
cubic millimeter	mm^3	6.102×10^{-5}	cu in.
degrees Celsius	°C	1.800 (°C)+ 32	°F
Kelvin	K	1.800	°R
grams per cubic meter	g/m^3	8.344	lb/mil.gal
		6.243×10^{-2}	lb/1000 cu ft
		8.347	lb/1000 gal
grams per cubic meter per day	$g/m^3 \cdot d$	2.720	lb/d/ac-ft
grams per cubic meter per second	$g/m^3 \cdot s$	0.224 7	lb/hr/cu ft
grams per kilogram	g/kg	1.000×10^{-3}	lb/lb
		2.000	lb/ton
grams per liter	g/L	0.0624	lb/cu ft
grams per meter	g/m	0.672 0	lb/1000 ft
grams per second	g/s	7.937	lb/hr
grams per square meter per day	$g/m^2 \cdot d$	8.922	lb/d/ac
		0.204 8	lb/d/1000 sq ft

grams per square meter per second	$g/m^2 \cdot s$	17.70	lb/d/sq ft
		0.737 3	lb/hr/sq ft
hectare	ha	2.471	ac (acre)
joule	J	0.7376	ft-lb
joules per cubic meter	J/m^3	1.051×10^{-3}	kWh/mil. gal
joules per kilogram	J/kg	4.299×10^{-4}	Btu/lb
		0.859 8	Btu/ton
		1.689×10^{-4}	hp-hr/1000 lb
joules per liter	J/L	8.461×10^{-5}	hp/gpm
		1.051	kWh/mil. gal
joules per meter	J/m	1.873×10^{-2}	ft-lb/in.
joules per square meter per second	$J/m^2 \cdot s$	0.317 1	Btu/hr/sq ft
kilogram	kg	2.205	lb (mass)
		1.102×10^{-3}	ton
		6.854×10^{-2}	slug
kilogram meter	kg·m	0.672 0	lb-ft
kilogram meter per second	kg·m/s	0.672 0	lb-ft/sec
kilograms per capita per day	kg/cap·d	2.205	lb/cap/d
kilograms per cubic meter	kg/m^3	6.243×10^{-2}	lb/cu ft
		1.686	lb/cu yd
		834 7	lb/mil. gal
		62.42	lb/1000 cu ft
kilograms per cubic meter per day	$kg/m^3 \cdot d$	6.242×10^{-2}	lb/cu ft
		62.42	lb/d/1000 cu ft
kilograms per cubic meter per hour	$kg/m^3 \cdot h$	6.242×10^{-2}	lb/hr/cu ft
kilograms per cubic meter per second	$kg/m^3 \cdot s$	224.8	lb/hr/cu ft
kilograms per day	kg/d	2.205	lb/d
kilograms per hectare per day	kg/ha·d	0.892 2	lb/d/ac
kilograms per hectare per year (annum)	kg/ha·a	0.892 2	lb/yr/ac
kilograms per hour	kg/h	2.205	lb/hr
kilograms per kilogram per second	kg/kg·s	8.64×10^4	lb/d/lb
kilograms per liter	kg/L	3.613×10^{-2}	lb/cu in.
		8.347	lb/gal
		8.347×10^6	lb/mil. gal

Table 2. Conversion from metric to customary units (in alphabetical order) (*continued*).

Multiply Metric Unit	Abbreviation	By	To Obtain Customary Unit
kilograms per meter	kg/m	0.672 0	lb/ft
kilograms per second	kg/s	1.905×10^5	lb/d
		7.936×10^3	lb/hr
kilograms per square meter	kg/m^2	0.204 8	lb/sq ft (mass dose)
kilograms per square meter per day	$kg/m^2 \cdot d$	0.204 8	lb/d/sq ft
kilograms per square meter per hour	$kg/m^2 \cdot h$	0.204 8	lb/hr/sq ft
kilograms per square meter per second	$kg/m^2 \cdot s$	1.770×10^4	lb/d/sq ft
kilograms per square meter per year (annum)	$kg/m^2 \cdot a$	0.204 8	lb/yr/sq ft
kilojoule	kJ	0.947 8	Btu
kilojoules per cubic meter	kJ/m^3	2.684×10^{-2}	Btu/cu ft
		1.051	kWh/mil. gal
		1.408×10^{-3}	hp-hr/1000 gal
kilojoules per kilogram	kJ/kg	0.430 0	Btu/lb
		859.8	Btu/ton
		0.252 0	kWh/ton
		0.126 0	kWh/1000 1b
		1.689×10^{-4}	hp-hr/lb
kilojoules per liter	kJ/L	1.410	Btu/gal
kilometer	km	0.621 4	mile
kilometers per hour	km/h	0.621 4	mph
kilonewton	kN	0.224 8	kip
kilonewton per meter	kN/m	0.737 5	kip-ft
kilonewtons per meter per second	kN/m·s	0.737 5	kip-ft/sec
kilopascal	kPa	9.872×10^{-3}	atm
		20.89	psf (force)
		0.145 0	psi (force)
		4.019	in. H_2O
		0.296 1	in. Hg
kilowatt	kW	1.341	hp
kilowatt per cubic meter	kW/m^3	5.076	hp/1000 gal
liter	L	3.532×10^{-2}	cu ft
		0.264 2	gal

