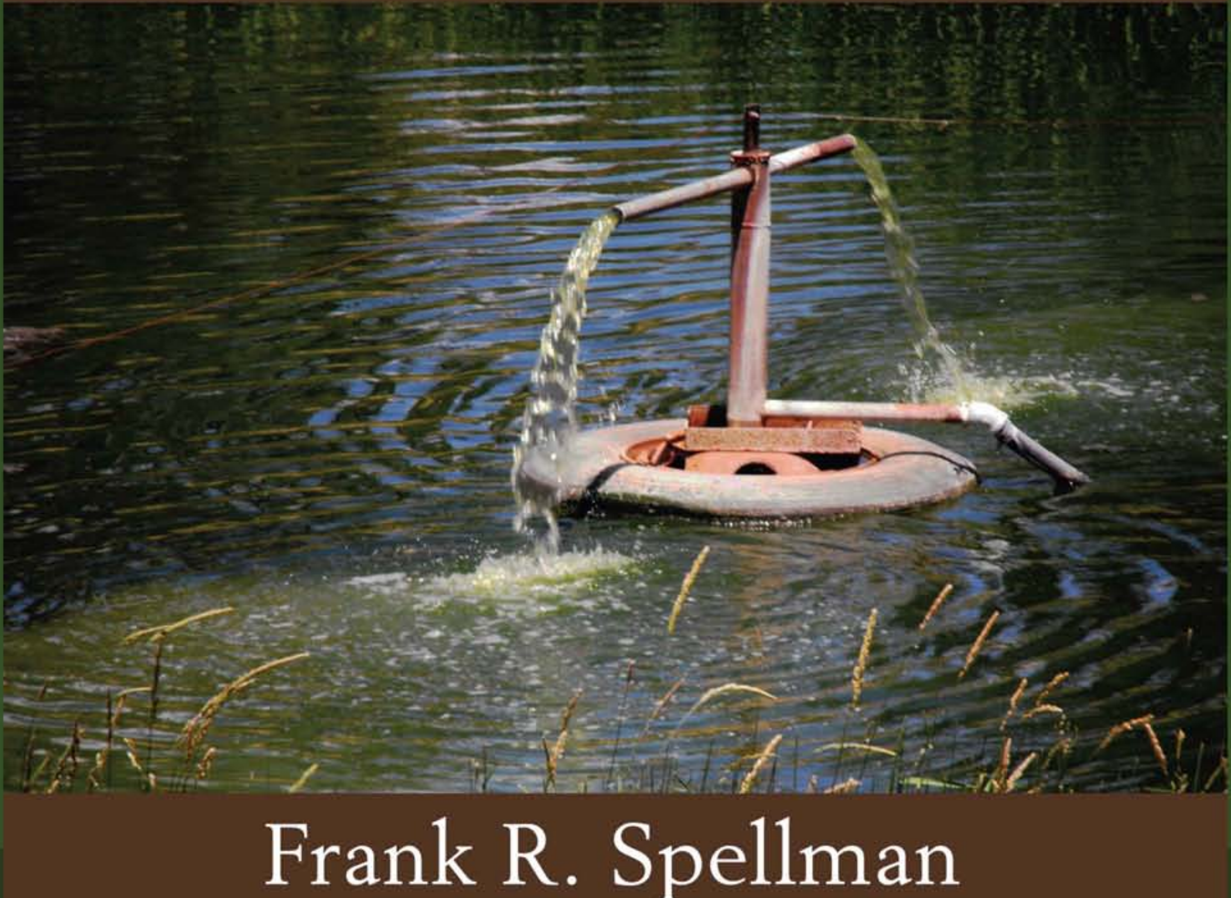
SECOND EDITION

Spellman's Standard Handbook *for* Wastewater Operators

VOLUME I

Fundamental Level



Frank R. Spellman

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PREFACE, 2ND EDITION

Hailed on first publication as a straightforward, practical, and to-the-point account of wastewater principles, practices, and operations for general readers, students, and wastewater operators in training and for all levels of operators at any level of licensure, the second edition of *Spellman's Standard Handbook for Wastewater Operators*, Volumes I, II, and III, continues to deal with the important aspects of wastewater operations and operator preparation for licensure examinations. In addition, based on constructive and helpful criticism of the original series, each volume has been upgraded, updated, and expanded to include additional pertinent information to help the user attain success by better preparing each qualified user for professional licensure.

Spellman's Standard Handbook for Wastewater Operators is more than just a three-volume study guide or readily accessible source of information for review when preparing wastewater personnel for operator certification and licensure. Instead, this three-volume handbook is a resource manual and troubleshooting guide that contains a compilation of wastewater treatment information, data, operation material, process control procedures and problem solving, safety and health information, new trends in wastewater treatment administration and technology, and numerous sample problem-solving practice sets. The most important aspects of the text are threefold:

1. It gives today's wastewater operators instant information they need to expand their knowledge—which aids them in the efficient operation of a wastewater treatment plant.
2. It provides the user with the basic information and sample problem-solving sets required to prepare for state licensing and certification examinations.
3. It provides user-friendly, straightforward, plain-English fundamental reference material and unit process troubleshooting guidance required on a daily basis not only by the plant manager, plant superintendent, chief operator, lab technician, and maintenance operator but also, more importantly, by the plant operator.

We could say that the primary goal of the handbook is to enhance the understanding, awareness, and abilities of practicing operators and those who aspire to be operators. The first volume (introductory), second volume (intermediate), and third volume (advanced) are designed to build on one another, providing increasingly advanced information.

The message of this handbook has not changed: None of us is chained to the knowledge we already have—we should strive to increase our technical knowledge and expertise constantly. For those preparing for operator licensing, this is critical, as wastewater treatment is a complex process. For those seasoned, licensed veteran operators, continuous review is also critical, because wastewater treatment is still an evolving, dynamic, ever-changing field. This handbook series (which we think of as "answer books") provides the means for reaching these goals.

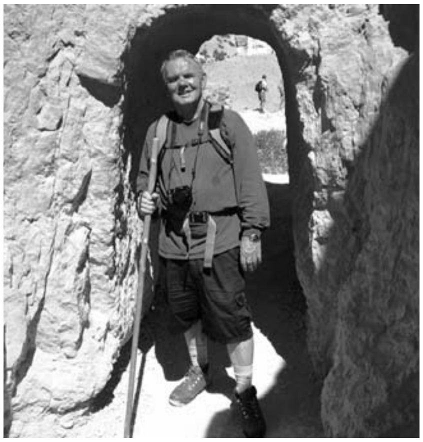
Contrary to popular belief (and simply put), treating wastewater is not just an art but both an art and a science. Treating wastewater successfully demands technical expertise, experience, and a broad range of available technologies, as well as an appreciation for and understanding of the fundamental environmental and health reasons for the processes involved. It demands unique vision and capabilities. This is where *Spellman's Standard Handbook for Wastewater Operators* comes in. From pumping and screening influent and treating the wastestream through managing biosolids, this handbook series provides easy-to-understand, state-of-the-art information beginning at the fundamental level for those preparing for the Class IV/III or Grade I/II operator examination, proceeds to the intermediate level for the Class III/II or Grade II/III operator examination, and finishes at the advanced level for the Class I/Grade IV/V wastewater operator license examination. Though the information in these volumes is aimed at three separate levels (fundamental, intermediate, and advanced), overlap between each volume ensures continuity and a smooth read from volume to volume. In essence, each volume is a reference text that enables the practitioner of the artful science of wastewater treatment to qualify for certification or refresh his or her memory in an easy, precise, efficient, effective manner.

This handbook was prepared to help operators obtain licensing and operate wastewater treatment plants properly. It can also be used as a textbook in technical training courses in technical schools and at the junior college level. Note that the handbook does not discuss the specific content of the examination. It reviews the wastewater operator's job-related knowledge identified by the examination developers as essential for a minimally competent Class IV through Class I or Grade I through Grade V wastewater treatment plant operator. Every attempt has been made to make the handbook as comprehensive as possible while maintaining its compact, practical format.

The bottom line: The handbook is not designed to simply teach the operator licensing exams, although it is immediately obvious to the users that the material presented will help them pass licensing exams. The material in each volume is intended for practical use and application. Applied math and chemistry are presented by way of real-world problems, and readers will learn how to maintain equipment. Apparatus used in the laboratory and in the field (e.g., valves and pumps) is also covered. Will the handbook series help the reader obtain a passing score on certification exams? Yes. If you follow it, use it, and reuse it, it will help—and that is the real bottom line.

Frank R. Spellman
Norfolk, Va.

ABOUT THE AUTHOR



Frank R. Spellman, PhD, is a retired assistant professor of environmental health at Old Dominion University, Norfolk, Virginia, and author of more than 65 books covering topics ranging from concentrated animal feeding operations (CAFOs) to all areas of environmental science and occupational health. Many of his texts are readily available online, and several have been adopted for classroom use at major universities throughout the United States, Canada, Europe, and Russia; two are currently being translated into Spanish for South American markets. Dr. Spellman has been cited in more than 400 publications. He serves as a professional expert witness for three law groups and as an incident/accident investigator for the U.S. Department of Justice and a northern Virginia law firm. In addition, he consults on homeland security vulnerability assessments for critical infrastructure including water/wastewater facilities nationwide and conducts pre-Occupational Safety and Health Administration (OSHA)/Environmental Protection Agency (EPA) audits throughout the country. Dr. Spellman receives frequent requests to co-author with well-recognized experts in several scientific fields; for example, he is a contributing author for the prestigious text *The Engineering Handbook*, 2nd ed. (CRC Press). Dr. Spellman lectures on sewage treatment, water treatment, and homeland security and health and safety topics throughout the country and teaches water/wastewater operator short courses at Virginia Tech (Blacksburg, Virginia). He holds a BA in public administration, a BS in business management, an MBA, an MS in environmental engineering, and a PhD in environmental engineering.

CHAPTER 1

INTRODUCTION

What is unsought will go undetected.

Sophocles

1.1 SETTING THE STAGE

In this second edition of *Spellman's Standard Handbook for Wastewater Operators*, Volume 1, *Fundamental Level*, the same successful and proven format used in the original is followed, but made better. Primarily designed to provide a readily accessible, user-friendly source of information for review in preparing for the first levels of licensure (i.e., for Class IV/III or Grade I/II state or local government-administered wastewater operator licensure examinations), this updated version of the handbook provides the necessary information to help the reader successfully study for and pass currently administered certification examinations. This volume also sets the stage for both Volumes 2 and 3 of the handbook, which are intended to prepare readers to sit for examinations for intermediate and advanced licensure (to Class II/I or Grade III/IV/V operator status).

As mentioned in the preface, each revised and updated volume has been expanded with additional information and example problems; for example, in Volume I we have added a chapter on basic microbiology. Moreover, whether you are an operator on the wet side, solid side, or maintenance side of treatment plant operations, a basic, but thorough, understanding of water hydraulics and pumping is necessary. In light of this, and based on user recommendations and other constructive criticism, we have not only upgraded but more than doubled the amount of water hydraulics and pumping information and real-world examples. Operational computation problems and examples in all major topic areas have been increased.

Every attempt has been made to format this presentation in a way that allows readers to build upon information presented, step by step and page by page, as they progress through the material. This handbook presents a basic summary of expert information available in many other sources (see Table 1.1). For additional information or more specific material on any of the topics presented, the user is advised to consult one or more of the references provided in Table 1.1. This fundamental-level handbook assumes that the reader is an operator-in-training who is currently preparing to sit for his or her first or second level of licensure (i.e., Class IV/III or Grade I/II operator licensure examination).

Note: In this handbook, the term "fundamental level" is used to refer to those first two steps in licensure, which is the case in many states.

Those people with limited experience who do not qualify to sit for subject examinations may find the material helpful but should augment the content of this handbook with other, more in-depth training such as the various field-study programs available from state water control boards, short courses presented by various universities (e.g., Virginia Tech), or technical training provided by technical schools. It is important to point out that changes in technology and regulations occur frequently in the water pollution industry. Because of this, it is important for the licensure candidate to stay abreast of these changes.

The handbook is divided into chapters with sections covering specific topic areas. At the end of many chapters, a series of review question is included. Upon completion of these chapters, answer the review questions, and check your answers with those given in Appendix A. The final chapter of the handbook includes a comprehensive practice examination. The purpose of the comprehensive practice examination is to test the level of knowledge the reader has attained through study of this handbook, knowledge gained through on-the-job experience, and knowledge gained from other sources. A score of 75% or above is considered "good"—more importantly, any questions missed signal to the user the need to go back and reread and study again the applicable areas. By using the final examination as a measuring stick, readers can gauge their level of knowledge in all pertinent areas and determine strong and weak points. When you get right down to it, shouldn't that be the purpose of any examination? That is, the examination should measure one's level of knowledge in such a way as to point to the proper direction to take to attain an even greater level of knowledge. This seems like a worthwhile objective, and it is. Answers to the final review examination in Chapter 20 are provided in Appendix B. The formula sheet provided in Appendix C should be used for reference; it can and should be used when taking the final examination.

1.2 WASTEWATER TREATMENT: THE MODEL

Figure 1.1 shows a basic schematic or model of a wastewater treatment process that provides primary and secondary treatment using the *activated sludge* process. In secondary treatment, which provides biochemical oxygen demand (BOD) removal beyond what is achievable by

TABLE 1.1 RECOMMENDED REFERENCE MATERIAL

1. *Small Water System Operation and Maintenance*, 3rd ed., Kerri, K.D. et al., California State University, Sacramento, CA, 1995.
2. *Water Distribution System Operation and Maintenance*, 4th ed., Kerri, K.D. et al., California State University, Sacramento, CA, 2002.
3. *Water Treatment Plant Operation*, Vols. I and II, Kerri, K.D. et al., California State University, Sacramento, CA, 2006 and 2008.
4. *Basic Mathematics*, Homestudy Course 3011-G, U.S. Centers for Disease Control, Atlanta, GA, 1986.
5. *Waterborne Disease Control*, Homestudy Course 3014-G, U.S. Centers for Disease Control, Atlanta, GA, 1981.
6. *Water Fluoridation*, Homestudy Course 3017-G, U.S. Centers for Disease Control, Atlanta, GA, 1982.
7. *Principles and Practices of Water Supply Operations*. Part 1. *Water Sources*, American Water Works Association, Denver, CO, 2003.
8. *Principles and Practices of Water Supply Operations*. Part 2. *Water Treatment*, American Water Works Association, Denver, CO, 2003.
9. *Principles and Practices of Water Supply Operations*. Part 3. *Water Transmission and Distribution*, American Water Works Association, Denver, CO, 2003.
10. *Principles and Practices of Water Supply Operations*. Part 4. *Water Quality*, American Water Works Association, Denver, CO, 2003.
11. *Reference Handbook: Basic Science Concepts and Applications*, American Water Works Association, Denver, CO, 1980.
12. *Handbook of Water Analysis*, 2nd ed., HACH Chemical Company, P.O. Box 389, Loveland, CO, 1992.
13. *Methods for Chemical Analysis of Water and Wastes*, EPA-6004-79-020, Environmental Monitoring and Support Laboratory, U.S. Office of Research and Development, Cincinnati, OH, 1979, revised 1983.
14. *Standard Methods for the Examination of Water and Wastewater*, American Public Health Association, Washington, D.C., current version.
15. *Basic Math Concepts for Water and Wastewater Plant Operators*, Price, J.K., Technomic Publishing Company, Lancaster, PA, 1991.
16. *Spellman's Standard Handbook for Wastewater Operators*, Vols. 1–3, Spellman, F.R., Technomic, Lancaster, PA, 1999–2000.
17. *The Handbook for Waterworks Operator Certification*, Vols. 1–3. Spellman, F.R. and Drinan, J., Technomic, Lancaster, PA, 2001.
18. *Electricity*, *Electronics*, *Pumping*, *Water Hydraulics*, *Piping and Valves*, and *Blueprint Reading*, Fundamentals for the Water and Wastewater Maintenance Operator Series, Spellman, F.R. and Drinan, J., Technomic, Lancaster, PA, 2000–2002.
19. *Wastewater Treatment Plants: Planning, Design, and Operation*, 2nd ed., Qasim, S.R., Technomic, Lancaster, PA, 1999.
20. *Simplified Wastewater Treatment Plant Operations*, Haller, E., Technomic, Lancaster, PA, 1999.
21. *Operation of Wastewater Treatment Plants: A Field Study Training Program*, Vol. I, 5th ed., Kerri, K.D. et al., California State University, Sacramento, CA, 2006.
22. *Operation of Wastewater Treatment Plants: A Field Study Training Program*, Vol. II, 7th ed., Kerri, K.D. et al., California State University, Sacramento, CA, 2007.

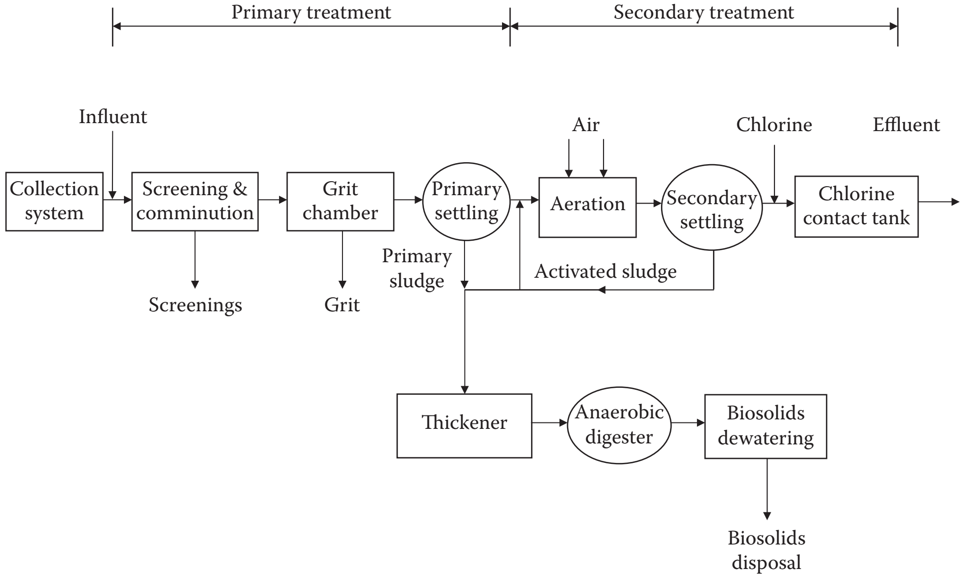


Figure 1.1 Schematic of a conventional wastewater treatment process utilizing primary and secondary treatment with the activated sludge process.

simple sedimentation, three approaches are commonly used: trickling filter, activated sludge, and oxidation ponds. We discuss these systems in detail later in the text. In Volume III of the series, we also discuss biological nutrient removal (BNR) and standard tertiary or advanced wastewater treatment.

The purpose of the model shown in Figure 1.1 is to allow readers to visually follow the wastewater treatment process step by step as it is presented in this text. The figure helps the reader understand how all the various unit processes sequentially follow and tie into each other. This format simply provides a pictorial presentation along with pertinent written information, enhancing the learning process.

The material in this handbook series is presented in a logical, step-by-step manner, which not only works to aid those who are studying to sit for licensure exams but is also helpful to those who use this handbook series as a ready reference or as a troubleshooting guide—that is, as an answer book. Speaking of answers, in reply to Sophocles' statement that opened this chapter, our counter response is that this handbook series makes information (answers) available; they only require detection. Detection is, of course, accomplished through use.

CHAPTER 2

WASTEWATER TERMINOLOGY AND DEFINITIONS

> If you wish to converse with me, define your terms.
>
> **Voltaire**

2.1 TERMINOLOGY AND DEFINITIONS

To learn wastewater treatment operations (or any other technology for that matter), you must master the language associated with the technology. Each technology has its own terms with definitions. Many of the terms used in wastewater treatment are unique; others combine words from many different technologies and professions. One thing is certain: Wastewater operators without a clear understanding of the terms related to their profession are ill equipped to perform their duties in the manner required. Usually, a handbook or text like this one includes a glossary of terms at the end of the work. In this handbook, however, we list and define many of the terms used right upfront. Experience has shown that an early introduction to keywords is a benefit to readers. An upfront introduction to key terms facilitates a more orderly, logical, systematic learning activity. Those terms not defined in this section are defined as they appear in the text. A short quiz on many of the following terms follows at the end of this chapter.

Absorb—To take in. Many things absorb water.

Acid rain—The acidic rainfall that results when rain combines with sulfur oxides emissions from combustion of fossil fuels (coal, for example).

Acre-feet (acre-foot)—An expression of water quantity. One acre-foot will cover 1 acre of ground 1 foot deep. An acre-foot contains 43,560 cubic feet, 1233 cubic meters, or 325,829 gallons (U.S). Also abbreviated as ac-ft.

Activated carbon—Derived from vegetable or animal materials by roasting in a vacuum furnace. Its porous nature gives it a very high surface area per unit mass—as much as 1000 square meters per gram, which is 10 million times the surface area of 1 gram of water in an open container. Used in adsorption (see definition), activated carbon adsorbs substances that are not or are only slightly adsorbed by other methods.

Activated sludge—The solids formed when microorganisms are used to treat wastewater using the activated sludge treatment process. It includes organisms, accumulated food materials, and waste products from the aerobic decomposition process.

Adsorption—The adhesion of a substance to the surface of a solid or liquid. Adsorption is often used to extract pollutants by causing them to attach to such adsorbents as activated carbon or silica gel. *Hydrophobic* (water-repulsing) adsorbents are used to extract oil from waterways in oil spills.

Advanced wastewater treatment—Treatment technology to produce an extremely high-quality discharge.

Aeration—The process of bubbling air through a solution, sometimes cleaning water of impurities by exposure to air.

Aerobic—Conditions in which free, elemental oxygen is present. Also used to describe organisms, biological activity, or treatment processes that require free oxygen.

Agglomeration—Floc particles colliding and gathering into a larger settleable mass.

Air gap—The air space between the free-flowing discharge end of a supply pipe and an unpressurized receiving vessel.

Algae bloom—A phenomenon whereby excessive nutrients within a river, stream, or lake causes an explosion of plant life that results in the depletion of the oxygen in the water needed by fish and other aquatic life. Algae bloom is usually the result of urban runoff (of lawn fertilizers, etc.). The potential tragedy is that of a "fish kill," where the stream life dies in one mass execution.

Alum—Aluminum sulfate, a standard coagulant used in water treatment.

Ambient—The expected natural conditions that occur in water unaffected or uninfluenced by human activities.

Anaerobic—Conditions in which no oxygen (free or combined) is available. Also used to describe organisms, biological activity, or treatment processes that function in the absence of oxygen.

Anoxic—Conditions in which no free, elemental oxygen is present. The only source of oxygen is combined oxygen, such as that found in nitrate compounds. Also used to describe biological activity of treatment processes that function only in the presence of combined oxygen.

Aquifer—A water-bearing stratum of permeable rock, sand, or gravel.

Aquifer system—A heterogeneous body of introduced permeable and less permeable material that acts as a water-yielding hydraulic unit of regional extent.

Artesian water—A well tapping a confined or artesian aquifer in which the static water level stands above the top of the aquifer. The term is sometimes used to include all wells tapping confined water. Wells with water level above the water table are said to have positive artesian head (pressure), and those with water level below the water table negative artesian head.

Average monthly discharge limitation—The highest allowable discharge over a calendar month.

Average weekly discharge limitation—The highest allowable discharge over a calendar week.

Backflow—Reversal of flow when pressure in a service connection exceeds the pressure in the distribution main.

Backwash—Fluidizing filter media with water, air, or a combination of the two so individual grains can be cleaned of the material that has accumulated during the filter run.

Bacteria—Any of a number of one-celled organisms, some of which cause disease.

Bar screen—A series of bars formed into a grid used to screen out large debris from influent flow.

Base—A substance that has a pH value between 7 and 14.

Basin—A groundwater reservoir defined by the overlying land surface and underlying aquifers that contain water stored in the reservoir.

Beneficial use of water—The use of water for any beneficial purpose. Such uses include domestic, irrigation, recreation, fish and wildlife, fire protection, navigation, power, and industrial uses, among others. The benefit varies from one location to another and by custom. What constitutes beneficial use is often defined by statute or court decisions.

Biochemical oxygen demand (BOD_5)—The oxygen used in meeting the metabolic needs of aerobic microorganisms in water rich in organic matter.

Biosolids[*]—Solid organic matter recovered from a sewage treatment process and used especially as fertilizer or soil amendment; usually

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[*] In this text, the term *biosolids* is used in many places to replace the standard term *sludge* (*activated sludge* being the exception). It is the opinion of the author that the term *sludge* is an ugly four-letter world inappropriate for describing biosolids. Biosolids are a product that can be reused; they have some value. Because biosolids have value, they certainly should not be classified as a waste product, and when the topic of biosolids for beneficial reuse is addressed, it is made clear that they are not a waste product.

referred to in the plural (*Merriam-Webster's Collegiate Dictionary*, 10th ed., 1998).

Biota—All the species of plants and animals indigenous to a certain area.

Boiling point—The temperature at which a liquid boils. The temperature at which the vapor pressure of a liquid equals the pressure on its surface. If the pressure of the liquid varies, the actual boiling point varies. The boiling point of water is 212° Fahrenheit or 100° Celsius.

Breakpoint—Point at which chlorine dosage satisfies chlorine demand.

Breakthrough—In filtering, when unwanted materials start to pass through the filter.

Buffer—A substance or solution that resists changes in pH.

Calcium carbonate—Compound that is principally responsible for hardness.

Calcium hardness—Portion of total hardness caused by calcium compounds.

Carbonaceous biochemical oxygen demand (CBOD)—The amount of biochemical oxygen demand that can be attributed to carbonaceous material.

Carbonate hardness—Caused primarily by compounds containing carbonate.

Chemical oxygen demand (COD)—The amount of chemically oxidizable materials present in the wastewater.

Chlorination—Disinfection of water using chlorine as the oxidizing agent.

Clarifier—A device designed to permit solids to settle or rise and be separated from the flow. Also known as a *settling tank* or *sedimentation basin*.

Coagulation—Neutralization of the charges of colloidal matter.

Coliform—A type of bacteria used to indicate possible human or animal contamination of water.

Combined sewer—A collection system that carries both wastewater and stormwater flows.

Comminution—A process to shred solids into smaller, less harmful particles.

Composite sample—A combination of individual samples taken in proportion to flow.

Connate water—Pressurized water trapped in the pore spaces of sedimentary rock at the time it was deposited. It is usually highly mineralized.

Consumptive use—(1) The quantity of water absorbed by crops and transpired or used directly in the building of plant tissue, together with the water evaporated from the cropped area. (2) The quantity of water transpired and evaporated from a cropped area or the normal loss of water from the soil by evaporation and plant transpiration. (3) The quantity of water discharged to the atmosphere or incorporated in the products of the process in connection with vegetative growth, food processing, or an industrial process.

Contamination (water)—Damage to the quality of water sources by sewage, industrial waste, or other material.

Cross-connection—A connection between a storm-drain system and a sanitary collection system, a connection between two sections of a collection system to handle anticipated overloads of one system, or a connection between drinking (potable) water and an unsafe water supply or sanitary collection system.

Daily discharge—The discharge of a pollutant measured during a calendar day or any 24-hour period that reasonably represents a calendar day for the purposes of sampling. Limitations expressed as weight are total mass (weight) discharged over the day; limitations expressed in other units are average measurement of the day.

Daily maximum discharge—The highest allowable values for a daily discharge.

Darcy's law—An equation for the computation of the quantity of water flowing through porous media. Darcy's law assumes that the flow is laminar and that inertia can be neglected. The law states that the rate of viscous flow of homogeneous fluids through isotropic porous media is proportional to, and in the direction of, the hydraulic gradient.

Detention time—The theoretical time water remains in a tank at a given flow rate.

Dewatering—The removal or separation of a portion of water present in a sludge or slurry.

Diffusion—The process by which both ionic and molecular species dissolved in water move from areas of higher concentration to areas of lower concentration.

Discharge monitoring report (DMR)—The monthly report required by the treatment plant's National Pollutant Discharge Elimination System (NPDES) discharge permit.

Disinfection—Water treatment process that kills pathogenic organisms.

Disinfection byproducts (DBPs)—Chemical compounds formed by the reaction of disinfectants with organic compounds in water.

Dissolved oxygen (DO)—The amount of oxygen dissolved in water or sewage. Concentrations of less than 5 parts per million (ppm) can limit aquatic life or cause offensive odors. Excessive organic matter present in water because of inadequate waste treatment and runoff from agricultural or urban land generally causes low DO.

Dissolved solids—The total amount of dissolved inorganic material contained in water or wastes. Excessive dissolved solids make water unsuitable for drinking or industrial uses.

Domestic consumption (use)—Water used for household purposes such as washing, food preparation, and showers. The quantity (or quantity per capita) of water consumed in a municipality or district for domestic uses or purposes during a given period, it sometimes encompasses all uses, including the quantity wasted, lost, or otherwise unaccounted for.

Drawdown—Lowering the water level by pumping. It is measured in feet for a given quantity of water pumped during a specified period, or after the pumping level has become constant.

Drinking water standards—Established by state agencies, the U.S. Public Health Service, and the Environmental Protection Agency (EPA) for drinking water in the United States.

Effluent—Something that flows out, usually a polluting gas or liquid discharge.

Effluent limitation—Any restriction imposed by the regulatory agency on quantities, discharge rates, or concentrations of pollutants discharged from point sources into state waters.

Energy—In scientific terms, the ability or capacity of doing work. Various forms of energy include kinetic, potential, thermal, nuclear, rotational, and electromagnetic. One form of energy may be changed to another, as when coal is burned to produce steam to drive a turbine, which produces electric energy.

Erosion—The wearing away of the land surface by wind, water, ice, or other geologic agents. Erosion occurs naturally from weather or runoff but is often intensified by human land-use practices.

Eutrophication—The process of enrichment of water bodies by nutrients. Eutrophication of a lake normally contributes to its slow evolution into a bog or marsh and ultimately to dry land. Eutrophication may be accelerated by human activities, thereby speeding up the aging process.

Evaporation—The process by which water becomes a vapor at a temperature below the boiling point.

Facultative—Organisms that can survive and function in the presence or absence of free, elemental oxygen.

Fecal coliform—The portion of the coliform bacteria group that is present in the intestinal tracts and feces of warm-blooded animals.

Field capacity—The capacity of soil to hold water. It is measured as the ratio of the weight of water retained by the soil to the weight of the dry soil.

Filtration—The mechanical process that removes particulate matter by separating water from solid material, usually by passing it through sand.

Floc—Solids that join to form larger particles that will settle better.

Flocculation—Slow mixing process in which particles are brought into contact, with the intent of promoting their agglomeration.

Flume—A flow rate measurement device.

Fluoridation—Chemical addition to water to reduce incidence of dental caries in children.

Food-to-microorganisms (F/M) ratio—An activated sludge process control calculation based on the amount of food (BOD_5 or COD) available per pound of mixed liquor volatile suspended solids.

Force main—A pipe that carries wastewater under pressure from the discharge side of a pump to a point of gravity flow downstream.

Grab sample—An individual sample collected at a randomly selected time.

Graywater—Water that has been used for showering, clothes washing, and faucet uses. Kitchen sink and toilet water is excluded. This water has excellent potential for reuse as irrigation for yards.

Grit—Heavy inorganic solids, such as sand, gravel, eggshells, or metal filings.

Groundwater—The supply of freshwater found beneath the Earth's surface (usually in aquifers) often used for supplying wells and springs. Because groundwater is a major source of drinking water, concern is growing over areas where leaching agricultural or industrial pollutants or substances from leaking underground storage tanks (USTs) are contaminating groundwater.

Groundwater hydrology—The branch of hydrology that deals with groundwater: its occurrence and movements, its replenishment and depletion, the properties of rocks that control groundwater movement and storage, and the methods of investigation and use of groundwater.

Groundwater recharge—The inflow to a groundwater reservoir.

Groundwater runoff—A portion of runoff that has passed into the ground, has become groundwater, and has been discharged into a stream channel as spring or seepage water.

Hardness—The concentration of calcium and magnesium salts in water.

Head loss—Amount of energy used by water in moving from one point to another.

Heavy metals—Metallic elements with high atomic weights, such as mercury, chromium, cadmium, arsenic, and lead. They can damage living things at low concentrations and tend to accumulate in the food chain.

Holding pond—A small basin or pond designed to hold sediment-laden or contaminated water until it can be treated to meet water quality standards or used in some other way.

Hydraulic cleaning—Cleaning pipe with water under enough pressure to produce high water velocities.

Hydraulic gradient—A measure of the change in groundwater head over a given distance.

Hydraulic head—The height above a specific datum (generally sea level) that water will rise in a well.

Hydrologic cycle (water cycle)—The cycle of water movement from the atmosphere to the Earth and back to the atmosphere through various processes. These processes include precipitation, infiltration, percolation, storage, evaporation, transpiration, and condensation.

Hydrology—The science dealing with the properties, distribution, and circulation of water.

Impoundment—A body of water, such as a pond confined by a dam, dike, floodgate, or other barrier, that is used to collect and store water for future use.

Industrial wastewater—Wastes associated with industrial manufacturing processes.

Infiltration—The gradual downward flow of water from the surface into soil material.

Infiltration/inflow—Extraneous flows in sewers; simply, inflow is water discharged into sewer pipes or service connections from such sources as foundation drains, roof leaders, cellar and yard area drains, cooling water from air conditioners, and other clean-water discharges from commercial and industrial establishments. Defined by Metcalf & Eddy (2003) as follows:

Delayed inflow—Stormwater requiring several days or more to drain through the sewer system. This category can include the discharge of sump pumps from cellar drainage as well as the slowed entry of surface water through manholes in ponded areas.

Direct flow—Those types of inflow that have a direct stormwater runoff connection to the sanitary sewer and cause an almost immediate increase in wastewater flows. Possible sources are roof leaders, yard and areaway drains, manhole covers, cross-connections from storm drains and catch basins, and combined sewers.

Infiltration—Water entering the collection system through cracks, joints, or breaks.

Steady inflow—Water discharged from cellar and foundation drains, cooling water discharges, and drains from springs and swampy areas. This type of inflow is steady and is identified and measured along with infiltration.

Total inflow—The sum of the direct inflow at any point in the system plus any flow discharged from the system upstream through overflows, pumping station bypasses, and the like.

Influent—Wastewater entering a tank, channel, or treatment process.

Inorganic chemical/compounds—Chemical substances of mineral origin, not of carbon structure. These include metals such as lead, iron (ferric chloride), and cadmium.

Ion exchange process—Used to remove hardness from water.

Jar test—Laboratory procedure used to estimate proper coagulant dosage.

Langelier saturation index (LI)—A numerical index that indicates whether calcium carbonate will be deposited or dissolved in a distribution system.

Leaching—The process by which soluble materials in the soil such as nutrients, pesticide chemicals, or contaminants are washed into a lower layer of soil or are dissolved and carried away by water.

License—A certificate issued by the State Board of Waterworks/Wastewater Works Operators authorizing the holder to perform the duties of a wastewater treatment plant operator.

Lift station—A wastewater pumping station designed to “lift” the wastewater to a higher elevation. A lift station normally employs pumps or other mechanical devices to pump the wastewater and discharges into a pressure pipe called a *force main*.

Maximum contaminant level (MCL)—An enforceable standard for protection of human health.

Mean cell residence time (MCRT)—The average length of time a mixed liquor suspended solids particle remains in the activated sludge process. May also be known as *sludge retention time*.

Mechanical cleaning—Clearing pipe by using equipment (bucket machines, power rodders, or hand rods) that scrapes, cuts, pulls, or pushes the material out of the pipe.

Membrane process—A process that draws a measured volume of water through a filter membrane with small enough openings to take out contaminants.

Metering pump—A chemical solution feed pump that adds a measured amount of solution with each stroke or rotation of the pump.

Milligrams per liter (mg/L)—A measure of concentration equivalent to parts per million (ppm).

Mixed liquor suspended solids—The suspended solids concentration of the mixed liquor.

Mixed liquor volatile suspended solids (MLVSS)—The concentration of organic matter in the mixed liquor suspended solids.

Nephelometric turbidity unit (NTU)—Indicates amount of turbidity in a water sample.

Nitrogenous oxygen demand (NOD)—A measure of the amount of oxygen required to biologically oxidize nitrogen compounds under specified conditions of time and temperature.

Nonpoint-source (NPS) pollution—Forms of pollution caused by sediment, nutrients, and organic and toxic substances originating from land-use activities that are carried to lakes and streams by surface runoff. Nonpoint-source pollution occurs when the rate of materials entering these water bodies exceeds natural levels.

NPDES permit—National Pollutant Discharge Elimination System permit, which authorizes the discharge of treated wastes and specifies the conditions that must be met for discharge.

Nutrients—Substances required to support living organisms. Usually refers to nitrogen, phosphorus, iron, and other trace metals.

Organic chemicals/compounds—Animal- or plant-produced substances containing mainly carbon, hydrogen, and oxygen, such as benzene and toluene.

Parts per million (ppm)—The number of parts by weight of a substance per million parts of water. This unit is commonly used to represent pollutant concentrations. Large concentrations are expressed in percentages.

Pathogenic—Disease causing. A pathogenic organism is capable of causing illness.

Percolation—The movement of water through the subsurface soil layers, usually continuing downward to the groundwater or water table reservoirs.

pH—A way of expressing both acidity and alkalinity on a scale of 0 to 14, with 7 representing neutrality; numbers less than 7 indicate increasing acidity, and numbers greater than 7 indicate increasing alkalinity.

Photosynthesis—A process in green plants in which water, carbon dioxide, and sunlight combine to form sugar.

Piezometric surface—An imaginary surface that coincides with the hydrostatic pressure level of water in an aquifer.

Point-source pollution—A type of water pollution resulting from discharges into receiving waters from easily identifiable points. Common point sources of pollution are discharges from factories and municipal sewage treatment plants.

Pollution—The alteration of the physical, thermal, chemical, or biological quality of, or the contamination of, any water in the state that renders the water harmful, detrimental, or injurious to humans, animal life, vegetation, property or public health, safety, or welfare, or impairs the usefulness or the public enjoyment of the water for any lawful or reasonable purpose.

Porosity—That part of a rock that contains pore spaces without regard to size, shape, interconnection, or arrangement of openings. It is expressed as percentage of total volume occupied by spaces.

Potable water—Water satisfactorily safe for drinking purposes from the standpoint of its chemical, physical, and biological characteristics.

Precipitate—A deposit on the Earth of hail, rain, mist, sleet, or snow; the common process by which atmospheric water becomes surface or subsurface water. The term *precipitation* is also commonly used to designate the quantity of water precipitated.

Preventive maintenance (PM)—Regularly scheduled servicing of machinery or other equipment using appropriate tools, tests, and lubricants. This type of maintenance can prolong the useful life of equipment and machinery and increase its efficiency by detecting and correcting problems before they cause a breakdown of the equipment.

Purveyor—An agency or person that supplies potable water.

Radon—A radioactive, colorless, odorless gas that occurs naturally in the earth. When trapped in buildings, concentrations build up and can cause health hazards such as lung cancer.

Recharge—The addition of water into a groundwater system.

Reservoir—A pond, lake, tank, or basin (natural or human made) where water is collected and used for storage. Large bodies of groundwater are called *groundwater reservoirs*; water behind a dam is also called a *reservoir of water*.

Reverse osmosis—Process in which almost pure water is passed through a semipermeable membrane.

Return activated sludge solids (RASS)—The concentration of suspended solids in the sludge flow being returned from the settling tank to the head of the aeration tank.

River basin—A term used to designate the area drained by a river and its tributaries.

Sanitary wastewater—Wastes discharged from residences and from commercial, institutional, and similar facilities that include both sewage and industrial wastes.

Schmutzdecke—Layer of solids and biological growth that forms on top of a slow sand filter, allowing the filter to remove turbidity effectively without chemical coagulation.

Scum—The mixture of floatable solids and water removed from the surface of the settling tank.

Sediment—Transported and deposited particles derived from rocks, soil, or biological material.

Sedimentation—A process that reduces the velocity of water in basins so suspended material can settle out by gravity.

Seepage—The appearance and disappearance of water at the ground surface. Seepage designates movement of water in saturated material. It differs from *percolation*, which is predominantly the movement of water in unsaturated material.

Septic tanks—Used to hold domestic wastes when a sewer line is not available to carry them to a treatment plant. The wastes are piped to underground tanks directly from a home or homes. Bacteria in the wastes decompose some of the organic matter, the sludge settles on the bottom of the tank, and the effluent flows out of the tank into the ground through drains.

Settleability—A process control test used to evaluate the settling characteristics of the activated sludge. Readings taken at 30 to 60 minutes are used to calculate the settled sludge volume (SSV) and the sludge volume index (SVI).

Settled sludge volume (SSV)—The volume (in percent) occupied by an activated sludge sample after 30 to 60 minutes of settling; normally written as SSV with a subscript to indicate the time of the reading used for calculation (SSV_{60} or SSV_{30}).

Sludge—The mixture of settleable solids and water removed from the bottom of the settling tank.

Sludge retention time (SRT)—See mean cell residence time.

Sludge volume index (SVI)—A process control calculation used to evaluate the settling quality of the activated sludge; requires the SSV_{30} and mixed liquor suspended solids test results to calculate.

Soil moisture (soil water)—Water diffused in the soil. It is found in the upper part of the zone of aeration from which water is discharged by transpiration from plants or by soil evaporation.

Specific heat—The heat capacity of a material per unit mass. The amount of heat (in calories) required to raise the temperature of 1 gram of a substance 1°C; the specific heat of water is 1 calorie.

Storm sewer—A collection system designed to carry only stormwater runoff.

Stormwater—Runoff resulting from rainfall and snowmelt.

Stream—A general term for a body of flowing water. In hydrology, the term is generally applied to the water flowing in a natural channel as distinct from a canal. More generally, it is applied to the water flowing in any channel, natural or artificial. Some types of streams include: (1) *ephemeral*, a stream that flows only in direct response to precipitation and whose channel is at all times above the water table; (2) *intermittent* or *seasonal*, a stream that flows only at certain times of the year when it receives water from springs, rainfall, or surface sources such as melting snow; (3) *perennial*, a stream that flows continuously; (4) *gaining*, an effluent stream or reach of a stream that receives water from the zone of saturation; (5) *insulated*, a stream or reach of a stream that is separated from the zones of saturation by an impermeable bed so it neither contributes water to the zone of saturation nor receives water from it; (6) *losing*, an influent stream or reach of a stream that contributes water to the zone of saturation; and (7) *perched*, either a losing stream or an insulated stream that is separated from the underlying groundwater by a zone of aeration.

Supernatant—The liquid standing above a sediment or precipitate.

Surface tension—The free energy produced in a liquid surface by the unbalanced inward pull exerted by molecules underlying the layer of surface molecules.

Surface water—Lakes, bays, ponds, impounding reservoirs, springs, rivers, streams, creeks, estuaries, wetlands, marshes, inlets, canals, gulfs inside the territorial limits of the state, and all other bodies of surface water, natural or artificial, inland or coastal, fresh or salt, navigable or nonnavigable, and including the beds and banks of all watercourses and bodies of surface water that are wholly or partially inside or bordering the state or subject to the jurisdiction of the state; except that waters in treatment systems which are authorized by state or federal law, regulation, or permit, and which are created for the purpose of water treatment, are not considered to be waters in the state.

Thermal pollution—The degradation of water quality by the introduction of a heated effluent. Primarily the result of the discharge of cooling waters from industrial processes (particularly from electrical power generation); waste heat eventually results from virtually every energy conversion.

Titrant—A solution of known strength of concentration; used in titration.

Titration—A process whereby a solution of known strength (titrant) is added to a certain volume of treated sample containing an indicator. A color change shows when the reaction is complete.

Titrator—An instrument, usually a calibrated cylinder (tube-form), used in titration to measure the amount of titrant being added to the sample.

Total dissolved solids—The amount of material (inorganic salts and small amounts of organic material) dissolved in water and commonly expressed as a concentration in terms of milligrams per liter.

Total suspended solids (TSS)—Total suspended solids in water, commonly expressed as a concentration in terms of milligrams per liter.

Toxicity—The occurrence of lethal or sublethal adverse effects on representative sensitive organisms due to exposure to toxic materials. Adverse effects caused by conditions of temperature, dissolved oxygen, or nontoxic dissolved substances are excluded from the definition of toxicity.

Transpiration—The process by which water vapor escapes from the living plant, principally the leaves, and enters the atmosphere.

Vaporization—The change of a substance from a liquid or solid state to a gaseous state.

Volatile organic compound (VOC)—Any organic compound that participates in atmospheric photochemical reactions except for those designated by the EPA Administrator as having negligible photochemical reactivity.

Waste activated sludge solids (WASS)—The concentration of suspended solids in the sludge being removed from the activated sludge process.

Wastewater—The water supply of a community after it has been soiled by use. Wastewater can also be defined as a community's spent water. Wastewater contains the impurities that were present when the water was obtained (water picks up impurities as it travels) and any impurities added through human uses. The term *sewage* is often used to refer to wastewater but is more properly applied to domestic or household wastewater. As mentioned, raw wastewater entering a treatment plant (or unit process) is referred to as *influent*. The treated water discharged from a wastewater treatment plant (or unit process) is known as *effluent*.

Water cycle—The process by which water travels in a sequence from the air (condensation) to the Earth (precipitation) and returns to the atmosphere (evaporation). It is also referred to as the *hydrologic cycle*.

Water quality—A term used to describe the chemical, physical, and biological characteristics of water with respect to its suitability for a particular use.

Water quality standard—A plan for water quality management containing four major elements: water use, criteria to protect users, implementation plans, and enforcement plans. An antidegradation statement is sometimes prepared to protect existing high-quality waters.

Water supply—Any quantity of available water.

Waterborne disease—A disease caused by a microorganism that is carried from one person or animal to another by water.

Watershed—The area of land that contributes surface runoff to a given point in a drainage system.

Weir—A device used to measure wastewater flow.

Zone of aeration—A region in the Earth above the water table. Water in the zone of aeration is under atmospheric pressure and would not flow into a well.

Zoogleal slime—The biological slime that forms on fixed-film treatment devices. It contains a wide variety of organisms essential to the treatment process.

2.2 CHAPTER REVIEW QUESTIONS

Matching Exercise

Match the definitions listed in Part A with the terms listed in Part B by placing the correct letter in the blank.

Note: After completing this exercise, compare your answers to those provided in Appendix A.