liters per capita	L/cap	3.532×10^{-2}	cu ft/cap
liters per capita per day	L/cap·d	0.264 2	gpd/cap
liters per cubic meter	L/m^3	133.7	cu ft/mil. gal
liters per cubic meter per second	L/m^3·s	0.488 8	cfm/cu ft
		59.99	cfm/1000 cu ft
		8.019	cfm/1000 gal
liters per hectare per second	L/ha·s	1.429×10^{-2}	cfs/ac
		9.149	cfs/sq mile
		6.418	gpm/ac
liters per kilogram	L/kg	239.6	gal/ton
liters per meter	L/m	425.2	gal/mile
liters per meter per second	L/m·s	0.645 9	cfm/ft
		4.832	gpm/ft
		6.958×10^{3}	gpd/ft
liters per second	L/s	127.1	cfh
		2.119	cfm
		3.532×10^{-2}	cfs
		2.282×10^{4}	gpd
		15.85	gpm
		2.283×10^{-2}	mgd
liters per square meter per day	L/m^2·d	2.455×10^{-2}	gpd/sq ft
liters per square meter per second	L/m^2·s	11.82	cfh/sq ft
		2.121×10^{3}	gpd/sq ft
		9.237×10^{-3}	gpd/ac
		1.473	gpm/sq ft
megagram or metric ton	Mg or t	1.102	ton (short)
		0.984 3	ton (long)
megagram per cubic meter	Mg/m^3	0.842 5	ton/cu yd
megagram per hectare	Mg/ha	0.446 0	ton/ac
megajoule	MJ	0.372 5	hp-hr
megajoules per cubic meter	MJ/m^3	8.460×10^{-2}	hp/gpm
		1.051×10^{-3}	kWh/gal
megajoules per kilogram	MJ/kg	168.9	hp-hr/1000 lb
		0.126 0	kWh/lb

Table 2. Conversion from metric to customary units (in alphabetical order) (*continued*).

Multiply Metric Unit	Abbreviation	By	To Obtain Customary Unit
megajoules per liter	MJ/L	1.051	kWh/gal
megaliter	ML	0.264 2	mil. gal
megaliters per day	ML/d	0.264 2	mgd
megaliters per hectare per day	ML/ha·d	0.106 9	mgd/ac
meter	m	3.281	ft
meters per hour	m/h	3.281	ft/hr
meters per second	m/s	3.281	fps
		2.238	mph
meters per second squared	m/s^2	3.281	ft/sec^2
micrograms per liter	μg/L	1.00 (app.)	ppb
micrometer	μm	1.000	micron
		3.937×10^{-2}	mil
miligram	mg	1.543×10^{-2}	grain
milligrams per liter	mg/L	5.841×10^{-2}	grains per gallon
		1.00 (app.)	ppm
milliliter	mL	6.102×10^{-2}	cu in.
milliliters per cubic meter	mL/m^3	0.133 7	cu ft/mil. gal
milliliters per kilogram	mL/kg	1.198×10^{-4}	gal/lb
		0.239 6	gal/ton
milliliters per meter per day per meter	(mL/m·d)/m	2.450×10^{-3}	gpd/ft/ft-head
milliliters per second	mL/s	0.951 5	gph
millimeter	mm	3.937×10^{-2}	in.
millimeters per hour	mm/h	3.937×10^{-2}	in./hr
millimeters per second	mm/s	0.196 9	fpm
		11.81	ft/hr
most probable number per cubic meter	MPN/m^3	1.000×10^{-4}	MPN/100 mL
most probable number per liter	MPN/L	0.100 0	MPN/100 mL

newton	N	0.224 8	lbf (force)
newton meter	N·m	0.737 6	ft-lb
newton meters per meter	N·m/m	0.224 8	lb-ft/ft dia
pascal	Pa	9.872×10^{-6}	atm
		3.345×10^{-4}	ft (head)
		2.089×10^{-2}	lb/sq ft
		1.450×10^{-4}	psi
pascal second	Pa·s	2.089×10^{-2}	lb-sec/sq ft
square kilometer	km^2	0.386 1	sq mile
square meter	m^2	2.471×10^{-4}	ac
		10.76	sq ft
square meters per cubic meter	m^2/m^3	3.048	sq ft/cu ft
square meters per meter	m^2/m	3.281	sq ft/ft
square meter per second	m^2/s	10.76	sq ft/sec
square millimeter	mm^2	1.550×10^{-3}	sq in.
ton (metric)	t	1.102×10^{-3}	lb
		0.984 3	ton (long)
		1.102	ton (short)
watt	W	3.412	Btu/hr
		947.8	Btu/sec
		44.27	ft-lb/min
		0.738 0	ft-lb/sec
		1.341×10^{-3}	hp
		2.400×10^{-2}	kWh/d
watts per cubic meter	W/m^3	5.076	hp/mil. gal
		3.797×10^{-2}	hp/1000 cu ft
watts per liter	W/L	5.076×10^{3}	hp/mil. gal
watts per square meter	W/m^2	9.290×10^{-2}	W/sq ft

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