Part A

1. A nonchemical turbidity removal layer in a slow sand filter ________
2. Region in Earth (soil) above the water table ________
3. Compound associated with photochemical reaction ________
4. Oxygen used in water-rich inorganic matter ________

5. A stream that receives water from the zone of saturation ________
6. The addition of water into a groundwater system ________
7. The natural water cycle ________
8. Present in intestinal tracts and feces of animals and humans ________
9. Discharge from a factory or municipal sewage treatment plant ________
10. Common to fixed-film treatment devices ________
11. Water that is identified as safe to drink ________
12. The capacity of soil to hold water ________
13. Used to measure acidity and alkalinity ________
14. Rain mixed with sulfur oxides ________
15. Enrichment of water bodies by nutrients ________
16. A solution of known strength or concentration ________
17. Water lost by foliage ________
18. Another name for a wastewater pumping station ________
19. Plants and animals indigenous to an area ________
20. The amount of oxygen dissolved in water ________
21. A stream that flows continuously ________
22. A result of excessive nutrients within a water body ________
23. Change in groundwater head over a given distance ________
24. Water trapped in sedimentary rocks ________
25. Heat capacity of a material per unit mass ________
26. A compound derived from material that once lived ________

Part B

a. pH
b. Algae bloom
c. Zone of aeration
d. Hydrological cycle
e. Point-source pollution
f. Perennial
g. Organic
h. Connate water
i. Fecal coliform
j. BOD
k. Field capacity
l. Transpiration
m. Biota
n. Specific heat
o. Schmutzdecke
p. Recharge
q. Zoogleal slime
r. Eutrophication
s. Gaining
t. VOC
u. Potable
v. Acid rain
w. Titrant
x. Lift station
y. DO
z. Hydraulic gradient

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CHAPTER 3

BASIC MATHEMATICS

3.1 INTRODUCTION

Most calculations required by wastewater operators and engineers (as with many others) start with the basics, such as addition, subtraction, multiplication, division, and sequence of operations. Although many of the operations are fundamental tools within each operator's toolbox, it is important to reuse these tools on a consistent basis to remain sharp in their use. Wastewater operators should master basic math definitions and the formation of problems; daily operations require calculation of percentage, average, simple ratio, geometric dimensions, threshold odor number, force, pressure, and head, and, at the higher levels of licensure, the use of dimensional analysis and advanced math operations.

3.2 BASIC MATH TERMINOLOGY, DEFINITIONS, AND CALCULATION STEPS

The following basic definitions will aid in understanding the material that follows.

- An *integer*, or an *integral number*, is a whole number; thus, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12 are the first 12 positive integers.
- A *factor*, or *divisor*, of a whole number is any other whole number that exactly divides it; thus, 2 and 5 are factors of 10.
- A *prime number* in math is a number that has no factors except itself and 1; examples of prime numbers are 1, 3, 5, 7, and 11.
- A *composite number* is a number that has factors other than itself and 1. Examples of composite numbers are 4, 6, 8, 9, and 12.

- A *common factor*, or *common divisor*, of two or more numbers is a factor that will exactly divide each of them. If this factor is the largest factor possible, it is called the *greatest common divisor.* Thus, 3 is a common divisor of 9 and 27, but 9 is the greatest common divisor of 9 and 27.
- A *multiple* of a given number is a number that is exactly divisible by the given number. If a number is exactly divisible by two or more other numbers, it is a common multiple of them. The least (smallest) such number is called the *lowest common multiple.* Thus, 36 and 72 are common multiples of 12, 9, and 4; however, 36 is the lowest common multiple.
- An *even number* is a number exactly divisible by 2; thus, 2, 4, 6, 8, 10, and 12 are even integers.
- An *odd number* is an integer that is not exactly divisible by 2; thus, 1,3, 5, 7, 9, and 11 are odd integers.
- A *product* is the result of multiplying two or more numbers together; thus, 25 is the product of 5 × 5. Also, 4 and 5 are factors of 20.
- A *quotient* is the result of dividing one number by another; for example, 5 is the quotient of 20 ÷ 4.
- A *dividend* is a number to be divided; a *divisor* is a number that divides; for example, in 100 ÷ 20 = 5, 100 is the dividend, 20 is the divisor, and 5 is the quotient.
- *Area* is the area of an object, measured in square units.
- *Base* is a term used to identify the bottom leg of a triangle, measured in linear units.
- *Circumference* is the distance around an object, measured in linear units. When determined for other than circles, it may be called the *perimeter* of the figure, object, or landscape.
- *Cubic units* are measurements used to express volume, cubic feet, cubic meters, etc.
- *Depth* is the vertical distance from the bottom of the tank to the top. This is normally measured in terms of liquid depth and given in terms of sidewall depth (SWD), measured in linear units.
- *Diameter* is the distance from one edge of a circle to the opposite edge passing through the center, measured in linear units.
- *Height* is the vertical distance from the base or bottom of a unit to the top or surface.
- *Linear units* are measurements used to express distances: feet, inches, meters, yards, etc.
- *Pi* (π) is a number used in calculations involving circles, spheres, or cones ($\pi = 3.14$).
- *Radius* is the distance from the center of a circle to the edge, measured in linear units.
- *Sphere* is a container shaped like a ball.

- *Square units* are measurements used to express area, square feet, square meters, acres, etc.
- *Volume* is the capacity of the unit (how much it will hold), measured in cubic units (cubic feet, cubic meters) or in liquid volume units (gallons, liters, million gallons).
- *Width* is the distance from one side of the tank to the other, measured in linear units.

3.2.1 Calculation Steps

Standard methodology used in making mathematical calculations includes the following:

1. If appropriate, make a drawing of the information in the problem.
2. Place the given data on the drawing.
3. Ask "What is the question?" followed by "What are they really looking for?"
4. If the calculation calls for an equation, write it down.
5. Fill in the data in the equation—look to see what is missing.
6. Rearrange or transpose the equation, if necessary.
7. If available, use a calculator.
8. Always write down the answer.
9. Check any solution obtained. Does the answer make sense?

Note: Solving word math problems is difficult for many operators. Solving these types of problems is made easier, however, by understanding a few key words.

3.2.2 Key Math Words

- *Of* means to multiply.
- *And* means to add.
- *Per* means to divide.
- *Less than* means to subtract.

3.2.3 Calculators

The old saying "Use it or lose it" amply applies to mathematics. Consider a person who first learned to perform long division, multiplication, square roots, adding and subtracting, decimals to fractions, and other math operations using nothing more than pencil and paper and his or her own brain power. Eventually, this same person is handed a pocket calculator that can produce all of these functions and much more simply by manipulating certain keys on a keyboard. This process involves little brainpower—nothing more than punching in correct numbers and operations to achieve an almost instant answer. Backspacing to the previous statement of “Use it or lose it” makes our point. As with other learned skills, how proficient we remain at performing a learned skill is directly proportionate to the amount of time we spend using the skill—whatever that might be. We either use it, or we lose it. The consistent use of calculators has caused many of us to forget how to perform basic math operations with pencil and paper—for example, how to perform long division.

There can be little doubt that the proper use of a calculator can reduce the time and effort required to perform calculations; thus, it is important to recognize the calculator as a helpful tool, with the help of a well-illustrated instruction manual, of course. The manual should be large enough to read, not an inch by an inch by a quarter of an inch in size. It should have examples of problems and answers with illustrations. Careful review of the instructions and working through example problems are the best ways to learn how to use the calculator.

Keep in mind that the calculator you select should be large enough so that you can use it. Many of the modern calculators have keys so small that it is almost impossible to hit just one key. You will be doing a considerable amount of work during this study effort—make it as easy on yourself as you can.

Another significant point to keep in mind when selecting a calculator is the importance of purchasing a unit that has the functions you need. Although a calculator with a lot of functions may look impressive, it can be complicated to use. Generally, the wastewater plant operator requires a calculator that can add, subtract, multiply, and divide. A calculator with a parentheses function is helpful, and, if you must calculate geometric means for fecal coliform reporting, logarithmic capability is helpful.

In many cases, calculators can be used to perform several mathematical functions in succession. Because various calculators are designed using different operating systems, you must review the instructions carefully to determine how to make the best use of the system.

Finally, it is important to keep a couple of basic rules in mind when performing calculations:

- Always write down the calculations you wish to perform.
- Remove any parentheses or brackets by performing the calculations inside first.

3.3 SEQUENCE OF OPERATIONS

Mathematical operations such as addition, subtraction, multiplication, and division are usually performed in a certain order or sequence. Typically, multiplication and division operations are done prior to addition and subtraction operations. In addition, mathematical operations are also generally performed from left to right using this hierarchy. The use of parentheses is also common to set apart operations that should be performed in a particular sequence.

Note: It is assumed that the reader has a fundamental knowledge of basic arithmetic and math operations; thus, the purpose of the following section is to provide a brief review of the mathematical concepts and applications frequently employed by wastewater operators.

3.3.1 Sequence of Operations Rules

Rule 1

In a series of additions, the terms may be placed in any order and grouped in any way; thus, $4 + 3 = 7$ and $3 + 4 = 7$; $(4 + 3) + (6 + 4) = 17$, $(6 + 3) + (4 + 4) = 17$, and $[6 + (3 + 4)] + 4 = 17$.

Rule 2

In a series of subtractions, changing the order or the grouping of the terms may change the result; thus, $100 - 30 = 70$, but $30 - 100 = -70$, and $(100 - 30) - 10 = 60$, but $100 - (30 - 10) = 80$.

Rule 3

When no grouping is given, the subtractions are performed in the order written, from left to right; thus, $100 - 30 - 15 - 4 = 51$ (by steps, $100 - 30 = 70$, $70 - 15 = 55$, $55 - 4 = 51$).

Rule 4

In a series of multiplications, the factors may be placed in any order and in any grouping; thus, $[(2 \times 3) \times 5] \times 6 = 180$ and $5 \times [2 \times (6 \times 3)] = 180$.

Rule 5

In a series of divisions, changing the order or the grouping may change the result; thus, $100 \div 10 = 10$ but $10 \div 100 = 0.1$, and $(100 \div 10) \div 2 = 5$ but $100 \div (10 \div 2) = 20$. Again, if no grouping is indicated, the divisions are performed in the order written, from left to right; thus, $100 \div 10 \div 2$ is understood to mean $(100 \div 10) \div 2$.

Rule 6

In a series of mixed mathematical operations, the convention is as follows: Whenever no grouping is given, multiplications and divisions are to be performed in the order written, then additions and subtractions in the order written.

3.3.2 Sequence of Operations Examples

In a series of additions, the terms may be placed in any order and grouped in any way:

$$3 + 6 = 10 \text{ and } 6 + 4 = 10$$

$$(4 + 5) + (3 + 7) = 19,\ (3 + 5) + (4 + 7) = 19, \text{ and } [7 + (5 + 4)] + 3 = 19$$

In a series of subtractions, changing the order or the grouping of the terms may change the result:

$$100 - 20 = 80, \text{ but } 20 - 100 = -80$$

$$(100 - 30) - 20 = 50, \text{ but } 100 - (30 - 20) = 90$$

When no grouping is given, the subtractions are performed in the order written—from left to right:

$$100 - 30 - 20 - 3 = 47$$

or by steps:

$$100 - 30 = 70,\ 70 - 20 = 50,\ 50 - 3 = 47$$

In a series of multiplications, the factors may be placed in any order and in any grouping:

$$[(3 \times 3) \times 5] \times 6 = 270 \text{ and } 5 \times [3 \times (6 \times 3)] = 270$$

In a series of divisions, changing the order or the grouping may change the result:

$$100 \div 10 = 10, \text{ but } 10 \div 100 = 0.1$$

$$(100 \div 10) \div 2 = 5, \text{ but } 100 \div (10 \div 2) = 20$$

If no grouping is indicated, the divisions are performed in the order written, from left to right:

$$100 \div 5 \div 2 \text{ is understood to mean } (100 \div 5) \div 2$$

In a series of mixed mathematical operations, the rule of thumb is that, whenever no grouping is given, multiplications and divisions are to be performed in the order written, then additions and subtractions in the order written.

3.4 PERCENT

The word "percent" means "by the hundred." Percentage is usually designated by the symbol %; thus, 15% means 15 percent or 15/100 or 0.15. These equivalents may be written in the reverse order: 0.15 = 15/100

= 15%. In wastewater treatment, percent is frequently used to express plant performance and for control of biosolids treatment processes. When working with percent, the following key points are important:

- *Percents* are another way of expressing a part of a whole.
- As mentioned, percent means "by the hundred," so a percentage is the number out of 100. To determine percent, divide the quantity we wish to express as a percent by the total quantity, then multiply by 100:

  $$\text{Percent (\%)} = \frac{\text{Part}}{\text{Whole}} \tag{3.1}$$

  For example, 22 percent (or 22%) means 22 out of 100, or 22/100. Dividing 22 by 100 results in the decimal 0.22:

  $$22\% = \frac{22}{100} = 0.22$$

- When using percentage in calculations (such as when used to calculate hypochlorite dosages and when the percent available chlorine must be considered), the percentage must be converted to an equivalent decimal number; this is accomplished by dividing the percentage by 100. For example, calcium hypochlorite (HTH) contains 65% available chlorine. What is the decimal equivalent of 65%? Because 65% means 65 per hundred, divide 65 by 100: 65/100, which is 0.65.
- Decimals and fractions can be converted to percentages. The fraction is first converted to a decimal, then the decimal is multiplied by 100 to get the percentage. For example, if a 50-foot-high water tank has 26 feet of water in it, how full is the tank in terms of the percentage of its capacity?

  $$\frac{26\text{ ft}}{50\text{ ft}} = 0.52 \text{ (decimal equivalent)}$$

  $$0.52 \times 100 = 52$$

  Thus, the tank is 52% full.

■ *Example 3.1*

Problem: The plant operator removes 6500 gal of biosolids from the settling tank. The biosolids contain 325 gal of solids. What is the percent solids in the biosolids?

Solution:

$$\text{Percent} = \frac{325\text{ gal}}{6500\text{ gal}} \times 100 = 5\%$$

■ *Example 3.2*

Problem: Convert 65% to decimal percent.

Solution:

$$\text{Decimal Percent} = \frac{\text{Percent}}{100} = \frac{65}{100} = 0.65$$

■ *Example 3.3*

Problem: Biosolids contains 5.8% solids. What is the concentration of solids in decimal percent?

Solution:

$$\text{Decimal Percent} = \frac{5.8\%}{100} = 0.058$$

Note: Unless otherwise noted, all calculations in the text using percent values require the percent to be converted to a decimal before use.

Note: To determine what quantity a percent equals, first convert the percent to a decimal then multiply by the total quantity.

$$\text{Quantity} = \text{Total} \times \text{Decimal Percent} \tag{3.2}$$

■ *Example 3.4*

Problem: Biosolids drawn from the settling tank is 5% solids. If 2800 gal of biosolids are withdrawn, how many gallons of solids are removed?

Solution:

$$\text{Gallons} = \frac{5\%}{100} \times 2800 \text{ gal} = 140 \text{ gal}$$

■ *Example 3.5*

Problem: Convert 0.55 to percent.

Solution:

$$0.55 = \frac{55}{100} = 55\%$$

To convert 0.55 to 55%, we simply move the decimal point two places to the right.

■ *Example 3.6*

Problem: Convert 7/22 to a decimal number to a percent.

Solution:

$$\frac{7}{22} = 0.318 = 0.318 \times 100 = 31.8\%$$

■ *Example 3.7*

Problem: What is the percentage of 3 ppm?

Note: Because 1 liter of water weighs 1 kg (1000 g = 1,000,000 mg), milligrams per liter is parts per million (ppm).

Solution: Because 3 parts per million (ppm) = 3 mg/L:

$$3 \text{ mg/L} = \frac{3 \text{ mg}}{1 \text{ L} \times 1,000,000 \text{ mg/L}} \times 100\%$$

$$= \frac{3}{10,000}\% = 0.0003\%$$

■ *Example 3.8*

Problem: How many milligrams per liter is a 1.4% solution?

Solution:

$$1.4\% = \frac{1.4}{100} \times 1,000,000 \text{ mg/L (the weight of 1 L water to } 10^6) = 14,000 \text{ mg/L}$$

■ *Example 3.9*

Problem: Calculate pounds per million gallons for 1 ppm (1 mg/L) of water.

Solution: Because 1 gal of water = 8.34 lb,

$$1 \text{ ppm} = \frac{1 \text{ gal}}{10^6 \text{ gal}} = \frac{1 \text{ gal} \times 8.34 \text{ lb/gal}}{1,000,000 \text{ gal}} = 8.34 \text{ lb/1,000,000 gal}$$

■ *Example 3.10*

Problem: How many pounds of activated carbon (AC) are needed with 42 lb of sand to make the mixture 26% AC?

Solution: Let x be the weight of AC:

$$\frac{x}{42 + x} = 0.26$$

$$x = 0.26(42 + x) = 10.92 + 0.26x$$

$$x = \frac{10.92}{0.74} = 14.76 \text{ lb}$$

■ *Example 3.11*

Problem: A pipe is laid at a rise of 140 mm in 22 m. What is the grade?

Solution:

$$\text{Grade} = \frac{140 \text{ mm}}{22 \text{ m}} \times 100\% = \frac{140 \text{ mm}}{22 \text{ m} \times 1000 \text{ mm}} \times 100\% = 0.64\%$$

■ *Example 3.12*

Problem: A motor is rated as 40 horsepower (hp); however, the output horsepower of the motor is only 26.5 hp. What is the efficiency of the motor?

Solution:

$$\text{Efficiency} = \frac{\text{Output (hp)}}{\text{Input (hp)}} \times 100\% = \frac{26.5 \text{ hp}}{40 \text{ hp}} \times 100\% = 66\%$$

3.5 SIGNIFICANT DIGITS

When rounding numbers, the following key points are important:

- Numbers are rounded to reduce the number of digits to the right of the decimal point. This is done for convenience, not for accuracy.
- A number is rounded off by dropping one or more numbers from the right and adding zeroes if necessary to place the decimal point. If the last figure dropped is 5 or more, increase the last retained figure by 1. If the last digit dropped is less than 5, do not increase the last retained figure. If the digit 5 is dropped, round off preceding digit to the nearest *even* number.

■ *Example 3.13*

Problem: Round off the following numbers to one decimal.

Solution:

34.73 = 34.7	34.45 = 34.4
34.75 = 34.8	34.35 = 34.4
34.77 = 34.8	

■ *Example 3.14*

Problem: Round off 10,546 to 4, 3, 2, and 1 significant figures.

Solution:

10,546 = 10,550 to 4 significant figures
10,546 = 10,500 to 3 significant figures
10,546 = 11,000 to 2 significant figures
10,547 = 10,000 to 1 significant figure

When determining significant figures, the following key points are important:

1. The concept of significant figures is related to rounding.
2. It can be used to determine where to round off.

Rule: Significant figures are those numbers that are known to be reliable. The position of the decimal point does not determine the number of significant figures.

Key Point: No answer can be more accurate than the least accurate piece of data used to calculate the answer.

■ *Example 3.15*

Problem: How many significant figures are in a measurement of 1.35?

Solution: Three significant figures: 1, 3, and 5.

■ *Example 3.16*

Problem: How many significant figures are in a measurement of 0.000135?

Solution: Again, three significant figures: 1, 3, and 5. The three zeros are used only to place the decimal point.

■ *Example 3.17*

Problem: How many significant figures are in a measurement of 103,500?

Solution: Four significant figures: 1, 0, 3, and 5. The remaining two zeros are used to place the decimal point.

■ ***Example 3.18***

Problem: How many significant figures are in 27,000.0?

Solution: There are six significant figures: 2, 7, 0, 0, 0, 0. In this case, the .0 means that the measurement is precise to 1/10 unit. The zeros indicate measured values and are not used solely to place the decimal point.

3.6 POWERS AND EXPONENTS

When working with powers and exponents, the following key points are important:

- *Powers* are used to identify *area*, as in square feet, and *volume*, as in cubic feet.
- Powers can also be used to indicate that a number should be squared, cubed, etc. This later designation is the number of times a number must be multiplied times itself.
- If all of the factors are alike, as $4 \times 4 \times 4 \times 4 = 256$, the product is called a *power*. Thus, 256 is a power of 4, and 4 is the *base* of the power. A *power* is a *product* obtained by using a base a certain number of times as a factor.
- Instead of writing $4 \times 4 \times 4 \times 4$, it is more convenient to use an *exponent* to indicate that the factor 4 is used as a factor four times. This exponent, a small number placed above and to the right of the base number, indicates how many times the base is to be used as a factor. Using this system of notation, the multiplication $4 \times 4 \times 4 \times 4$ is written as 4^4. The ^{4} is the *exponent*, showing that 4 is to be used as a factor 4 times.
- These same consideration apply to letters (*a*, *b*, *x*, *y*, etc.) as well:

$$z^2 = z \times z$$

$$z^4 = z \times z \times z \times z$$

Key Point: When a number or letter does not have an exponent, it is considered to have an exponent of one.

The powers of 1:

$1^0 = 1$ $1^3 = 1$

$1^1 = 1$ $1^4 = 1$

$1^2 = 1$

The powers of 10:

$10^0 = 1$ $10^3 = 1000$

$10^1 = 10$ $10^4 = 10,000$

$10^2 = 100$

■ ***Example 3.19***

Problem: How is the term 2^3 written in expanded form?

Solution: The power (exponent) of 3 means that the base number (2) is multiplied by itself three times:

$$2^3 = 2 \times 2 \times 2$$

■ ***Example 3.20***

Problem: How is the term $(3/8)^2$ written in expanded form?

Solution: In this example, $(3/8)^2$ means:

$$(3/8)^2 = 3/8 \times 3/8$$

Key Point: When parentheses are used, the exponent refers to the entire term within the parentheses.

Note: When a negative exponent is used with a number or term, a number can be reexpressed using a positive exponent:

$$6^{-3} = 1/6^3$$

Another example is

$$11^{-5} = 1/11^5$$

■ ***Example 3.21***

Problem: How is the term 8^{-3} written in expanded form?

$$8^{-3} = \frac{1}{8^3} = \frac{1}{8 \times 8 \times 8}$$

Note: A number or letter written as, for example, 3^0 or X^0 does not equal 3×1 or $X \times 1$, but simply 1.

3.7 AVERAGES (ARITHMETIC MEAN)

Whether we speak of harmonic mean, geometric mean, or arithmetic mean, each represents the “center,” or “middle,” of a set of numbers. They capture the intuitive notion of a “central tendency” that may be present in the data. In statistical analysis, an “average of data” is a number that indicates the middle of the distribution of data values.

An *average* is a way of representing several different measurements as a single number. Although averages can be useful in that they tell us “about” how much or how many, they can also be misleading, as we demonstrate below. You will find two kinds of averages in environmental engineering calculations: the *arithmetic* mean (or simply *mean*) and the *median.*

Definition: The mean (what we usually refer to as an *average*) is the total of values of a set of observations divided by the number of observations. We simply add up all of the individual measurements and divide by the total number of measurements we took.

■ *Example 3.22*

Problem: The operator of a waterworks or wastewater treatment plant takes a chlorine residual measurement every day; part of the operator's log is shown below. Find the mean.

Monday	0.9 mg/L
Tuesday	1.0 mg/L
Wednesday	0.9 mg/L
Thursday	1.3 mg/L
Friday	1.1 mg/L
Saturday	1.4 mg/L
Sunday	1.2 mg/L

Solution: Add up the seven chlorine residual readings: 0.9 + 1.0 + 0.9 + 1.3 + 1.1 + 1.4 + 1.2. = 7.8. Next, divide by the number of measurements—in this case, 7:

$$7.8 \div 7 = 1.11$$

The mean chlorine residual for the week was 1.11 mg/L.

■ *Example 3.23*

Problem: A water system has four wells with the following capacities: 115 gallons per minute (gpm), 100 gpm, 125 gpm, and 90 gpm. What is the mean?

Solution:

$$115 \text{ gpm} + 100 \text{ gpm} + 125 \text{ gpm} + 90 \text{ gpm} = 430$$

$$430 \div 4 = 107.5 \text{ gpm}$$

■ *Example 3.24*

Problem: A water system has four storage tanks. Three of them have a capacity of 100,000 gal each, while the fourth has a capacity of 1 million gal. What is the mean capacity of the storage tanks?

Solution: The mean capacity of the storage tanks is

$$100{,}000 + 100{,}000 + 100{,}000 + 1{,}000{,}000 = 1{,}300{,}000$$

$$1{,}300{,}000 \div 4 = 325{,}000 \text{ gal}$$

Note: Notice that no tank in Example 3.24 has a capacity anywhere close to the mean.

■ *Example 3.25*

Problem: Effluent biochemical oxygen demand (BOD) test results for the treatment plant during the month of August are shown below:

Test 1	22 mg/L
Test 2	33 mg/L
Test 3	21 mg/L
Test 4	13 mg/L

What is the average effluent BOD for the month of August?

Solution:

$$22 + 33 + 21 + 13 = 89$$

$$89 \div 4 = 22.3 \text{ mg/L}$$

■ *Example 3.26*

Problem: For the primary influent flow, the following composite-sampled solids concentrations were recorded for the week:

Monday	310 mg/L
Tuesday	322 mg/L
Wednesday	305 mg/L
Thursday	326 mg/L
Friday	313 mg/L
Saturday	310 mg/L
Sunday	320 mg/L
Total	2206 mg/L

What is the average SS?

Solution:

$$\text{Average SS} = \frac{\text{Sum of all measurements}}{\text{Number of measurements used}}$$

$$= \frac{2206 \text{ mg/L}}{7} = 315.1 \text{ mg/L}$$

3.8 RATIOS

A *ratio* is the established relationship between two numbers; it is simply one number divided by another number. For example, if someone says, “I’ll give you four to one the Redskins over the Cowboys in the Super Bowl,” what does that person mean?

Four to one, or 4:1, is a ratio. If someone gives you four to one, it’s his or her $4 to your $1. As another more pertinent example, if an average of 3 cubic feet (ft^3) of screenings are removed from each million gallons (MG) of wastewater treated, the ratio of screenings removed to treated wastewater is 3:1. Ratios are normally written using a colon (such as 2:1) or as a fraction (such as 2/1).

When working with ratios, the following key points are important to remember.

- One place where fractions are used in calculations is when ratios are used, such as calculating solutions.
- A ratio is usually stated in the form A is to B as C is to D, which can be written as two fractions that are equal to each other:

$$\frac{A}{B} = \frac{C}{D}$$

- Cross-multiplying solves ratio problems; that is, we multiply the left numerator (A) by the right denominator (D) and say that the product is equal to the left denominator (B) times the right numerator (C):

$$A \times D = B \times C \text{ (or, } AD = BC\text{)}$$

- If one of the four items is unknown, dividing the two known items that are multiplied together by the known item that is multiplied by the unknown solves the ratio. For example, If 2 lb of alum are needed to treat 500 gal of water, how many pounds of alum will we need to treat 10,000 gal? We can state this as a ratio: “2 lb of alum is to 500 gal of water as *x* lb of alum is to 10,000 gal of water.” This is set up in this manner:

$$\frac{1 \text{ lb alum}}{500 \text{ gal water}} = \frac{x \text{ lb alum}}{10{,}000 \text{ gal water}}$$

Cross-multiplying:

$$500 \times x = 1 \times 10{,}000$$

Transposing:

$$\frac{1 \times 10{,}000}{500} = 20 \text{ lb alum}$$

To calculate proportion, suppose, for example, that 5 gal of fuel costs $5.40. What will 15 gal cost?

$$\frac{5\text{ gal}}{\$5.40} = \frac{15\text{ gal}}{\$y}$$

$$5\text{ gal} \times y = 15\text{ gal} \times \$5.40 = 81$$

$$y = \frac{81}{5} = \$16.20$$

■ *Example 3.27*

Problem: If a pump will fill a tank in 20 hr at 4 gpm, how long will it take a 10-gpm pump to fill the same tank?

Solution: First, analyze the problem. Here, the unknown is some number of hours. But, should the answer be larger or smaller than 20 hr? If a 4-gpm pump can fill the tank in 20 hr, a larger (10-gpm) pump should be able to complete the filling in less than 20 hr. Therefore, the answer should be less than 20 hours. Now set up the proportion:

$$\frac{x\text{ hr}}{20\text{ hr}} = \frac{4\text{ gpm}}{10\text{ gpm}}$$

$$x = \frac{(4 \times 20)}{10} = 8\text{ hr}$$

■ *Example 3.28*

Problem: Solve for the unknown value x in the problem given below.

$$\frac{36}{180} = \frac{x}{4450}$$

Solution:

$$\frac{4450 \times 36}{180} = x = 890$$

■ *Example 3.29*

Problem: Solve for the unknown value x in the problem given below.

$$\frac{3.4}{2} = \frac{6}{x}$$

Solution:

$$3.4 \times x = 2 \times 6$$

$$x = \frac{2 \times 6}{3.4} = 3.53$$

■ ***Example 3.30***

Problem: 1 lb of chlorine is dissolved in 65 gal of water. To maintain the same concentration, how many pounds of chlorine would have to be dissolved in 150 gal of water?

Solution:

$$\frac{1\text{ lb}}{65\text{ gal}} = \frac{x\text{ lb}}{150\text{ gal}}$$

$$65 \times x = 1 \times 150$$

$$x = \frac{1 \times 150}{65} = 2.3\text{ lb}$$

■ ***Example 3.31***

Problem: It takes 5 workers 50 hr to complete a job. At the same rate, how many hours would it take 8 workers to complete the job?

Solution:

$$\frac{5\text{ workers}}{8\text{ workers}} = \frac{x\text{ hr}}{50\text{ hr}}$$

$$x = \frac{5 \times 50}{8} = 31.3\text{ hr}$$

■ ***Example 3.32***

Problem: If 1.6 L of activated sludge (biosolids) with volatile suspended solids (VSS) of 1900 mg/L is mixed with 7.2 L of raw domestic wastewater with BOD of 250 g/L, what is the food-to-microorganisms (F/M) ratio?

Solution:

$$\text{F/M Ratio} = \frac{\text{Amount of BOD}}{\text{Amount of VSS}}$$

$$= \frac{250\text{ mg/L} \times 7.2\text{ L}}{1900\text{ mg/L} \times 1.6\text{L}} = \frac{0.59}{1} = 0.59$$

3.9 DIMENSIONAL ANALYSIS

Dimensional analysis is a problem-solving method that uses the fact that any number or expression can be multiplied by 1 without changing its value. It is a useful technique used to check if a problem is set up correctly. In using dimensional analysis to check a math setup, we work with the dimensions (units of measure) only—not with numbers.

An example of dimensional analysis that is common to everyday life is the unit pricing found in many hardware stores. A shopper can purchase a 1-lb box of nails for 98¢ at a local hardware store, but a nearby warehouse store sells a 5-lb bag of the same nails for $3.50. The shopper will analyze this problem almost without thinking about it. The solution calls for reducing the problem to the price per pound. The pound is selected without much thought because it is the unit common to both stores. The shopper will pay 70¢ a pound for the nails at the warehouse store but 98¢ at the local hardware store. Implicit in the solution to this problem is knowing the unit price, which is expressed in dollars per pound ($/lb).

Note: Unit factors may be made from any two terms that describe the same or equivalent amounts of what we are interested in; for example, we know that 1 inch = 2.54 centimeters.

In order to use the dimensional analysis method, we must know how to perform three basic operations.

3.9.1 Basic Operation: Division of Units

To complete a division of units, always ensure that all units are written in the same format; it is best to express a horizontal fraction (such as gal/ft^2) as a vertical fraction.

Horizontal to vertical:

$$\text{gal/ft}^3 \text{ to } \frac{\text{gal}}{\text{ft}^3}$$

$$\text{psi to } \frac{\text{lb}}{\text{in.}^2}$$

The same procedures are applied in the following examples.

$$\text{ft}^3\text{/min becomes } \frac{\text{ft}^3}{\text{min}}$$

$$\text{s/min becomes } \frac{\text{s}}{\text{min}}$$

3.9.2 Basic Operation: Divide by a Fraction

We must know how to divide by a fraction. For example,

$$\frac{\left(\dfrac{\text{lb}}{\text{day}}\right)}{\left(\dfrac{\text{min}}{\text{day}}\right)} \text{ becomes } \frac{\text{lb}}{\text{day}} \times \frac{\text{day}}{\text{min}}$$

In the above, notice that the terms in the denominator were inverted before the fractions were multiplied. This is a standard rule that must be followed when dividing fractions.

Another example is:

$$\frac{\text{mm}^2}{\left(\dfrac{\text{mm}^2}{\text{m}^2}\right)} \text{ becomes } \text{mm}^2 \times \frac{\text{m}^2}{\text{mm}^2}$$

3.9.3 Basic Operation: Cancel or Divide Numerators and Denominators

We must know how to cancel or divide terms in the numerator and denominator of a fraction. After fractions have been rewritten in the vertical form and division by the fraction has been reexpressed as multiplication, as shown above, then the terms can be canceled (or divided) out.

Note: For every term that is canceled in the numerator of a fraction, a similar term must be canceled in the denominator and *vice versa*, as shown below:

$$\frac{\text{kg}}{\cancel{\text{d}}} \times \frac{\cancel{\text{d}}}{\text{min}} = \frac{\text{kg}}{\text{min}}$$

$$\cancel{\text{mm}^2} \times \frac{\text{m}^2}{\cancel{\text{mm}^2}} = \text{m}^2$$

$$\frac{\cancel{\text{gal}}}{\text{min}} \times \frac{\text{ft}^3}{\cancel{\text{gal}}} = \frac{\text{ft}^3}{\text{min}}$$

Question: How do we calculate units that include exponents?

Answer: When written with exponents, such as ft^3, a unit can be left as is or put in expanded form, (ft)(ft)(ft), depending on other units in the calculation. The point is that it is important to ensure that square and cubic terms are expressed uniformly, such as sq ft or ft^2 and cu ft or ft^3. For dimensional analysis, the latter system is preferred.

For example, to convert a volume of 1400 ft^3 to gallons, we will use 7.48 gal/ft^3 in the conversions. The question becomes do we multiply or divide by 7.48? In this instance, it is possible to use dimensional analysis to answer this question of whether we multiply or divide by 7.48.

To determine if the math setup is correct, only the dimensions are used. First, try dividing the dimensions:

$$\frac{\text{ft}^3}{\text{gal/ft}^3} = \frac{\text{ft}^3}{\left(\dfrac{\text{gal}}{\text{ft}^3}\right)}$$

Multiply the numerator and denominator to get:

$$\frac{\text{ft}^6}{\text{gal}}$$

So, by dimensional analysis, we have determined that if we divide the two dimensions (ft^3 and gal/ft^3) then the units of the answer are ft^6/gal, not gal. It is clear that division is not the right approach to making this conversion.

What would have happened if we had multiplied the dimensions instead of dividing?

$$\text{ft}^3 \times (\text{gal/ft}^3) = \text{ft}^3 \times \left(\frac{\text{gal}}{\text{ft}^3}\right)$$

Multiply the numerator and denominator to obtain:

$$\frac{\text{ft}^3 \times \text{gal}}{\text{ft}^3}$$

and cancel common terms to obtain:

$$\frac{\cancel{\text{ft}^3} \times \text{gal}}{\cancel{\text{ft}^3}}$$

Obviously, by multiplying the two dimensions (ft^3 and gal/ft^3), the answer will be in gallons, which is what we want. Thus, because the math setup is correct, we would then multiply the numbers to obtain the number of gallons:

$$(1400\ \text{ft}^3) \times (7.48\ \text{gal/ft}^3) = 10{,}472\ \text{gal}$$

Now, let's try another problem with exponents. We wish to obtain an answer in square feet. If we are given the two terms—70 ft^3/s and 4.5 ft/s—is the following math setup correct?

$$(70\ \text{ft}^3/\text{s}) \times (4.5\ \text{ft/s})$$

First, only the dimensions are used to determine if the math setup is correct. By multiplying the two dimensions, we get:

$$(\text{ft}^2/\text{s}) \times (\text{ft/s}) = \frac{\text{ft}^3}{\text{s}} \times \frac{\text{ft}}{\text{s}}$$

Multiply the terms in the numerators and denominators of the fraction:

$$\frac{\text{ft}^3 \times \text{ft}}{\text{s} \times \text{s}} = \frac{\text{ft}^4}{\text{s}^2}$$

Obviously, the math setup is incorrect because the dimensions of the answer are not square feet; therefore, if we multiply the numbers as shown above, the answer will be wrong.

Let's try division of the two dimensions instead:

$$(\mathrm{ft}^3/\mathrm{s}) = \frac{\left(\dfrac{\mathrm{ft}^3}{\mathrm{s}}\right)}{\left(\dfrac{\mathrm{ft}}{\mathrm{s}}\right)}$$

Invert the denominator and multiply to get:

$$= \frac{\mathrm{ft}^3}{\mathrm{s}} \times \frac{\mathrm{s}}{\mathrm{ft}} = \frac{(\mathrm{ft} \times \mathrm{ft} \times \mathrm{ft}) \times \mathrm{s}}{\mathrm{s} \times \mathrm{ft}} = \frac{(\mathrm{ft} \times \mathrm{ft} \times \cancel{\mathrm{ft}}) \times \cancel{\mathrm{s}}}{\cancel{\mathrm{s}} \times \cancel{\mathrm{ft}}} = \mathrm{ft}^2$$

Because the dimensions of the answer are square feet, this math setup is correct; therefore, by dividing the numbers as was done with units, the answer will also be correct.

$$\frac{70\ \mathrm{ft}^3/\mathrm{s}}{4.5\ \mathrm{ft/s}} = 15.56\ \mathrm{ft}^2$$

■ *Example 3.33*

Problem: We are given two terms, 5 m/s and 7 m^2, and the answer to be obtained should be in cubic meters per second (m^3/s). Is multiplying the two terms the correct math setup?

Solution:

$$(\mathrm{m/s}) \times (\mathrm{m}^2) = \frac{\mathrm{m}}{\mathrm{s}} \times \mathrm{m}^2$$

Multiply the numerators and denominator of the fraction:

$$\frac{\mathrm{m} \times \mathrm{m}^2}{\mathrm{s}} = \frac{\mathrm{m}^3}{\mathrm{s}}$$

Because the dimensions of the answer are cubic meters per second (m^3/s), the math setup is correct; therefore, multiply the numbers to get the correct answer:

$$5\ \mathrm{m/s} \times 7\ \mathrm{m}^2 = 35\ \mathrm{m}^3/\mathrm{s}$$

■ *Example 3.34*

Problem: The flow rate in a water line is 2.3 ft^3/s. What is the flow rate expressed as gallons per minute?

Solution: Set up the math problem and then use dimensional analysis to check the math setup:

$$(2.3\ \text{ft}^3/\text{s}) \times (7.48\ \text{gal/ft}^3) \times (60\ \text{s/min})$$

Dimensional analysis can be used to check the math setup:

$$(\text{ft}^3/\text{s}) \times (\text{gal/ft}^3) \times (\text{s/min}) = \frac{\text{ft}^3}{\text{s}} \times \frac{\text{gal}}{\text{ft}^3} \times \frac{\text{s}}{\text{min}} = \frac{\cancel{\text{ft}^3}}{\cancel{\text{s}}} \times \frac{\text{gal}}{\cancel{\text{ft}^3}} \times \frac{\cancel{\text{s}}}{\text{min}} = \frac{\text{gal}}{\text{min}}$$

The math setup is correct as shown above; therefore, this problem can be multiplied out to get the answer in correct units:

$$(2.3\ \text{ft}^3/\text{s}) \times (7.48\ \text{gal/ft}^3) \times (60\ \text{s/min}) = 1032.24\ \text{gal/min}$$

■ *Example 3.35*

Problem: During an 8-hr period, a water treatment plant treated 3.2 million gallons of water. What is the plant total volume treated per day, assuming the same treatment rate?

Solution:

$$\frac{3.2\ \text{million gal}}{8\ \text{hr}} \times \frac{24\ \text{hr}}{\text{day}} = \frac{3.2 \times 24}{8}\ \text{MGD} = 9.6\ \text{MGD}$$

■ *Example 3.36*

Problem: 1 MGD equals how many cubic feet per second (cfs)?

Solution:

$$1\ \text{MGD} = \frac{10^6}{1\ \text{day}} = \frac{10^6\ \text{gal} \times 0.1337\ \text{ft}^3/\text{gal}}{1\ \text{day} \times 86{,}400\ \text{s/day}} = \frac{133{,}700}{86{,}400} = 1.547\ \text{cfs}$$

■ *Example 3.37*

Problem: A 10-gal empty tank weighs 4.6 lb. What is the total weight of the tank filled with 6 gal of water?

Solution:

$$\text{Weight of water} = 6\ \text{gal} \times 8.34\ \text{lb/gal} = 50.04\ \text{lb}$$

$$\text{Total weight} = 50.04 + 4.6\ \text{lb} = 54.6\ \text{lb}$$

■ ***Example 3.38***

Problem: The depth of biosolids applied to the biosolids drying bed is 10 in. What is the depth in centimeters (2.54 cm = 1 in.)?

Solution:

$$10\text{ in.} = 10 \times 2.54\text{ cm} = 25.4\text{ cm}$$

3.10 GEOMETRICAL MEASUREMENTS

Wastewater treatment plants consist of a series of tanks and channels. Proper design and operational control requires the engineer and operator to perform several process control calculations. Many of these calculations include parameters such as the circumference or perimeter, area, or volume of the tank or channel as part of the information necessary to determine the result. Many process calculations require computation of surface areas. To aid in performing these calculations, the following definitions and relevant equations used to calculate areas and volumes for several geometric shapes are provided.

3.10.1 Definitions

Area—The area of an object, measured in square units.

Base—The term used to identity the bottom leg of a triangle, measured in linear units.

Circumference—The distance around an object, measured in linear units. When determined for other than circles, it may be called the *perimeter* of the figure, object, or landscape.

Cubic units—Measurements used to express volume, cubic feet, cubic meters, etc.

Depth—The vertical distance from the bottom of the tank to the top. It is normally measured in terms of liquid depth and given in terms of sidewall depth (SWD), measured in linear units.

Diameter—The distance, measured in linear units, from one edge of a circle to the opposite edge passing through the center.

Height—The vertical distance, measured in linear units, from one end of an object to the other.

Length—The distance, measured in linear units, from one end of an object to the other.

Linear units—Measurements used to express distance (e.g., feet, inches, meters, yards).

Pi (π)—A number used in calculations involving circles, spheres, or cones ($\pi = 3.14$).

Radius—The distance, measured in linear units, from the center of a circle to the edge.

Sphere—A container shaped like a ball.

Square units—Measurements used to express area (e.g., square feet, square meters, acres).

Volume—The capacity of a unit (how much it will hold), measured in cubic units (e.g., cubic feet, cubic meters) or in liquid volume units (e.g., gallons, liters, million gallons).

Width—The distance from one from one side of the tank to the other, measured in linear units.

3.10.2 Relevant Geometric Equations

Circumference C of a circle: $C = \pi d = 2\pi r$

Perimeter P of a square with side a: $P = 4a$

Perimeter P of a rectangle with sides a and b: $P = 2a + 2b$

Perimeter P of a triangle with sides a, b, and c: $P = a + b + c$

Area A of a circle with radius r ($d = 2r$): $A = \pi d^2/4 = \pi r^2$

Area A of a square with sides a: $A = a^2$

Area A of a rectangle with sides a and b: $A = ab$

Area A of a triangle with base b and height h: $A = 0.5bh$

Area A of an ellipse with major axis a and minor axis b: $A = \pi ab$

Area A of a trapezoid with parallel sides a and b and height h: $A = 0.5(a + b)h$

Area A of a duct (in ft^2) when d is in inches: $A = \pi d^2/576 = 0.005454d^2$

Volume V of a sphere with a radius r ($d = 2r$): $V = 1.33\pi r^3 = 0.1667\pi d^3$

Volume V of a cube with sides a: $V = a^3$

Volume V of a rectangular solid (sides a and b and height c): $V = abc$

Volume V of a cylinder with a radius r and height h: $V = \pi r^2 h = \pi d^2 h/4$

Volume V of a pyramid with base area B and height h: $V = 0.33Bh$

3.10.3 Geometrical Calculations

3.10.3.1 Perimeter and Circumference

On occasion, it may be necessary to determine the distance around grounds or landscapes. To measure the distance around property, buildings, and basin-like structures, it is necessary to determine either perimeter or circumference. The *perimeter* is the distance around an object; a border or outer boundary. *Circumference* is the distance around a circle or circular object, such as a clarifier. Distance is a linear measurement that defines the distance (or length) along a line. Standard units of measurement such as inches, feet, yards, and miles and metric units such as centimeters, meters, and kilometers are used. The perimeter (P) of a rectangle (a four-sided figure with four right angles) is obtained by adding the lengths (L_i) of the four sides (see Figure 3.1):

$$\text{Perimeter} = L_1 + L_2 + L_3 + L_4 \tag{3.3}$$

■ *Example 3.39*

Problem: Find the perimeter of the rectangle shown in Figure 3.2.

Solution:

$$P = 35 \text{ ft} + 8 \text{ ft} + 35 \text{ ft} + 8 \text{ ft} = 86 \text{ ft}$$

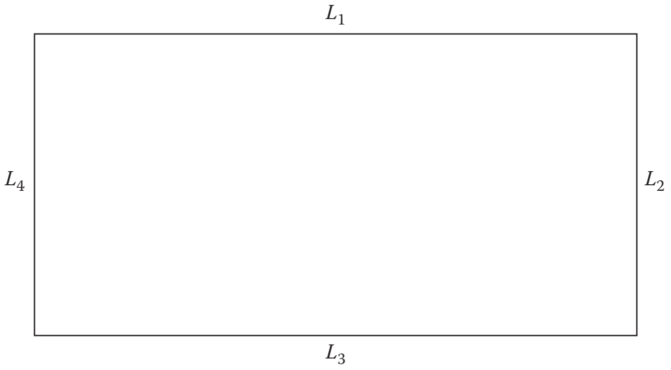

Figure 3.1 Perimeter.

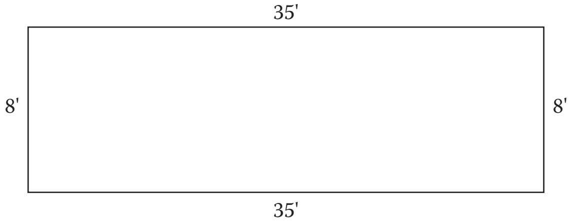

Figure 3.2 Rectangle for Example 3.39.

■ *Example 3.40*

Problem: What is the perimeter of a rectangular field if its length is 100 ft and its width is 50 ft?

Solution:

$$P = (2 \times \text{Length}) + (2 \times \text{width}) = (2 \times 100 \text{ ft}) + (2 \times 50 \text{ ft})$$

$$= 200 \text{ ft} + 100 \text{ ft} = 300 \text{ ft}$$

■ *Example 3.41*

Problem: What is the perimeter of a square with 8-in. sides?

Solution:

$$P = (2 \times \text{Length}) + (2 \times \text{Width}) = (2 \times 8 \text{ in.}) + (2 \times 8 \text{ in.})$$

$$= 16 \text{ in.} + 16 \text{ in.} = 32 \text{ in.}$$

The *circumference* is the length of the outer border of a circle. The circumference is found by multiplying pi (π) times the *diameter* (D) (a straight line passing through the center of a circle, or the distance across the circle; see Figure 3.3):

$$C = \pi D \tag{3.4}$$

where:

C = circumference.

π = pi = 3.1416.

D = diameter.

Use this calculation if, for example, the circumference of a circular tank must be determined.

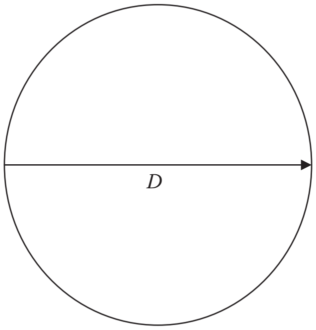

Figure 3.3 Diameter of circle.

■ *Example 3.42*

Problem: Find the circumference of a circle that has a diameter of 25 feet ($\pi = 3.14$)

Solution:

$$C = \pi \times 25 \text{ ft} = 3.14 \times 25 \text{ ft} = 78.5 \text{ ft}$$

■ *Example 3.43*

Problem: A circular chemical holding tank has a diameter of 18 m. What is the circumference of this tank?

Solution:

$$C = \pi \times 18 \text{ m} = 3.14 \times 18 \text{ m} = 56.52 \text{ m}$$

■ *Example 3.44*

Problem: An influent pipe inlet opening has a diameter of 6 ft. What is the circumference of the inlet opening in inches?

Solution:

$$C = \pi \times 6 \text{ ft} = 3.14 \times 6 \text{ ft} = 18.84 \text{ ft}$$

3.10.3.2 Area

For area measurements in water/wastewater operations, three basic shapes are particularly important—namely, circles, rectangles, and triangles. Area is the amount of surface an object contains or the amount of material it takes to cover the surface. The area on top of a chemical tank is called the *surface area.* The area of the end of a ventilation duct is called the *cross-sectional area* (the area at right angles to the length of ducting). Area is usually express in square units, such as square inches (in.^{2}) or square feet (ft^2). Land may also be expressed in terms of square miles (sections) or acres (43,560 ft^2) or in the metric system as hectares.

A *rectangle* is a two-dimensional box. The area of a rectangle is found by multiplying the length (L) times width (W) (see Figure 3.4).

$$\text{Area} = L \times W \tag{3.5}$$

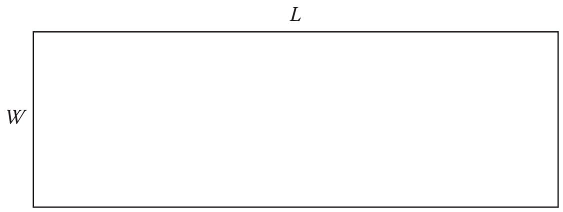

Figure 3.4 Area of rectangle.

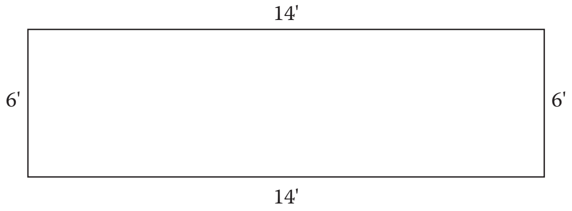

Figure 3.5 Rectangle for Example 3.45.

■ *Example 3.45*

Problem: Find the area of the rectangle shown in Figure 3.5.

Solution:

$$\text{Area} = L \times W = 14 \text{ ft} \times 6 \text{ ft} = 84 \text{ ft}^2$$

To find the area of a circle, we need to introduce a new term, the *radius*, which is represented by *r*. The circle shown in Figure 3.6 has a radius of 6 ft. The radius is any straight line that radiates from the center of the circle to some point on the circumference. By definition, all radii (plural of radius) of the same circle are equal. The surface area of a circle is determined by multiplying π times the radius squared:

$$\text{Area of circle} = \pi r^2 \tag{3.6}$$

where:

A = area.

π = pi = 3.14.

r = radius of circle = one half of the diameter.

■ *Example 3.46*

Problem: What is the area of the circle shown in Figure 3.6?

Solution:

$$\text{Area of circle} = \pi r^2 = \pi 6^2 = 3.14 \times 36 = 113 \text{ ft}^2$$

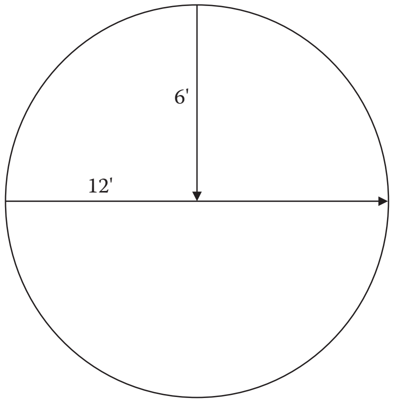

Figure 3.6 Circle for Example 3.46.

If we were assigned to paint a water storage tank, we must know the surface area of the walls of the tank to determine how much paint is required. In this case, we need to know the area of a circular or cylindrical tank. To determine the surface area of the tank, we need to visualize the cylindrical walls as a rectangle wrapped around a circular base. The area of a rectangle is found by multiplying the length by the width; in the case of a cylinder, the width of the rectangle is the height of the wall, and the length of the rectangle is the distance around the circle (circumference).

Thus, the area (A) of the side wall of a circular tank is found by multiplying the circumference of the base ($C = \pi \times D$) times the height of the wall (H):

$$A = \pi \times D \times H \tag{3.7}$$

$$A = \pi \times 20 \text{ ft} \times 25 \text{ ft} = 3.14 \times 20 \text{ ft} \times 25 \text{ ft} = 1570 \text{ ft}^2$$

To determine the amount of paint needed, remember to add the surface area of the top of the tank, which is 314 ft^2. Thus, the amount of paint needed must cover 1570 ft^2 + 314 ft^2 = 1884 ft^2. If the tank floor should be painted, add another 314 ft^2.

3.10.3.3 Volume

Volume is the amount of space occupied by or contained in an object (see Figure 3.7). It is expressed in cubic units, such as cubic inches (in.^3), cubic feet (ft^3), or acre-feet (1 acre-foot = 43,560 ft^3). The volume (V) of a rectangular object is obtained by multiplying the length times the width times the depth or height:

$$V = L \times W \times H \tag{3.8}$$

where:

L = length.

W = width.

D (or H) = depth (or height).

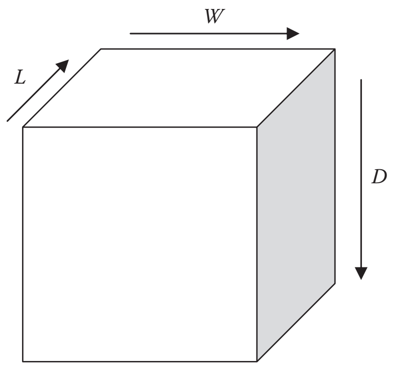

Figure 3.7 Volume.

TABLE 3.1 VOLUME FORMULAS

Sphere volume	=	$(\pi/6) \times (\text{diameter})^3$
Cone volume	=	$1/3 \times (\text{volume of a cylinder})$
Rectangular tank volume	=	$(\text{Area of rectangle}) \times (D \text{ or } H)$
	=	$(L \times W) \times (D \text{ or } H)$
Cylinder volume	=	$(\text{Area of cylinder}) \times (D \text{ or } H)$
	=	$\pi r^2 \times (D \text{ or } H)$
Triangle volume	=	$(\text{Area of triangle}) \times (D \text{ or } H)$
	=	$(bh/2) \times (D \text{ or } H)$

■ *Example 3.47*

Problem: A unit rectangular process basin has a length of 15 ft, width of 7 ft, and depth of 9 ft. What is the volume of the basin?

Solution:

$$V = L \times W \times D = 15 \text{ ft} \times 7 \text{ ft} \times 9 \text{ ft} = 945 \text{ ft}^3$$

For wastewater operators, representative surface areas are most often rectangles, triangles, circles, or a combination of these. Practical volume formulas used in water/wastewater calculations are given in Table 3.1. To determine the volume of round pipe and round surface areas, the following examples are helpful.

■ *Example 3.48*

Problem: Find the volume of a 3-in. round pipe that is 300 ft long.

Solution:

1. Change the diameter (D) of the pipe from inches to feet by dividing by 12:

$$D = 3 \div 12 = 0.25 \text{ ft}$$

2. Find the radius (R) by dividing the diameter by 2:

$$R = 0.25 \text{ ft} \div 2 = 0.125$$

3. Find the volume (V):

$$V = L \times \pi r^2 = 300 \text{ ft} \times 3.14 \times 0.0156 = 14.72 \text{ ft}^2$$

■ *Example 3.49*

Problem: Find the volume of a smokestack that is 24 in. in diameter (entire length) and 96 in. tall.

Solution: First find the radius of the stack. The radius is one half the diameter, so 24 in. ÷ 2 = 12 in. Now find the volume:

$$V = H \times \pi r^2 = 96 \text{ in.} \times \pi \times (12 \text{ in.})^2 = 96 \text{ in.} \times \pi \times 144 \text{ in.}^2 = 43{,}407 \text{ ft}^3$$

To determine the volume of a cone and sphere, we use the following equations and examples:

$$\text{Volume of cone} = \frac{\pi}{12} \times \text{Diameter} \times \text{Diameter} \times \text{Height} \tag{3.9}$$

$$\frac{\pi}{12} = \frac{3.14}{12} = 0.262$$

Note: The diameter used here is the diameter of the base of the cone.

■ *Example 3.50*

Problem: The bottom section of a circular settling tank has the shape of a cone. How many cubic feet of water are contained in this section of the tank if the tank has a diameter of 120 ft and the cone portion of the unit has a depth of 6 ft?

Solution:

$$\text{Volume of cone} = 0.262 \times 120\text{ ft} \times 120\text{ ft} \times 6\text{ ft} = 22{,}637\text{ ft}^3$$

$$\text{Volume of sphere} = \frac{\pi}{6} \times \text{Diameter} \times \text{Diameter} \times \text{Diameter} \tag{3.10}$$

$$\frac{\pi}{6} = \frac{3.14}{6} = 0.524$$

■ *Example 3.51*

Problem: What is the volume (in cubic feet) of a gas storage container that is spherical and has a diameter of 60 ft?

Solution:

$$\text{Volume (ft}^3) = 0.524 \times 60\text{ ft} \times 60\text{ ft} \times 60\text{ ft} = 113{,}184\text{ ft}^3$$

Circular process and various water and chemical storage tanks are commonly found in water/wastewater treatment. A circular tank consists of a circular floor surface with a cylinder rising above it (see Figure 3.8). The volume of a circular tank is calculated by multiplying the surface area times the height of the tank walls.

■ *Example 3.52*

Problem: If a tank is 20 feet in diameter and 25 feet deep, how many gallons of water will it hold?

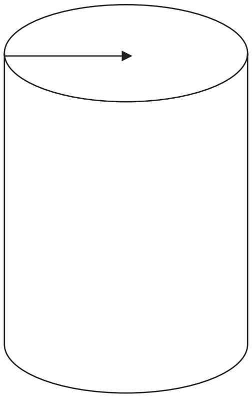

Figure 3.8 Circular or cylindrical water tank.

Hint: In this type of problem, calculate the surface area first, multiply by the height, and then convert to gallons.

Solution:

$$r = D \div 2 = 20 \text{ ft} \div 2 = 10 \text{ ft}$$

$$A = \pi \times r^2 = \pi \times 10 \text{ ft} \times 10 \text{ ft} = 314 \text{ ft}^2$$

$$V = \mathrm{A} \times \mathrm{H} = 314 \text{ ft}^2 \times 25 \text{ ft} = 7850 \text{ ft}^3 \times 7.5 \text{ gal/ft}^3 = 58{,}875 \text{ gal}$$

3.11 MASS BALANCE AND MEASURING PLANT PERFORMANCE

The simplest way to express the fundamental engineering principle of *mass balance* is to say, “Everything has to go somewhere.” More precisely, the *law of conservation of mass* says that when chemical reactions take place matter is neither created nor destroyed. This important concept allows us to track materials (e.g., pollutants, microorganisms, chemicals) from one place to another.

The concept of mass balance plays an important role in treatment plant operations (especially wastewater treatment) where we assume a balance exists between the material entering and leaving the treatment plant or a treatment process: “What comes in must equal what goes out.” The concept is very helpful in evaluating biological systems, sampling and testing procedures, and many other unit processes within the treatment system.

In the following sections, we illustrate how the mass balance concept is used to determine the quantity of solids entering and leaving settling tanks, as well as BOD removal.

3.11.1 Mass Balance for Settling Tanks

The mass balance for the settling tank calculates the quantity of solids entering and leaving the unit.

Note: The two numbers (in, influent; out, effluent) must be within 10 to 15% of each other to be considered acceptable. Larger discrepancies may indicate sampling errors, increasing solids levels in the unit, or undetected solids discharge in the tank effluent.

To get a better feel for how the mass balance for settling tanks procedure is formatted for actual use, consider the steps below that are used in Example 3.53:

1. Determine pounds of influent suspended solids.
2. Determine pounds of effluent suspended solids.
3. Calculate biosolids solids out (pounds of biosolids solids pumped per day).
4. Calculate mass balance = solids in – (solids out + biosolids solids pumped).

■ *Example 3.53*

Problem: A settling tank receives a daily flow of 4.20 MGD. The influent contains 252 mg/L suspended solids, and the unit effluent contains 140 mg/L suspended solids. The biosolids pump operates 10 min/hr and removes biosolids at the rate of 40 gpm. The biosolids is 4.2% solids. Determine if the mass balance for solids removal is within the acceptable 10 to 15% range.

Solution:

1. Solids in (influent) = 252 mg/L × 4.20 MGD × 8.34 = 8827 lb/day.
2. Solids out (effluent) = 140 mg/L × 4.20 MGD × 8.34 = 4904 lb/day.
3. Calculate biosolids solids out:

$$\text{Biosolids Solids} = 10\,\frac{\text{min}}{\text{hr}} \times 24\,\frac{\text{hr}}{\text{day}} \times 40\text{ gpm} \times 8.34 \times 0.042 = 3363\text{ lb/day}$$

4. Mass balance = 8827 lb/day – (4904 lb/day + 3363 lb/day) = 560 lb, or 6.3%.

3.11.2 Mass Balance Using BOD Removal

The amount of BOD removed by a treatment process is directly related to the quantity of solids the process will generate. Because the actual amount of solids generated will vary with operational conditions and design, exact figures must be determined on a case-by-case basis;

TABLE 3.2 GENERAL CONVERSION RATES

Process Type	Conversion Factor (lb solids/lb BOD removal)
Primary treatment	1.7
Trickling filters	1.0
Rotating biological contactors	1.0
Activated biosolids with primary	0.7
Activated biosolids without primary	
Conventional	0.85
Extended air	0.65
Contact stabilization	1.0
Step feed	0.85
Oxidation ditch	0.65

however, research has produced general conversion rates for many of the common treatment processes. These values are given in Table 3.2 and can be used if plant-specific information is unavailable.

Using these factors, the mass balance procedure determines the amount of solids the process is anticipated to produce. This is compared with the actual biosolids production to determine the accuracy of the sampling, the potential for solids buildup in the system, or unrecorded solids discharges.

1. BOD_{in} = Influent BOD × Flow × 8.34
2. BOD_{out} = Effluent BOD × Flow × 8.34.
3. BOD removed (lb) = $\text{BOD}_{\text{in}} - \text{BOD}_{\text{out}}$
4. Solids generated (lb) = BOD removed (lb) × Factor
5. Solids removed (lb/day) = Sludge pumped (gpd) × %Solids × 8.34
6. Effluent solids (mg/L) = Flow (MGD) × 8.34

■ *Example 3.54*

Problem: A conventional activated biosolids system with primary treatment is operating at the levels listed below. Does the mass balance for the activated biosolids system indicate that a problem exists?

Plant influent BOD = 250 mg/L

Primary effluent BOD = 166 mg/L

Activated biosolids system effluent BOD = 25 mg/L

Activated biosolids system effluent TSS = 19 mg/L

Plant flow = 11.40 MGD

Waste concentration = 6795 mg/L

Waste flow = 0.15 MGD

Solution:

$\text{BOD}_{\text{in}} = 166 \text{ mg/L} \times 11.40 \text{ MGD} \times 8.34 = 15{,}783 \text{ lb/day}$

$\text{BOD}_{\text{out}} = 25 \text{ mg/L} \times 11.40 \text{ MGD} \times 8.34 = 2377 \text{ lb/day}$

$\text{BOD removed} = 15{,}783 \text{ lb/day} - 2377 \text{ lb/day} = 13{,}406 \text{ lb/day}$

$\text{Solids produced} = 13{,}406 \text{ lb/day} \times 0.7 \text{ lb solids/lb BOD} = 9384 \text{ lb/day}$

$\text{Solids removed} = 6795 \text{ mg/L} \times 0.15 \text{ MGD} \times 8.34 = 8501 \text{ lb/day}$

$\text{Difference} = 9384 \text{ lb/day} - 8501 \text{ lb/day} = 883 \text{ lb/day, or } 9.4\%$

These results are within the acceptable range.

Note: We have demonstrated two ways in which mass balance can be used; however, it is important to note that the mass balance concept can be used for all aspects of wastewater and solids treatment. In each case, the calculations must take into account all of the sources of material entering the process and all of the methods available for removal of solids.

3.12 FORCE, PRESSURE, AND HEAD CALCULATIONS

Before we review calculations involving force, pressure, and head, we must first define these terms:

- *Force*—The push exerted by water on any confined surface. Force can be expressed in pounds, tons, grams, or kilograms.
- *Pressure*—The force per unit area. The most common way of expressing pressure is in pounds per square inch (psi).
- *Head*—The vertical distance or height of water above a reference point. Head is usually expressed in feet. In the case of water, head and pressure are related.
- *Force* vs. *pressure*—Figure 3.9 helps to illustrate these terms. A cubical container measuring 1 ft on each side can hold 1 ft^3 of water. A basic fact of science states that 1 ft^3 of water weighs 62.4 lb and contains 7.48 gal. The force acting on the bottom of the container

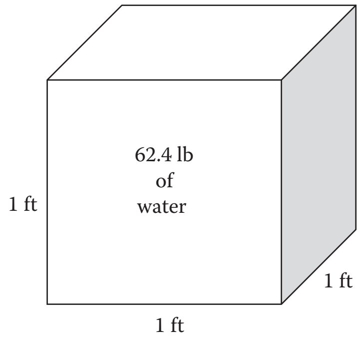

Figure 3.9 One cubic foot of water weighs 62.4 lb.

would be 62.4 pounds per square foot (lb/ft^2). The area of the bottom in square inches is:

$$1\ ft^2 = 12\ in. \times 12\ in. = 144\ in.^2$$

Therefore, the pressure in pounds per square inch (psi) is:

$$\frac{62.4\ lb/ft^2}{1\ ft^2} = \frac{62.4\ lb/ft^2}{144\ in.^2/ft^2} = 0.433\ lb/in.^2\ (psi)$$

If we use the bottom of the container as our reference point, then the head would be 1 ft. From this, we can see that 1 ft of head is equal to 0.433 psi, which is an important parameter to remember. Figure 3.10 illustrates some other important relationships between pressure and head. Based on this information, we can develop the following equations for calculating pressure and head:

Key Point: Force acts in a particular direction. Water in a tank exerts force down on the bottom and out of the sides. Pressure, however, acts in all directions. A marble at a water depth of 1 ft would have 0.433 psi of pressure acting inward on all sides.

$$\text{Pressure (psi)} = 0.433 \times \text{Head (ft)} \tag{3.11}$$

$$\text{Head (ft)} = 2.31 \times \text{Pressure (psi)} \tag{3.12}$$

3.12.1 Head

As mentioned, head is the vertical distance the water must be lifted from the supply tank or unit process to the discharge. The total head includes the vertical distance the liquid must be lifted (*static head*), the loss to friction (*friction head*), and the energy required to maintain the desired velocity (*velocity head*):

$$\text{Total Head} = \text{Static Head} + \text{Friction Head} + \text{Velocity Head} \tag{3.13}$$

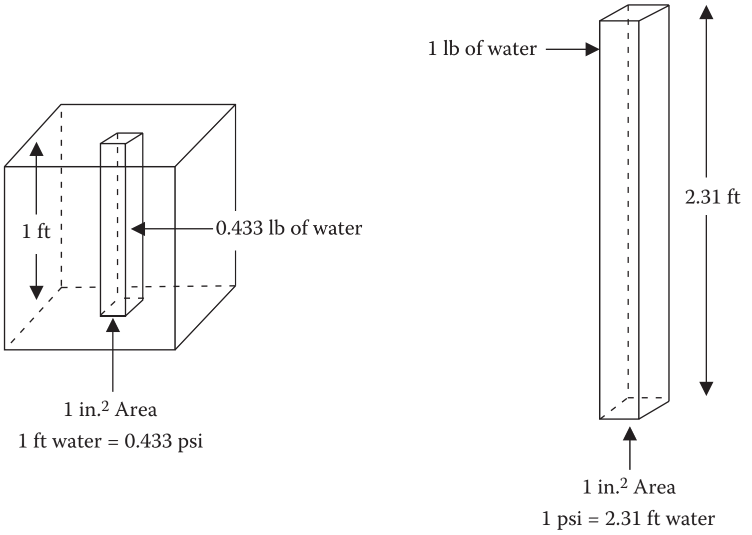

Figure 3.10 Relationship between pressure and head.

3.12.2 Static Head

Static head is the actual vertical distance the liquid must be lifted.

$$\text{Static Head} = \text{Discharge Elevation} - \text{Supply Elevation} \tag{3.14}$$

■ ***Example 3.55***

Problem: The supply tank is located at elevation 108 ft. The discharge point is at elevation 205 ft. What is the static head in feet?

Solution:

$$\text{Static Head (ft)} = 205\text{ ft} - 108\text{ ft} = 97\text{ ft}$$

3.12.3 Friction Head

Friction head is the equivalent distance of the energy that must be supplied to overcome friction. Engineering references include tables showing the equivalent vertical distance for various sizes and types of pipes, fittings, and valves. The total friction head is the sum of the equivalent vertical distances for each component:

$$\text{Friction Head (ft)} = \text{Energy losses due to friction} \tag{3.15}$$

3.12.4 Velocity Head

Velocity head is the equivalent distance of the energy consumed in achieving and maintaining the desired velocity in the system:

$$\text{Velocity Head (ft)} = \text{Energy losses to maintain velocity} \tag{3.16}$$

3.12.5 Total Dynamic Head (Total System Head)

$$\text{Total head} = \text{Static Head} + \text{Friction Head} + \text{Velocity Head} \tag{3.17}$$

3.12.6 Pressure and Head

The pressure exerted by water/wastewater is directly proportional to its depth or head in the pipe, tank, or channel. If the pressure is known, the equivalent head can be calculated:

$$\text{Head (ft)} = \text{Pressure (psi)} \times 2.31\text{ ft/psi} \tag{3.18}$$

■ ***Example 3.56***

Problem: The pressure gauge on the discharge line from the influent pump reads 75.3 psi. What is the equivalent head in feet?

Solution:

$$\text{Head (ft)} = 75.3 \times 2.31\text{ ft/psi} = 173.9\text{ ft}$$

3.12.7 Head and Pressure

If the head is known, the equivalent pressure can be calculated by:

$$\text{Pressure (psi)} = \frac{\text{Head (ft)}}{2.31 \text{ ft/psi}} \tag{3.19}$$

■ ***Example 3.57***

Problem: A tank is 15 feet deep. What is the pressure in psi at the bottom of the tank when it is filled with wastewater?

Solution:

$$\text{Pressure (psi)} = \frac{15 \text{ ft}}{2.31 \text{ ft/psi}} = 6.49 \text{ psi}$$

Before we look at a few example problems dealing with force, pressure, and head, it is important to review the key points related to force, pressure, and head:

1. By definition, water weighs 62.4 lb/ft^3.
2. The surface of any one side of a 1-ft^3 cube contains 144 in.^{2} (12 in. × 12 in. = 144 in.^{2}); therefore, the cube contains 144 columns of water that are 1 ft tall and 1 inch square.
3. The weight of each of these pieces can be determined by dividing the weight of the water in the cube by the number of square inches:

$$\text{Weight} = \frac{62.4 \text{ lb}}{144 \text{ in.}^2} = 0.433 \text{ lb/in.}^2 \text{ or } 0.433 \text{ psi}$$

4. Because this is the weight of one column of water 1 ft tall, the true expression would be 0.433 pounds per square inch per foot of head, or 0.433 psi/ft.

Note: 1 foot of head = 0.433 psi.

In addition to remembering the important parameter that 1 ft of head = 0.433 psi, it is important to understand the relationship between pressure and feet of head—in other words, how many feet of head 1 psi represents. This is determined by dividing 1 ft by 0.433 psi:

$$\text{Feet of head} = \frac{1 \text{ ft}}{0.433 \text{ psi}} = 2.31 \text{ ft/psi}$$

If a pressure gauge reads 12 psi, the height of the water necessary to represent this pressure would be 12 psi × 2.31 ft/psi = 27.7 feet.

Note: Both of the above conversions are commonly used in water/wastewater treatment calculations; however, the most accurate conversion is 1 ft = 0.433 psi. This is the conversion we use throughout this text.

■ *Example 3.58*

Problem: Convert 40 psi to feet head.

Solution:

$$\frac{40\text{ psi}}{1} \times \frac{\text{ft}}{0.433\text{ psi}} = 92.4\text{ ft}$$

■ *Example 3.59*

Problem: Convert 40 ft to psi.

Solution:

$$40\frac{\text{ft}}{1} \times \frac{0.433\text{ psi}}{1\text{ ft}} = 17.32\text{ psi}$$

As the above examples demonstrate, when attempting to convert psi to feet we *divide* by 0.433, and when attempting to convert feet to psi we *multiply* by 0.433. The above process can be most helpful in clearing up confusion about whether to multiply or divide; however, there is another approach that may be more beneficial and easier for many operators to use. Notice that the relationship between psi and feet is almost 2 to 1. It takes slightly more than 2 feet to make 1 psi; therefore, in a problem where the data are provided in pressure and the result should be in feet, the answer will be at least twice as large as the starting number. For instance, if the pressure were 25 psi, we intuitively know that the head is over 50 feet, so we must divide by 0.433 to obtain the correct answer.

■ *Example 3.60*

Problem: Convert a pressure of 45 psi to feet of head.

Solution:

$$45\frac{\text{psi}}{1} \times \frac{1\text{ ft}}{0.433\text{ psi}} = 104\text{ ft}$$

■ *Example 3.61*

Problem: Convert 15 psi to feet.

Solution:

$$15\frac{\text{psi}}{1} \times \frac{1\text{ ft}}{0.433\text{ psi}} = 34.6\text{ ft}$$

■ *Example 3.62*

Problem: Between the top of a reservoir and the watering point, the elevation is 125 feet. What will the static pressure be at the watering point?

Solution:

$$125\,\frac{\text{psi}}{1} \times \frac{1\text{ ft}}{0.433\text{ psi}} = 288.7\text{ ft}$$

■ *Example 3.63*

Problem: Find the pressure (psi) in a tank 12 ft deep at a point 5 ft below the water surface.

Solution:

$$\text{Pressure (psi)} = 0.433 \times 5\text{ ft} = 2.17\text{ psi}$$

■ *Example 3.64*

Problem: A pressure gauge at the bottom of a tank reads 12.2 psi. How deep is the water in the tank?

Solution:

$$\text{Head (ft)} = 2.31 \times 12.2\text{ psi} = 28.2\text{ ft}$$

■ *Example 3.65*

Problem: What is the pressure (static pressure) 4 miles beneath the ocean surface?

Solution: Change miles to feet, then to psi:

$$5280\text{ ft/mile} \times 4 = 21{,}120\text{ ft}$$

$$\frac{21{,}120\text{ ft}}{2.31\text{ ft/psi}} = 9143\text{ psi}$$

■ *Example 3.66*

Problem: A 150-ft-diameter cylindrical tank contains 2.0 MG water. What is the water depth? At what pressure would a gauge at the bottom read in psi?

Solution:

1. Change MG to cubic feet:

$$\frac{2{,}000{,}000\text{ gal}}{7.48} = 267{,}380\text{ ft}^3$$

2. Using volume, solve for depth:

$$\text{Volume} = .785 \times D^2 \times \text{Depth}$$

$$267{,}380\ \text{ft}^3 = .785 \times (150)^2 \times \text{Depth}$$

$$\text{Depth} = 15.1\ \text{ft}$$

■ *Example 3.67*

Problem: The pressure in a pipe is 70 psi. What is the pressure in feet of water? What is the pressure in psf?

Solution:

1. Convert pressure to feet of water:

$$70\ \text{psi} \times 2.31\ \text{ft/psi} = 161.7\ \text{ft of water}$$

2. Convert psi to psf:

$$70\ \text{psi} \times 144\ \text{in.}^2/\text{ft}^2 = 10{,}080\ \text{psf}$$

■ *Example 3.68*

Problem: The pressure in a pipeline is 6476 psf. What is the head on the pipe?

$$\text{Head on pipe} = \text{Feet of pressure}$$

$$\text{Pressure} = \text{Weight} \times \text{Height}$$

$$6476\ \text{psf} = 62.4\ \text{lb/ft}^3 \times \text{Height}$$

$$\text{Height} = 104\ \text{ft}$$

3.13 MOVING AVERAGE

When performing process control calculations, the use of a 7-day moving average is recommended. The moving average is a mathematical method to level the impact of any one test result. The moving average is determined by adding the test results collected during the past 7 days and dividing by the number of tests:

$$\text{Moving Avg.} = \frac{\text{Test 1} + \text{Test 2} + \text{Test 3} + \text{Test 4} + \text{Test 5} + \text{Test 6} + \text{Test 7}}{\text{No. of tests performed during the 7 days}}$$

■ *Example 3.69*

Problem: Calculate the 7-day moving average for days 7, 8, and 9:

Day	MLSS	Day	MLSS
1	3340	6	2780
2	2480	7	2476
3	2398	8	2756
4	2480	9	2655
5	2558	10	2396

Solution:

$$\text{Moving Avg., day 7} = \frac{3340 + 2480 + 2398 + 2480 + 2558 + 2780 + 2476}{7} = 2645$$

$$\text{Moving Avg., day 8} = \frac{2480 + 2398 + 2480 + 2558 + 2780 + 2476 + 2756}{7} = 2561$$

$$\text{Moving Avg., day 9} = \frac{2398 + 2480 + 2558 + 2780 + 2476 + 2756 + 2655}{7} = 2586$$

3.14 CHAPTER REVIEW QUESTIONS

Note: Answers to chapter review questions are provided in Appendix A.

3.1 $56 - 7 + 25 \div 5 \times 7 \times 3 \div 15 - 7 \times 8 =$ ____________?

3.2 What is the circumference in feet of a circle that is 140 ft in diameter?

3.3 What is the area in square feet of a rectangle that is 120 ft long and 60 ft wide?

3.4 A circular tank is 20 ft deep at the outer wall. The bottom of the tank is cone shaped, and the depth at the center of the tank is 25 ft. If the tank is 80 ft in diameter, what is the total volume of the tank, including the cone-shaped portion at the bottom?

3.5 The sludge contains 6.50% solids. If 8000 gal of sludge are removed from the primary settling tank, how many pounds of solids are removed?

3.6 A lab test indicates that a 600-g sample of sludge contains 20 g of solids. What is the percent solids in the sludge sample?

3.7 A lab test indicates that a 500-g sample of sludge contains 20 g of solids. What is the percent solids in the sludge sample?

Use the following information for Questions 3.8 to 3.12:

Primary settling tank

Number = 3

Length = 130 ft

Width = 110 ft

Water depth = 12 ft

Aeration tank

Number = 4

Length = 250 ft

Width = 110 ft

Water depth = 14 ft

Secondary settling tank

Number = 4

Diameter = 100 ft

Water depth = 18 ft

3.8 The effluent weir on the secondary settling tank is located along the outer edge of the tank. What is the weir length in feet for each settling tank?

3.9 What is the surface area of each of the primary settling tanks in square feet?

3.10 What is the volume of each of the aeration tanks in cubic feet?

3.11 You wish to install a fence around each aeration tank to prevent falls into the tanks. How many feet of fence must be ordered?

3.12 The secondary settling tanks consist of a cylindrical section 18 ft deep and a cone-shaped bottom that has a depth of 10 ft. What is the total volume of each settling tank in cubic feet?

Use the following information for Questions 3.13 and 3.14:

	Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**	**Day 8**	**Day 9**
BOD	19	21	34	45	12	17	78	53	10
TSS	23	34	19	31	5	27	93	34	9
Fecal	1	21	123	2	10	230	13	23	1100

3.13 What is the average BOD for the period covered by the data provided above?

3.14 What is the 7-day moving average for TSS on day 8 and day 9?

REFERENCES AND RECOMMENDED READING

Price, J.K. (1991). *Basic Math Concepts: For Water and Wastewater Plant Operators*. Lancaster, PA: Technomic Publishing Company.

Spellman, F.R. (2004). *Mathematics for Water and Wastewater Operators*. Boca Raton, FL: CRC Press.

CHAPTER 4

CONVERSIONS

4.1 CONVERSION FACTORS

Sometimes we have to convert between different units. Suppose that a 60-inch piece of wood is attached to a 6-foot piece of wood. How long are they together? Obviously, we cannot find the answer to this question by adding 60 to 6, because the two figures are given in different units. Before we can add the two numbers, we have to convert one of them to the unit of the other. When we have two numbers in the same units, then we can add them.

To perform this conversion, we need a *conversion factor*. In this case, we need to know how many inches make up a foot: 12 inches = 1 foot. Knowing this, we can perform the calculation in two steps:

1. 60 inches is really 60/12 = 5 feet
2. 5 feet + 6 feet = 11 feet

From this example, it can be seen that a conversion factor changes known quantities in one unit of measure to an equivalent quantity in another unit of measure.

To make the conversion from one unit to another, we must know two things:

1. The exact number that relates the two units
2. Whether to multiply or divide by that number

When making conversions, confusion over whether to multiply or divide is common; on the other hand, the number that relates the two units is usually known and, thus, is not a problem. Understanding the proper methodology—the "mechanics"—to use for various operations requires practice and common sense. Along with using the proper mechanics (and practice and common sense) in making conversions, probably the easiest and fastest method to convert units is to use a conversion table.

The simplest conversion requires that the measurement be multiplied or divided by a constant value. For example, in wastewater treatment, if the depth of biosolids on a drying bed is 0.85 feet, multiplying by 12 inches per foot converts the measured depth to inches (10.2 inches). Likewise, if the depth of the solids blanket in the secondary clarifier is measured as 16 inches, dividing by 12 inches per foot converts the depth measurement to feet (1.33 feet).

Key Point: To convert in the opposite direction (i.e., inches to feet), divide by the factor rather than multiply.

Table 4.1 lists many of the conversion factors used in water/wastewater treatment. Note that Table 4.1 is designed with a unit of measure in the left and right columns and a constant (conversion factor) in the center column.

4.1.1 Weight, Concentration, and Flow

Using Table 4.1 to convert from one unit expression to another and *vice versa* is good practice; however, when making conversions to solve process computations in wastewater treatment, we must be familiar with conversion calculations based upon a relationship among weight, concentration, and flow or volume. The basic relationship is:

$$\text{Weight} = \text{Concentration} \times \text{Flow or Volume} \times \text{Factor} \qquad (4.1)$$

Table 4.2 summarizes weight, volume, and concentration calculations. With practice, many of these calculations become second nature to operators; the calculations are important relationships and are used often in wastewater treatment process control calculations, so on-the-job practice is possible.

The following conversion factors are used extensively in wastewater operations and are commonly required to solve problems on licensure examinations; the operator should keep them in hand, within easy grasp:

- 7.48 gallons per ft^3
- 3.785 liters per gallon
- 454 grams per pound
- 1000 milliliters per liter
- 1000 milligrams per gram
- 1 cubic foot per second (cfs) = 0.6465 million gallons per day (MGD)

TABLE 4.1 CONVERSION TABLE

To Convert	Multiply by	To Get
Feet	12	Inches
Yards	3	Feet
Yards	36	Inches
Inches	2.54	Centimeters
Meters	3.3	Feet
Meters	100	Centimeters
Meters	1000	Millimeters
Square yards	9	Square feet
Square feet	144	Square inches
Acres	43,560	Square feet
Cubic yards	27	Cubic feet
Cubic feet	1728	Cubic inches
Cubic feet (water)	7.48	Gallons
Cubic feet (water)	62.4	Pounds
Acre-feet	43,560	Cubic feet
Gallons (water)	8.34	Pounds
Gallons (water)	3.785	Liters
Gallons (water)	3785	Milliliters
Gallons (water)	3785	Cubic centimeters
Gallons (water)	3785	Grams
Liters	1000	Milliliters
Days	24	Hours
Days	1440	Minutes
Days	86,400	Seconds
Million gallons/day	1,000,000	Gallons/day
Million gallons/day	1.55	Cubic feet/second
Million gallons/day	3.069	Acre-feet/day
Million gallons/day	36.8	Acre-inches/day
Million gallons/day	3785	Cubic meters/day
Gallons/minute	1440	Gallons/day
Gallons/minute	63.08	Liters/minute
Pounds	454	Grams
Grams	1000	Milligrams
Pressure (psi)	2.31	Head (water) (ft)
Horsepower	33,000	Foot-pounds/minute
Horsepower	0.746	Kilowatts
To Get	**Divide by**	**To Convert**

Note: Density (also called *specific weight*) is mass per unit volume and may be measured as lb/ft^3, lb/gal, g/mL, or g/m^3. If we take a fixed-volume container, fill it with a fluid, and weigh it, we can determine the density of the fluid (after subtracting the weight of the container).

- Water weighs 8.34 lb/gal (density = 8.34 lb/gal)
- 1 milliliter of water weighs 1 gram (density = 1 g/mL)
- Water weighs 62.4 lb/ft^3 (density = 8.34 lb/gal)
- 8.34 lb/gal = mg/L (converts dosage in mg/L into lb/day/MGD); for example, 1 mg/L × 10 MGD × 8.34 lb/gal = 83.4 lb/day

TABLE 4.2 WEIGHT, VOLUME, AND CONCENTRATION CALCULATIONS

To Calculate	Use This Formula
Pounds	Concentration (mg/L) × Tank Volume (MG) × 8.34 lb/MG/mg/L
Pounds/day	Concentration (mg/L) × Flow (MGD) × 8.34 lb/MG/mg/L
Million gallons/day	$\frac{\text{Quantity (lb/day)}}{\text{Concentration (mg/L)} \times 8.34\ \text{lb/MG/mg/L}}$
Milligrams/liter	$\frac{\text{Quantity (lb)}}{\text{Tank Volume (MG)} \times 8.34\ \text{lb/MG/mg/L}}$
Kilograms/liter	Concentration (mg/L) × Volume (MG) × 3.785 lb/MG/mg/L
Kilograms/day	Concentration (mg/day) × Flow (MGD) × 3.785 lb/MG/mg/L
Pounds/dry ton	Concentration (mg/kg) × 0.002 lb/dt/mg/kg

- 1 psi = 2.31 feet of water (head)
- 1 foot head = 0.433 psi
- $°F = 9/5(°C + 32)$
- $°C = 5/9(°F - 32)$
- Average water usage: 100 gallons/capita/day (gpcd)
- Persons per single-family residence: 3.7

4.1.2 Table Conversions

Note: Use Table 4.1 and Table 4.2 to make the conversions indicated in the following example problems. Other conversions are presented in appropriate sections of the text.

■ *Example 4.1*

Use the following to convert cubic feet (ft^3) to gallons (gal):

$$\text{Gallons} = \text{ft}^3 \times \text{gal/ft}^3$$

Problem: How many gallons of biosolids can be pumped to a digester that has 3600 ft^3 of volume available?

Solution:

$$\text{Gallons} = 3600\ \text{ft}^3 \times 7.48\ \text{gal/ft}^3 = 26{,}928\ \text{gal}$$

■ *Example 4.2*

Use the following to convert gallons (gal) to cubic feet (ft^3):

$$\text{Cubic feet} = \frac{\text{Gallons}}{7.48\ \text{gal/ft}^3}$$

Problem: How many cubic feet of biosolids are removed when 18,200 gal are withdrawn?

Solution:

$$\text{Cubic feet} = \frac{18{,}200 \text{ gal}}{7.48 \text{ gal/ft}^3} = 2433 \text{ ft}^3$$

■ *Example 4.3*

Use the following to convert gallons (gal) to pounds (lb):

$$\text{Pounds (lb)} = \text{Gallons} \times 8.34 \text{ lb/gal}$$

Problem: If 1650 gallons of solids are removed from the primary settling tank, how many pounds of solids are removed?

Solution:

$$\text{Pounds} = 1650 \text{ gal} \times 8.34 \text{ lb/gal} = 13{,}761 \text{ lb}$$

■ *Example 4.4*

Use the following to convert pounds (lb) to gallons (gal):

$$\text{Gallons} = \frac{\text{Pounds}}{8.34 \text{ lb/gal}}$$

Problem: How many gallons of water are required to fill a tank that holds 7540 pounds of water?

Solution:

$$\text{Gallons} = \frac{7540 \text{ lb}}{8.34 \text{ lb/gal}} = 904 \text{ gal}$$

■ *Example 4.5*

Use the following to convert milligrams per liter (mg/L) to pounds (lb):

$$\text{Pounds} = \text{Concentration (mg/L)} \times \text{Volume (MG)} \times 8.34 \text{ lb/MG/mg/L}$$

Note: For many operations, concentrations in milligrams per liter or parts per million determined by laboratory testing must be converted to quantities of pounds, kilograms, pounds per day, or kilograms per day.

Problem: The solids concentration in the aeration tank is 2580 mg/L. The aeration tank volume is 0.95 MG. How many pounds of solids are in the tank?

Solution:

$$\text{Pounds} = 2580\ \text{mg/L} \times 0.95\ \text{MG} \times 8.34\ \text{lb/MG/mg/L} = 20{,}441.3\ \text{lb}$$

■ *Example 4.6*

Use the following to convert milligrams per liter (mg/L) to pounds per day (lb/day):

$$\text{Pounds per day} = \text{Concentration (mg/L)} \times \text{Flow (MGD)} \times 8.34\ \text{lb/MG/mg/L}$$

Problem: How many pounds of solids are discharged per day when the plant effluent flow rate is 4.75 MGD and the effluent solids concentration is 26 mg/L?

Solution:

$$\text{Pounds per day} = 26\ \text{mg/L} \times 4.75\ \text{MGD} \times 8.34\ \text{lb/MG/mg/L} = 1030\ \text{lb/day}$$

■ *Example 4.7*

Use the following to convert milligrams per liter (mg/L) to kilograms per day (kg/day):

$$\text{kg/day} = \text{Concentration (mg/L)} \times \text{Volume (MG)} \times 3.785\ \text{kg/MG/mg/L}$$

Problem: The effluent contains 26 mg/L of BOD_5. How many kilograms per day of BOD_5 are discharged when the effluent flow rate is 9.5 MGD?

Solution:

$$\text{kg/day} = 26\ \text{mg/L} \times 9.5\ \text{MG} \times 3.785\ \text{kg/MG/mg/L} = 934\ \text{kg/day}$$

■ *Example 4.8*

Use the following to convert pounds (lb) to milligrams per liter (mg/L):

$$\text{Concentration (mg/L)} = \frac{\text{Quantity (lb)}}{\text{Volume (MG)} \times 8.34\ \text{lb/MG/mg/L}}$$

Problem: The aeration tank contains 89,990 pounds of solids. The volume of the aeration tank is 4.45 MG. What is the concentration of solids in the aeration tank in milligrams per liter?

Solution:

$$\text{Concentration} = \frac{89{,}990\ \text{lb}}{4.45\ \text{MG} \times 8.34\ \text{lb/MG/mg/L}} = 2425\ \text{mg/L}$$

■ *Example 4.9*

Use the following to convert pounds per day (lb/day) to milligrams per liter (mg/L):

$$\text{Concentration (mg/L)} = \frac{\text{Quantity (lb/day)}}{\text{Volume (MGD)} \times 8.34\ \text{lb/MG/mg/L}}$$

Problem: The disinfection process uses 4820 pounds per day of chlorine to disinfect a flow of 25.2 MGD. What is the concentration of chlorine applied to the effluent?

Solution:

$$\text{Concentration} = \frac{4820\ \text{lb/day}}{25.2\ \text{MGD} \times 8.34\ \text{lb/MG/mg/L}} = 22.9\ \text{mg/L}$$

■ *Example 4.10*

Use the following to convert pounds (lb) to flow in million gallons per day (MGD):

$$\text{Flow (MGD)} = \frac{\text{Quantity (lb/day)}}{\text{Concentration (mg/L)} \times 8.34\ \text{lb/MG/mg/L}}$$

Problem: 9640 pounds of solids must be removed from the activated biosolids process per day. The waste activated biosolids concentration is 7699 mg/L. How many million gallons per day of waste activated biosolids must be removed?

Solution:

$$\text{Flow} = \frac{9640\ \text{lb/day}}{7699\ \text{mg/L} \times 8.34\ \text{lb/MG/mg/L}} = 0.15\ \text{MGD}$$

■ *Example 4.11*

Use the following to convert million gallons per day (MGD) to gallons per minute (gpm):

$$\text{Flow (gpm)} = \frac{\text{Flow (MGD)} \times 1{,}000{,}000\ \text{gal/MG}}{1440\ \text{min/day}}$$

Problem: The current flow rate is 5.55 MGD. What is the flow rate in gallons per minute?

Solution:

$$\text{Flow} = \frac{5.55\ \text{MGD} \times 1{,}000{,}000\ \text{gal/MG}}{1440\ \text{min/day}} = 3854\ \text{gpm}$$

■ *Example 4.12*

Use the following to convert million gallons per day (MGD) to gallons per day (gpd):

$$\text{Flow (gpd)} = \text{Flow (MGD)} \times 1{,}000{,}000 \text{ gal/MG}$$

Problem: The influent meter reads 28.8 MGD. What is the current flow rate in gallons per day?

Solution:

$$\text{Flow} = 28.8 \text{ MGD} \times 1{,}000{,}000 \text{ gal/MG} = 28{,}800{,}000 \text{ gpd}$$

■ *Example 4.13*

Use the following to convert million gallons per day (MGD) to cubic feet per second (cfs):

$$\text{Flow (cfs)} = \text{Flow (MGD)} \times 1.55 \text{ cfs/MGD}$$

Problem: The flow rate entering the grit channel is 2.89 MGD. What is the flow rate in cubic feet per second?

Solution:

$$\text{Flow} = 2.89 \text{ MGD} \times 1.55 \text{ cfs/MGD} = 4.48 \text{ cfs}$$

■ *Example 4.14*

Use the following to convert gallons per minute (gpm) to million gallons per day (MGD):

$$\text{Flow (MGD)} = \frac{\text{Flow (gpm)} \times 1440 \text{ min/day}}{1{,}000{,}000 \text{ gal/MG}}$$

Problem: The flow meter indicates that the current flow rate is 1469 gpm. What is the flow rate in MGD?

Solution:

$$\text{Flow} = \frac{1469 \text{ gpm} \times 1440 \text{ min/day}}{1{,}000{,}000 \text{ gal/MG}} = 2.12 \text{ MGD (rounded)}$$

■ *Example 4.15*

Use the following to convert gallons per day (gpd) to million gallons per day (MGD):

$$\text{Flow (MGD)} = \frac{\text{Flow (gpd)}}{1{,}000{,}000 \text{ gal/MG}}$$

Problem: The totalizing flow meter indicates that 33,444,950 gal of wastewater have entered the plant in the past 24 hr. What is the flow rate in MGD?

Solution:

$$\text{Flow} = \frac{33{,}444{,}950 \text{ gpd}}{1{,}000{,}000 \text{ gal/MG}} = 33.44 \text{ MGD}$$

■ *Example 4.16*

Use the following to convert flow in cubic feet per second (cfs) to million gallons per day (MGD):

$$\text{Flow (MGD)} = \frac{\text{Flow (cfs)}}{1.55 \text{ cfs/MG}}$$

Problem: The flow in a channel is determined to be 3.89 cfs. What is the flow rate in million gallons per day?

Solution:

$$\text{Flow} = \frac{3.89 \text{ cfs}}{1.55 \text{ cfs/MG}} = 2.5 \text{ MGD}$$

■ *Example 4.17*

Problem: The water in a tank weighs 675 lb. How many gallons does it hold?

Solution: Water weighs 8.34 lb/gal; therefore:

$$\text{Gallons} = \frac{675 \text{ lb}}{8.34 \text{ lb/gal}} = 80.9 \text{ gal}$$

■ *Example 4.18*

Problem: A liquid chemical weighs 62 lb/ft^3. How much does a 5-gal can of it weigh?

Solution: Solve for specific gravity, get lb/gal, and multiply by 5.

$$\text{Specific Gravity} = \frac{\text{Weight of chemical}}{\text{Weight of water}} = \frac{62 \text{ lb/ft}^3}{62.4 \text{ lb/ft}^3} = .99$$

$$.99 = \frac{\text{Weight of chemical (lb/gal)}}{8.34 \text{ lb/gal}}$$

$$.99 \times 8.34 \text{ lb/gal} = 8.26 \text{ lb/gal}$$

$$8.26 \text{ lb/gal} \times 5 \text{ gal} = 41.3 \text{ lb}$$

■ *Example 4.19*

Problem: A wooden piling with a diameter of 16 in. and a length of 16 ft weighs 50 lb/ft^3. If it is inserted vertically into a body of water, what vertical force is required to hold it below the water surface?

Solution: If this piling had the same weight as water, it would rest just barely submerged. Find the difference between its weight and that of the same volume of water. That is the weight required to keep it down.

$$62.4 \text{ lb/ft}^3 \text{ (water)} - 50.0 \text{ lb/ft}^3 \text{ (piling)} = 12.4 \text{ lb/ft}^3$$

$$\text{Volume of piling} = .785 \times 1.332 \times 16 \text{ ft} = 22.21 \text{ ft}^3$$

$$\text{Weight to hold piling down} = 12.4 \text{ lb/ft}^3 \times 22.21 \text{ ft}^3 = 275.4 \text{ lb}$$

■ *Example 4.20*

Problem: A liquid chemical with a specific gravity (SG) of 1.22 is pumped at a rate of 40 gpm. How many pounds per day are being delivered by the pump?

Solution: Solve for pounds pumped per minute, then change to lb/day.

$$8.34 \text{ lb/gal water} \times 1.22 \text{ SG liquid chemical} = 10.2 \text{ lb/gal liquid}$$

$$40 \text{ gal/min} \times 10.2 \text{ lb/gal} = 408 \text{ lb/min}$$

$$408 \text{ lb/min} \times 440 \text{ min/day} = 587{,}520 \text{ lb/day}$$

■ *Example 4.21*

Problem: A cinder block weighs 70 lb in air. When immersed in water, it weighs 40 lb. What are the volume and specific gravity of the cinder block?

Solution: The cinder block displaces 30 lb of water; solve for cubic feet of water displaced (equivalent to volume of cinder block).

$$\frac{30 \text{ lb water displaced}}{62.4 \text{ lb/ft}^3} = .48 \text{ ft}^3 \text{ water displaced}$$

Cinder block volume = .48 ft^3; weight = 70 lb.

$$\frac{70 \text{ lb}}{.48 \text{ ft}^3} = 145.8 \text{ lb/ft}^3 \text{ density of cinder block}$$

$$\text{Specific Gravity} = \frac{\text{Density of cinder block}}{\text{Density of water}} = \frac{145.8}{62.4} = 2.34$$

4.1.3 Temperature Conversions

Most wastewater operators are familiar with the formulas used for Fahrenheit and Celsius temperature conversions:

$$°C = 5/9(°F - 32)$$

$$°F = 9/5(°C) + 32$$

The difficulty arises when one tries to recall these formulas from memory. Probably the easiest way to recall these important formulas is to remember three basic steps for both Fahrenheit and Celsius conversions:

1. Add 40°.
2. Multiply by the appropriate fraction (5/9 or 9/5).
3. Subtract 40°.

Obviously, the only variable in this method is the choice of 5/9 or 9/5 in the multiplication step. To make the proper choice, you must be familiar with the two scales. The freezing point of water is 32° on the Fahrenheit scale and 0° on the Celsius scale. The boiling point of water is 212° on the Fahrenheit scale and 100° on the Celsius scale. What does all this mean?

Note: Notice, for example, that at the same temperature, higher numbers are associated with the Fahrenheit scale and lower numbers with the Celsius scale. This important relationship helps you decide whether to multiply by 5/9 or 9/5. Let's look at a few conversion problems to see how the three-step process works.

■ *Example 4.22*

Suppose that we wish to convert 240°F to Celsius. Using the three-step process, we proceed as follows:

1. Add 40°:

   $$240° + 40° = 280°$$

2. We must multiply 280° by either 5/9 or 9/5. Because the conversion is to the Celsius scale, we will be moving to a number smaller than 280. Through reason and observation, obviously, if 280 were multiplied by 9/5, the result would be almost the same as multiplying by 2, which would double 280 rather than make it smaller. If we multiply by 5/9, the result will be about the same as multiplying by 1/2, which would cut 280 in half. Because in this problem we wish to move to a smaller number, we should multiply by 5/9:

   $$(5/9) \times (380°) = 156.0°C$$

3. Now subtract 40°:

   $$156.0°C - 40.0°C = 116.0°C$$

   Therefore, 240°F = 116.0°C.

■ ***Example 4.23***

Problem: Convert 22°C to Fahrenheit.

Solution:

1. Add 40°:

$$22° + 40° = 62°$$

Because we are converting from Celsius to Fahrenheit, we are moving from a smaller to a larger number, and 9/5 should be used in the multiplications.

2. Multiply by 9/5:

$$(9/5) \times (62°) = 112°$$

3. Subtract 40:

$$112° - 40° = 72°$$

Thus, 22°C = 72°F.

Obviously, knowing how to make these temperature conversion calculations is useful; however, in practical *in situ* or non-*in situ* operations, you may wish to use a temperature conversion table.

4.1.4 Population Equivalent or Unit Loading Factor

When a wastewater characterization study is required, pertinent data are often unavailable. When this is the case, *population equivalent* or *unit per capita loading* factors are used to estimate the total waste loadings to be treated. If we know the BOD contribution of a discharger, we can determine the loading placed upon the wastewater treatment system in terms of equivalent number of people. The BOD contribution of a person is normally assumed to be 0.17 lb BOD/day. To determine the population equivalent of a wastewater flow, divide the lb BOD/day content by the lb BOD/day contributed per person (e.g., 0.17 lb BOD/day).

$$\text{PE (people)} = \frac{\text{BOD}_5 \text{ concentration (lb/day)}}{0.17 \text{ lb BOD}_5\text{/day/person}} \tag{4.2}$$

■ ***Example 4.24***

Problem: A new industry wishes to connect to the city's collection system. The industrial discharge will contain an average BOD concentration of 389 mg/L, and the average daily flow will be 72,000 gpd. What is the population equivalent of the industrial discharge?

Solution: First, convert flow rate to million gallons per day:

$$\text{Flow} = \frac{72{,}000 \text{ gpd}}{1{,}000{,}000 \text{ gal/MG}} = 0.072 \text{ MGD}$$

Next, calculate the population equivalent:

$$\text{PE (people)} = \frac{389\text{ mg/L} \times 0.072\text{ MGD} \times 8.34\text{ lb/MG/mg/L}}{0.17\text{ lb BOD/person/day}} = 1374\text{ people}$$

■ *Example 4.25*

Problem: An industry proposes to discharge 3455 lb of BOD_5 to the town sewer system. What is the population equivalent of the proposed discharge?

Solution:

$$\text{PE} = \frac{3455\text{ lb/day}}{0.17\text{ lb BOD/person/day}} = 20{,}324\text{ people}$$

■ *Example 4.26*

Problem: A 0.5-MGD wastewater flow has a BOD concentration of 1600 mg/L BOD. Using an average of 0.17 lb BOD/day/person, what is the population equivalent of this wastewater flow?

Solution:

Hint: Don't forget to convert mg/L BOD to lb/day BOD, then divide by 0.17 lb BOD/day/person.

$$\text{PE} = \frac{\text{BOD (lb/day)}}{\text{lb BOD/person/day}}$$

$$= \frac{1600\text{ mg/L} \times 0.5\text{ MGD} \times 8.34\text{ lb/gal}}{0.17\text{ lb BOD/person/day}} = 39{,}247\text{ people}$$

4.1.5 Specific Gravity and Density

Specific gravity is the ratio of the density of a substance to that of a standard material under standard conditions of temperature and pressure. The specific gravity of water is 1.0 (one). Any substance with a density greater than that of water will a specific gravity greater than 1.0, and any substance with a density less than that of water will have a specific gravity less than 1.0. Specific gravity can be used to calculate the weight of a gallon of liquid chemical.

$$\text{Chemical (lb/gal)} = \text{Water (lb/gal)} \times \text{Specific Gravity (Chemical)} \tag{4.3}$$

■ *Example 4.27*

Problem: The label states that the ferric chloride solution has a specific gravity of 1.58. What is the weight of 1 gal of ferric chloride solution?

Solution:

$$\text{Ferric chloride} = 8.34\ \text{lb/gal} \times 1.58 = 13.2\ \text{lb/gal}$$

■ *Example 4.28*

Problem: If we say that the density of gasoline is 43 lb/ft^3, what is the specific gravity of gasoline?

Solution: The specific gravity of gasoline is the comparison (or ratio) of the density of gasoline to that of water:

$$\text{Specific Gravity} = \frac{\text{Density of gasoline}}{\text{Density of water}} = \frac{43\ \text{lb/ft}^3}{62.4\ \text{lb/ft}^3} = 0.69$$

Note: Because the specific gravity of gasoline is less than 1.0 (lower than the specific gravity of water), it will float in water. If the specific gravity of gasoline were greater than the specific gravity of water, it would sink.

4.2 CHAPTER REVIEW QUESTIONS

4.1 The depth of water in the grit channel is 36 in. What is the depth in feet?

4.2 The operator withdraws 5269 gal of solids from the digester. How many pounds of solids have been removed?

4.3 Sludge added to the digester causes a 1996-ft^3 change in the volume of sludge in the digester. How many gallons of sludge have been added?

4.4 The plant effluent contains 35 mg/L solids. The effluent flow rate is 3.69 MGD. How many pounds per day of solids are discharged?

4.5 Plant effluent contains 26 mg/L of BOD_5. The effluent flow rate is 7.25 MGD. How many kilograms per day of BOD_5 are being discharged?

4.6 The operator wishes to remove 3540 lb/day of solids from the activated sludge process. The waste activated sludge concentration is 3524 mg/L. What is the required flow rate in million gallons per day?

4.7 The plant influent includes an industrial flow that contains 235 mg/L BOD. The industrial flow is 0.70 MGD. What is the population equivalent for the industrial contribution in people per day?

4.8 Determine the per capita characteristics of BOD and suspended solids (SS) if garbage grinders are installed in a community. Assume that the average per capita flow is 110 gpd and that the typical average per capita contributions for domestic wastewater with ground kitchen waste are BOD 0.21 lb/capita/day; SS is 0.28 lb/capita/day.

4.9 The label of hypochlorite solution states that the specific gravity of the solution is 1.1545. What is the weight of a gallon of the hypochlorite solution?

CHAPTER 5

MEASURING PLANT PERFORMANCE

5.1 INTRODUCTION

To evaluate how well a plant or unit process is performing, *performance efficiency* or *percent (%) removal* is used. The results obtained can be compared with those listed in the plant's operations and maintenance (O&M) manual to determine if the facility is performing as expected. This chapter presents sample calculations often used to measure plant performance or efficiency.

The *efficiency* of a unit process is its effectiveness in removing various constituents from the wastewater or water. Suspended solids and biochemical oxygen demand (BOD) removal are therefore the most common calculations of unit process efficiency.

In wastewater treatment, the efficiency of a sedimentation basin may be affected by such factors as the types of solids in the wastewater, the temperature of the wastewater, and the age of the solids. Typical removal efficiencies for a primary sedimentation basin are as follows:

• Settleable solids	90–99%
• Suspended solids	40–60%
• Total solids	10–15%
• BOD	20–50%

5.2 PLANT PERFORMANCE EFFICIENCY

Note: The calculation used for determining the performance (percent removal) for a digester is different from that used for performance (percent removal) for other processes. Care must be taken to select the correct formula.

$$\text{\% Removal} = \frac{(\text{Influent Concentration} - \text{Effluent Concentration}) \times 100}{\text{Influent Concentration}} \tag{5.1}$$

■ ***Example 5.1***

Problem: The influent BOD_5 is 247 mg/L, and the plant effluent BOD is 17 mg/L. What is the percent removal?

Solution:

$$\text{\% Removal} = \frac{(247\text{ mg/L} - 17\text{ mg/L}) \times 100}{247\text{ mg/L}} = 93\%$$

5.3 UNIT PROCESS PERFORMANCE/EFFICIENCY

Equation 5.1 is also used to determine unit process efficiency. The concentration entering the unit and the concentration leaving the unit (e.g., primary, secondary) are used to determine the unit performance:

$$\text{\% Removal} = \frac{(\text{Influent Concentration} - \text{Effluent Concentration}) \times 100}{\text{Influent Concentration}}$$

■ ***Example 5.2***

Problem: The primary influent BOD is 235 mg/L, and the primary effluent BOD is 169 mg/L. What is the percent removal?

Solution:

$$\text{\% Removal} = \frac{(235\text{ mg/L} - 169\text{ mg/L}) \times 100}{235\text{ mg/L}} = 28\%$$

5.4 PERCENT VOLATILE MATTER REDUCTION IN SLUDGE

The calculation used to determine *percent volatile matter reduction* is more complicated because of the changes occurring during biosolids digestion:

$$\text{\%VM Reduction} = \frac{\left(\text{\%VM}_{in} - \text{\%VM}_{out}\right) \times 100}{\text{\%VM}_{in} - \left(\text{\%VM}_{in} \times \text{\%VM}_{out}\right)}$$

■ ***Example 5.3***

Problem: Using the digester data provided below, determine the percent volatile matter reduction for the digester:

Raw biosolids volatile matter = 74%

Digested biosolids volatile matter = 54%

Solution:

$$\%\text{VM Reduction} = \frac{(0.74 - 0.54) \times 100}{0.74 - (0.74 \times 0.54)} = 59\%$$

5.5 CHAPTER REVIEW QUESTIONS

Use the following information for the chapter review questions:

Plant influent
Flow = 8.25 MGD
Suspended solids = 350 mg/L
BOD = 225 mg/L
Primary effluent
Flow = 8.35 MGD
Suspended solids = 144 mg/L
BOD = 175 mg/L
Active sludge effluent
Flow = 8.35 MGD
Suspended solids = 17 mg/L
BOD = 24 mg/L
Anaerobic digester
Solids in = 6.6%
Solids out = 13.4%
Volatile matter in = 66.3%
Volatile matter out = 49.1%

5.1 What is the plant percent removal for BOD_5?

5.2 What is the plant percent removal of TSS?

5.3 What is the primary treatment percent removal of BOD_5?

5.4 What is the primary treatment percent removal of total suspended solids (TSS)?

5.5 What is the percent volatile matter reduction in the anaerobic digestion process?

CHAPTER 6

HYDRAULIC DETENTION TIME

6.1 INTRODUCTION

The term *detention time*, or *hydraulic detention time* (HDT), refers to the average length of time (theoretical time) a drop of water, wastewater, or suspended particles remains in a tank or channel. It is calculated by dividing the water/wastewater in the tank by the flow rate through the tank. The units of flow rate used in the calculation are dependent on whether the detention time is to be calculated in seconds, minutes, hours, or days. Detention time is used in conjunction with various treatment processes, including sedimentation and coagulation–flocculation.

Generally, in practice, detention time is associated with the amount of time required for a tank to empty. The range of detention time varies with the process; for example, in a tank used for sedimentation, detention time is commonly measured in minutes. The calculation methods used to determine detention time are illustrated in the following sections.

6.2 DETENTION TIME IN DAYS

The general hydraulic detention time calculation is:

$$\text{Hydraulic Detention Time (HDT)} = \frac{\text{Tank Volume}}{\text{Flow Rate}} \tag{6.1}$$

This general formula is then modified based on the information provided or available and the normal range of detention times for the unit being evaluated:

$$\text{Hydraulic Detention Time (days)} = \frac{\text{Tank Volume (ft}^3) \times 7.48\ \text{gal/ft}^3}{\text{Flow (gpd)}} \tag{6.2}$$

■ ***Example 6.1***

Problem: An anaerobic digester has a volume of 2,200,000 gal. What is the detention time in days when the influent flow rate is 0.06 MGD?

Solution:

$$\text{Detention Time} = \frac{2{,}200{,}000\ \text{gal}}{0.06\ \text{MGD} \times 1{,}000{,}000\ \text{gal/MG}} = 37\ \text{days}$$

6.3 DETENTION TIME IN HOURS

$$\text{Detention Time (hr)} = \frac{\text{Tank Volume (ft}^3) \times 7.48\ \text{gal/ft}^3 \times 24\ \text{hr/day}}{\text{Flow (gpd)}} \tag{6.3}$$

■ ***Example 6.2***

Problem: A settling tank has a volume of 40,000 ft^3. What is the detention time in hours when the flow is 4.35 MGD?

Solution:

$$\text{Detention Time} = \frac{40{,}000\ \text{ft}^3 \times 7.48\ \text{gal/ft}^3 \times 24\ \text{hr/day}}{4.35\ \text{MGD} \times 1{,}000{,}000\ \text{gal/MG}} = 1.7\ \text{hr}$$

6.4 DETENTION TIME IN MINUTES

$$\text{Detention Time (min)} = \frac{\text{Tank volume (ft}^3) \times 7.48\ \text{gal/ft}^3 \times 1440\ \text{min/day}}{\text{Flow (gpd)}} \tag{6.4}$$

■ ***Example 6.3***

Problem: A grit channel has a volume of 1240 ft^3. What is the detention time in minutes when the flow rate is 4.1 MGD?

Solution:

$$\text{Detention Time} = \frac{1240\ \text{ft}^3 \times 7.48\ \text{gal/ft}^3 \times 1440\ \text{min/day}}{4{,}100{,}000\ \text{gal/day}} = 3.26\ \text{min}$$

Note: The tank volume and the flow rate must be in the same dimensions before calculating the hydraulic detention time.

6.5 CHAPTER REVIEW QUESTIONS

6.1 The influent flow rate to a primary settling tank is 1.35 MGD. The tank is 70 ft in length and 16 ft wide and has a water depth of 10 ft. What is the detention time of the tank in hours?

Use the following data for the remaining chapter review questions:

Plant influent

Flow = 8.40 MGD

Grit chamber

Number = 2

Channel length = 60 ft

Channel width = 4 ft

Water depth = 2.8 ft

Primary settling

Number = 2

Length = 160 ft

Width = 110 ft

Water depth = 12 ft

Anaerobic digester

Flow = 19,000 gpd

Volume = 110,000 ft^3

6.2 What is the hydraulic detention time in hours for primary settling when both tanks are in service?

6.3 What is the hydraulic detention time in the grit channel in minutes when both channels are in service?

6.4 What is the hydraulic detention time of the anaerobic digester in days?

CHAPTER 7

WASTEWATER SOURCES AND CHARACTERISTICS

7.1 INTRODUCTION

This chapter describes individual pollutants and stressors that affect water quality. Knowledge of the parameters and characteristics most commonly associated with wastewater treatment processes is essential for the wastewater operator. Wastewater practitioners are encouraged to take a holistic approach to managing water quality problems.

It is important to point out that when this text refers to *water quality*, the definition used is predicated on the intended use of the water or treated wastewater. Many parameters have evolved that qualitatively reflect the impact that various contaminants (impurities) have on selected water uses; the following sections provide a brief discussion of these parameters.

It is also important to point out that wastewater treatment is designed to use the natural purification processes (self-purification processes of streams and rivers) to the maximum extent possible. In fact, we can say that the unit processes that make up the entire process that is wastewater treatment are nothing more than a stream or river in a box. No one is arguing that there are no differences between the stream or river and the treatment plant; for example, the treatment plant completes its treatment process in a controlled environment rather than over many miles of stream or river. Moreover, the treatment plant is also designed to remove other contaminants that are not normally subject to the natural processes and to treat the solids that are generated through the treatment unit process steps. The typical wastewater treatment plant is designed to serve many different purposes:

- Protect public health.
- Protect public water supplies.
- Protect aquatic life.
- Preserve the best uses of the waters.
- Protect adjacent lands.

Wastewater treatment is a series of steps. Each of the steps can be accomplished using one or more treatment processes or types of equipment. The major categories of treatment steps are:

- *Preliminary treatment* removes materials that would damage plant equipment or occupy treatment capacity without being treated.
- *Primary treatment* removes settleable and floatable solids (may not be present in all treatment plants).
- *Secondary treatment* removes BOD_5 and dissolved and colloidal suspended organic matter by biological action; organics are converted to stable solids, carbon dioxide, and more organisms.
- *Advanced waste treatment* uses physical, chemical, and biological processes to remove additional BOD_5, solids, and nutrients (not present in all treatment plants).
- *Disinfection* removes microorganisms to eliminate or reduce the possibility of disease when the flow is discharged.
- *Sludge treatment* stabilizes the solids removed from the wastewater during treatment, inactivates pathogenic organisms, and reduces the volume of the sludge by removing water.

The various treatment processes described above are discussed in detail later in this handbook.

Because wastewater operators are expected to have a well-rounded knowledge not only of treatment unit processes but also of the substance (the wastestream) they are treating, in this chapter we describe the sources and various characteristics of wastewater they treat.

7.2 WASTEWATER SOURCES

The principal sources of domestic wastewater in a community are residential areas and commercials districts. Other important sources include institutional and recreational facilities and stormwater (runoff) and groundwater (infiltration). Each source produces wastewater with specific characteristics. Wastewater is generated by five major sources: human and animal wastes, household wastes, industrial wastes, stormwater runoff, and groundwater infiltration:

- *Human and animal wastes* include the solid and liquid discharges of humans and animals and are considered by many to be the most dangerous from a human health viewpoint. The primary health issue relates to the millions of bacteria, viruses, and other microorganisms (some of which may be pathogenic) present in the wastestream.

- *Household wastes* are wastes, other than human and animal wastes, that are discharged from the home. Household wastes usually contain paper; household cleaners; detergents; trash; garbage; pharmaceuticals and personal care products (PPCPs), which are products used by individuals for personal health or cosmetic reasons or by agribusiness to enhance the growth or health of livestock; and other substances the homeowner discharges into the sewer system.
- *Industrial wastes* include industry-specific materials that can be discharged from industrial processes into the collection system. They typically contain chemicals, dyes, acids, alkalis, grit, detergents, and highly toxic materials.
- *Stormwater runoff* is carried by collection systems designed to carry both the wastes of the community and stormwater. In this type of system, when a storm event occurs, the wastestream can contain large amounts of sand, gravel, and other grit as well as excessive amounts of water.
- *Groundwater infiltration* occurs when groundwater enters older, improperly sealed collection systems through cracks or unsealed pipe joints. This can add not only large amounts of water to wastewater flows but also additional grit.

Wastewater can be classified according to the sources of flows: domestic, sanitary, industrial, combined, or stormwater:

- *Domestic (sewage) wastewater* mainly contains human and animal wastes, household wastes, small amounts of groundwater infiltration, and small amounts of industrial wastes.
- *Sanitary wastewater* consists of domestic wastes and significant amounts of industrial wastes. In many cases, the industrial wastes can be treated without special precautions; however, in some cases, the industrial wastes will require special precautions or a pretreatment program to ensure that the wastes do not cause compliance problems for the wastewater treatment plant.
- *Industrial wastewater* includes industrial wastes only. Often the industry will determine that it is easier and more economical to treat its waste independent of domestic waste.
- *Combined wastewater* is the combination of sanitary wastewater and stormwater runoff. All of the wastewater and stormwater of a community is transported through one system to the treatment plant.
- *Stormwater* is carried by a separate collection system (no sanitary waste); it can include street debris, road salt, and grit.

7.3 PHYSICAL CHARACTERISTICS OF WATER/WASTEWATER

The physical characteristics of wastewater are more germane to the discussion at hand—namely, the parameters and characteristics that can be used to describe water quality. The physical characteristics for water (and thus wastewater) are those that are apparent to the senses of smell, taste, sight, and touch. Solids, turbidity, color, taste, odor, and temperature also fall into this category.

7.3.1 Solids

Other than gases, all contaminants of water contribute to the solids content. Classified by their size and state, by their chemical characteristics, and by their size distribution, solids can be dispersed in water in both suspended and dissolved forms. With regard to size, solids in water and wastewater can be classified as suspended, settleable, colloidal, or dissolved. Solids are also characterized as being *volatile* or *nonvolatile*. The distribution of solids is determined by computing the percentage of filterable solids by size range. Solids typically include inorganic solids, such as silt, sand, gravel, and clay from riverbanks, and organic matter, such as plant fibers and microorganisms from natural or human-made sources. We use the term *siltation* to describe the suspension and deposition of small sediment particles in waterbodies. In flowing water, many of these contaminants result from the erosive action of water flowing over surfaces.

Sedimentation and siltation can severely alter aquatic communities. Sedimentation may clog and abrade fish gills, suffocate eggs and aquatic insect larvae on the bottom, and fill in the pore space between bottom cobbles where fish lay eggs. Suspended silt and sediment interfere with recreational activities and the aesthetic enjoyment of streams and lakes by reducing water clarity and filling in lakes. Sediment may also carry other pollutants into surface waters. Nutrients and toxic chemicals may attach to sediment particles on land and ride the particles into surface waters, where the pollutants may settle with the sediment or detach and become soluble in the water column.

Suspended solids are a measure of the weight of relatively insoluble materials in the ambient water. These materials enter the water column as soil particles from land surfaces or sand, silt, and clay from stream-bank erosion of channel scour. Suspended solids can include both organic (detritus and biosolids) and inorganic (sand or finer colloids) constituents.

In water, suspended material is objectionable because it provides adsorption sites for biological and chemical agents. These adsorption sites give attached microorganisms a protective barrier against the chemical action of chlorine. In addition, suspended solids in water may be degraded biologically, resulting in objectionable byproducts. Thus, the removal of these solids is of great concern in the production of clean, safe drinking water and wastewater effluent.

In water treatment, the most effective means of removing solids from water is by filtration. It should be pointed out, however, that not all solids, such as colloids and other dissolved solids, can be removed by filtration.

In wastewater treatment, the level of suspended solids is an important water-quality parameter and is used to measure the quality of the wastewater influent, to monitor performance of several processes, and to measure the quality of effluent. Wastewater is normally 99.9% water and 0.1% solids. If a wastewater sample is evaporated, the solids remaining are referred to as *total solids*. The U.S. Environmental Protection Agency (USEPA) has set a maximum suspended solids standard of 30 mg/L for most treated wastewater discharges.

7.3.2 Turbidity

One of the first things that is noticed about water is its clarity. The clarity of water is usually measured by its *turbidity*. Turbidity is a measure of the extent to which light is either absorbed or scattered by suspended material in water. Both the size and surface characteristics of the suspended material influence absorption and scattering.

Although algae blooms can make waters turbid, in surface water most turbidity is related to the smaller inorganic components of the suspended solids burden, primarily the clay particles. Microorganisms and vegetable material may also contribute to turbidity. Wastewaters from industry and households usually contain a wide variety of turbidity-producing materials. Detergents, soaps, and various emulsifying agents contribute to turbidity.

In water treatment, turbidity is useful in defining drinking-water quality. In wastewater treatment, turbidity measurements are particularly important whenever ultraviolet (UV) radiation is used in the disinfection process. For UV to be effective in disinfecting wastewater effluent, UV light must be able to penetrate the stream flow. Obviously, stream flow that is turbid works to reduce the effectiveness of irradiation (penetration of light).

The colloidal material associated with turbidity provides adsorption sites for microorganisms and chemicals that may be harmful or cause undesirable tastes and odors. Moreover, the adsorptive characteristics of many colloids work to provide protection sites for microorganisms from disinfection processes. Turbidity in running waters interferes with light penetration and photosynthetic reactions.

7.3.3 Color

Color is another physical characteristic by which the quality of water can be judged. Pure water is colorless. Water takes on color when foreign substances such as organic matter from soils, vegetation, minerals, and aquatic organisms are present. Color can also be contributed to water by municipal and industrial wastes.

TABLE 7.1 SIGNIFICANCE OF COLOR IN WASTEWATER INFLUENT

Color	Problem Indicated
Gray	None
Red	Blood or other industrial wastes
Green, yellow	Industrial wastes (e.g., paints) not pretreated
Red or other soil	Surface runoff into influent; industrial flows
Black	Septic conditions or industrial flows

Color in water is classified as either *true color* or *apparent color.* The color of water that is partly due to dissolved solids remaining after removal of suspended matter is the true color. Color contributed by suspended matter is said to be the apparent color. In water treatment, true color is the most difficult to remove.

Note: Water has an intrinsic color, and this color has a unique origin. Intrinsic color is easy to discern, as can be seen in Crater Lake, Oregon, which is known for its intense blue color. The appearance of the lake varies from turquoise to deep navy blue, depending on whether the sky is hazy or clear. Pure water and ice have a pale blue color.

The obvious problem with colored water is that it is not acceptable to the public; that is, given a choice, the public prefers clear, uncolored water. Another problem with colored water is the effect it has on laundering, papermaking, manufacturing, textiles, and food processing. The color of water has a profound impact on its marketability for both domestic and industrial use.

In water treatment, color is not usually considered unsafe or unsanitary, but it is a treatment problem with regard to exerting a chlorine demand, which reduces the effectiveness of chlorine as a disinfectant.

In wastewater treatment, color is not necessarily a problem but instead is an indicator of the *condition* of the wastewater. Condition, along with odor, provides a qualitative indication of the age of the wastewater. Early in the flow, wastewater is a light brownish-gray color. The color of wastewater containing dissolved oxygen (DO) is normally gray. Black-colored wastewater usually accompanied by foul odors and containing little or no DO is said to be septic. Table 7.1 provides wastewater color information. As travel time in the collection system increases (flow becomes increasingly more septic) and more anaerobic conditions develop, the color of the wastewater changes from gray to dark gray and ultimately to black.

7.3.4 Taste and Odor

Taste and *odor* are used jointly in the vernacular of water science. Reference is made to odor in wastewater treatment; taste, obviously, is not a consideration. Domestic sewage should have a musty odor.

TABLE 7.2 ODORS IN WASTEWATER TREATMENT PLANT

Odor	Location	Problem	Possible Solution
Earthy, musty	Primary and secondary units	No problem (normal)	None required
Hydrogen sulfide	Influent	Septic (rotten egg odor)	Aerate, chlorinate, oxonizate
	Primary clarifier	Septic sludge	Remove sludge
	Activated sludge	Septic sludge	Remove sludge
	Trickling filters	Septic conditions	More air, less BOD
	Secondary clarifier	Septic conditions	Remove sludge
	Chlorine contact tank	Septic conditions	Remove sludge
	General plant	Septic conditions	Good housekeeping
Chlorine	Chlorine contact tank	Improper chlorine dosage	Adjust chlorine dosage
Industrial odors	General plant	Inadequate pretreatment	Enforce sewer use regulation

Bubbling gas or a foul odor may indicate industrial wastes, anaerobic (septic) conditions, and operational problems. Refer to Table 7.2 for typical wastewater odors, possible problems, and solutions.

In wastewater, odors are of major concern, especially to those who reside in close proximity to a wastewater treatment plant. These odors are generated by gases produced by decomposition of organic matter or by substances added to the wastewater. Because these substances are volatile, they are readily released to the atmosphere at any point where the wastestream is exposed, particularly if there is turbulence at the surface.

Most people would argue that all wastewater is the same; it has a disagreeable odor. It is hard to argue against the disagreeable odor; however, one wastewater operator declared that, "Wastewater smells great. It smells just like money to me—money in the bank." This was an operator's view. Another opinion of odor problems resulting from wastewater operations given by an odor control manager was quite different. He considered odor control to be a never-ending problem, as the odors must be contained.

In most urban plants, it has become necessary to physically cover all source areas such as treatment basins, clarifiers, aeration basins, and contact tanks to prevent odors from leaving the processes. These contained spaces must then be positively vented to wet-chemical scrubbers to prevent the buildup of a toxic concentration of gas.

7.3.5 Temperature

Heat is added to surface and groundwater in many ways. Some of these are natural, some artificial. For example, heat is added by natural means to Yellowstone Lake, Wyoming. This lake, one of the world's largest freshwater lakes, resides in a caldera situated at more than 7700 feet (the largest high-altitude lake in North America). When one attempts to swim in Yellowstone Lake (without a wetsuit), the bitter cold of the water literally takes one's breath away; however, if it were not for the hydrothermal discharges that occur in Yellowstone, the water would be even colder. With regard to water heated by human influences, this most commonly occurs whenever a raw water source is used for cooling water in industrial operations. The influent to industrial facilities is at normal ambient temperature. When it is used to cool machinery and industrial processes, however, and then discharged back to the receiving body it is often heated.

The problem with a temperature increase in surface waters is that it affects the solubility of oxygen in water, the rate of bacterial activity, and the rate at which gases are transferred to and from the water.

In wastewater treatment, the temperature of wastewater varies greatly, depending on the type of operations being conducted at a particular installation. Wastewater is generally warmer than the water supply because of the addition of warm water from industrial activities and households. Wide variations in wastewater temperature indicate heated or cooled discharges, often of substantial volume. They have any number of sources; for example, decreased temperatures after a snowmelt or rain event may indicate serious infiltration. In the treatment process itself, temperature not only influences the metabolic activities of the microbial population but also has a profound effect on such factors as gas-transfer rates and the settling characteristics of the biological solids.

Key Point: Temperature is not normally used to evaluate either water or wastewater; however, temperature is an important parameter in natural surface water systems, which are subject to great temperature variations.

7.4 CHEMICAL CHARACTERISTICS OF WASTEWATER

The chemical characteristics of wastewater consist of: (1) organic matter, (2) inorganic matter, and (3) gases. According to Metcalf & Eddy (2003), in "wastewater of medium strength, about 75% of the suspended solids and 40% of the filterable solids are organic in nature." The organic substances of interest in this discussion include proteins, oil and grease, carbohydrates, and detergents (surfactants).

7.4.1 Organic Substances

Proteins are nitrogenous organic substances of high molecular weight found in the animal kingdom and to a lesser extent in the plant kingdom. The amount present varies from a small percentage found in tomatoes and other watery fruits and in the fatty tissues of meat to a high percentage in lean meats and beans. All raw foodstuffs, plant and animal, contain proteins. Proteins consist wholly or partially of very large numbers of amino acids. They also contain carbon, hydrogen, oxygen, sulfur, phosphorous, and a fairly high and constant proportion of nitrogen. The molecular weight of proteins is quite high.

Coakley (1975) noted that proteinaceous materials constitute a large part of the wastewater biosolids, and that the biosolids particles, if they do not consist of pure protein, will be covered with a layer of protein that will govern their chemical and physical behavior. Moreover, the protein content ranges between 15 and 30% of the organic matter present for digested biosolids and from 28 to 50% in the case of activated biosolids. Proteins and urea are the chief sources of nitrogen in wastewater. When proteins are present in large quantities, microorganisms decompose, producing end products that have objectionable foul odors. During this decomposition process, proteins are hydrolyzed to amino acids, then further degraded to ammonia, hydrogen sulfide, and simple organic compounds.

Oils and *grease* are other major components of foodstuffs. They are usually related to spills or other releases of petroleum products. Minor oil and grease problems can result from runoff from highways during wet weather or improper disposal of motor oil in storm drains. Oils and grease are insoluble in water but dissolve in organic solvents such as petroleum, chloroform, and ether. Fats, oils, waxes, and other related constituents found in wastewater are commonly grouped under the category of grease. Fats and oils found in domestic wastewater generally include butter, lard, margarine, and vegetable fats and oils. Fats, which are compounds of alcohol and glycerol, are among the more stable of organic compounds and are not easily decomposed by bacteria; however, they can be broken down by mineral acids, resulting in the formation of fatty acids and glycerin. When these glycerides of fatty acids are liquid at ordinary temperature, they are considered to be oils; those that are solid are considered to be fats.

The grease content of wastewater can cause many problems in wastewater treatment unit processes; for example, a high grease content can cause clogging of filters, nozzles, and sand beds (Gilcreas et al., 1975). Moreover, grease can coat the walls of sedimentation tanks and decompose and increase the amount of scum. Additionally, if grease is not removed before discharge of the effluent, it can interfere with the biological processes in the surface waters and create unsightly floating matter and films (Rowe and Abdel-Magid, 1995). In the treatment process, grease can coat trickling filters and interfere with the activated sludge process, which in turn interferes with the transfer of oxygen from the liquid to the interior of living cells (Sawyer et al., 1994).

Carbohydrates, which are widely distributed in nature and found in wastewater, are organic substances that include starch, cellulose, sugars, and wood fibers; they contain carbon, hydrogen, and oxygen. Sugars are soluble but starches are insoluble in water. The primary function of carbohydrates in higher animals is to serve as a source of energy. In lower organisms (e.g., bacteria), carbohydrates are utilized to synthesize fats and proteins as well as energy. In the absence of oxygen, the end products of decomposition of carbohydrates are organic acids, alcohols, and gases, such as carbon dioxide and hydrogen sulfide. The formation of large quantities of organic acids can affect the treatment process by overtaxing the buffering capacity of the wastewater, resulting in a drop in pH and a cessation of biological activity.

Detergents, or *surfactants*, are large organic molecules that are slightly soluble in water and cause foaming in wastewater treatment plants and in the surface waters into which the effluent is discharged. Probably the most serious effect that detergents can have on wastewater treatment processes is in their tendency to reduce the oxygen uptake in biological processes. According to Rowe and Abdel-Magid (1995), detergents affect wastewater treatment processes in that "they lower the surface, or interfacial, tension of water and increase its ability to wet surfaces with which they come in contact; emulsify grease and oil, deflocculate colloids; induce flotation of solids and give rise to foams; and may kill useful bacteria and other living organisms." Since the development and increasing use of synthetic detergents, many of these problems have been reduced or eliminated.

7.4.2 Inorganic Substances

Several inorganic components are common to both wastewater and natural waters and are important in establishing and controlling water quality. Inorganic load in water is the result of discharges of treated and untreated wastewater, various geologic formations, and inorganic substances left in the water after evaporation. Natural waters dissolve rocks and minerals with which they come in contact. As mentioned, many of the inorganic constituents found in natural waters are also found in wastewater. Many of these constituents are added via human use. These inorganic constituents include pH, chlorides, alkalinity, nitrogen, phosphorus, sulfur, toxic inorganic compounds, and heavy metals.

When the *pH* of a water or wastewater is considered, we are simply referring to the hydrogen ion concentration. Acidity, or the concentration of hydrogen ions, drives many chemical reactions in living organisms. A pH value of 7 represents a neutral condition. A low pH value (less than 5) indicates acidic conditions; a high pH (greater than 9) indicates alkaline conditions. Many biological processes, such as reproduction, cannot function in acidic or alkaline waters. Acidic conditions also aggravate toxic contamination problems because sediments release toxicants in acidic waters.

Many of the important properties of wastewater are due to the presence of weak acids and bases and their salts. The wastewater treatment process is made up of several different unit processes (these are discussed later). It can be safely stated that one of the most important unit processes in the overall wastewater treatment process is disinfection. pH has an effect on disinfection. This is particularly the case with regard to disinfection using chlorine; for example, with increases in pH, the amount of contact time needed for disinfection using chlorine increases. Common sources of acidity include mine drainage, runoff from mine tailings, and atmospheric deposition.

Chloride, in the form of the Cl^- ion, is one of the major inorganic constituents in water and wastewater. Sources of chlorides in natural waters include: (1) leaching of chloride from rocks and soils; (2) in coastal areas, saltwater intrusion; (3) agricultural, industrial, domestic, and human wastewater; and (4) infiltration of groundwater into sewers adjacent to saltwater. The salty taste produced by the chloride concentration in potable water is variable and depends on the chemical composition of the water. In wastewater, the chloride concentration is higher than in raw water because sodium chloride (salt) is a common part of the diet and passes unchanged through the digestive system. Because conventional methods of waste treatment do not remove chloride to any significant extent, higher than usual chloride concentrations can be taken as an indication that the body of water is being used for waste disposal (Metcalf & Eddy, 2003).

As mentioned earlier, *alkalinity* is a measure of the buffering capacity of water and in wastewater helps to resist changes in pH caused by the addition of acids. Alkalinity is caused by chemical compounds dissolved from soil and geologic formations and is mainly due to the presence of hydroxyl and bicarbonate ions. These compounds are mostly the carbonates and bicarbonates of calcium, potassium, magnesium, and sodium. Wastewater is usually alkaline. Alkalinity is important in wastewater treatment because anaerobic digestion requires sufficient alkalinity to ensure that the pH will not drop below 6.2; if alkalinity does drop below this level, the methane bacteria cannot function. For the digestion process to operate successfully, the alkalinity must range from about 1000 to 5000 mg/L as calcium carbonate. Alkalinity in wastewater is also important when chemical treatment is used, in biological nutrient removal, and whenever ammonia is removed by air stripping.

In domestic wastewater, "nitrogen compounds result from the biological decomposition of proteins and from urea discharged in body waste" (Peavy et al. 1987). In wastewater treatment, biological treatment cannot proceed unless *nitrogen*, in some form, is present. Nitrogen must be present in the form of organic nitrogen (N), ammonia (NH_3), nitrite (NO_2), or nitrate (NO_3). Organic nitrogen includes such natural constituents as peptides, proteins, urea, nucleic acids, and numerous synthetic organic materials. Ammonia is present naturally in wastewaters. It is produced primarily by deaeration of organic nitrogen-containing compounds and by hydrolysis of urea. Nitrite, an intermediate oxidation state of nitrogen, can enter a water system through its use as a corrosion inhibitor in industrial applications. Nitrate is derived from the oxidation of ammonia.

Nitrogen data are essential in evaluating the treatability of wastewater by biological processes. If nitrogen is not present in sufficient amounts, it may be necessary to add it to the waste to make it treatable. When the treatment process is complete, it is important to determine how much nitrogen is in the effluent. This is important because the discharge of nitrogen into receiving waters may stimulate algal and aquatic plant growth. These, of course, exert a high oxygen demand at nighttime, which adversely affects aquatic life and has a negative impact on the beneficial use of water resources.

Phosphorus (P) is a macronutrient that is necessary to all living cells and is a ubiquitous constituent of wastewater. It is primarily present in the form of phosphates, the salts of phosphoric acid. Municipal wastewaters may contain 10 to 20 mg/L phosphorus as P, much of which comes from phosphate builders in detergents. Because of noxious algae blooms that occur in surface waters, there is much interest in controlling the amount of phosphorus compounds that enter surface waters in domestic and industrial waste discharges and natural runoff. This is particularly the case in the United States, where approximately 15% of the population contributes wastewater effluents to lakes, resulting in *eutrophication* of these water bodies. Eutrophication leads to significant changes in water quality. Reducing phosphorus inputs to receiving waters can control this problem.

Sulfur (S) is required for the synthesis of proteins and is released in their degradation. The sulfate ion occurs naturally in most water supplies and is present in wastewater as well. Sulfate is reduced biologically to sulfide, which in turn can combine with hydrogen to form hydrogen sulfide (H_2S). H_2S is toxic to animals and plants; moreover, in certain concentrations, H_2S is a deadly toxin. H_2S in interceptor systems can cause severe corrosion to pipes and appurtenances

Toxic inorganic compounds such as copper, lead, silver, arsenic, boron, and chromium are classified as priority pollutants and are toxic to microorganisms. Thus, they must be taken into consideration in the design and operation of a biological treatment process. When introduced into a treatment process, these contaminants can kill off the microorganisms needed for treatment and thus stop the treatment process.

Heavy metals are major toxicants found in industrial wastewaters; they may adversely affect the biological treatment of wastewater. Mercury, lead, cadmium, zinc, chromium, and plutonium are among the so-called heavy metals, which have a high atomic mass. (It should be noted that the term *heavy metals* is rather loose and is taken by some to include arsenic, beryllium, and selenium, which are not really metals and are better termed *toxic metals*.) The presence of any of these metals in excessive quantities will interfere with many beneficial uses of water because of their toxicity. Urban runoff is a major source of lead and zinc in many water bodies. (*Note:* Lead is a toxic metal that is harmful to human health; there is *no* safe level for lead exposure. It is estimated that up to 20% of the total lead exposure in children can be attributed to a waterborne route, consuming contaminated water.) The lead comes from the exhaust of automobiles using leaded gasoline, whereas zinc comes from tire wear.

7.5 BIOLOGICAL CHARACTERISTICS OF WATER/WASTEWATER

Specialists or practitioners who work in the water/wastewater treatment field must have not only a general understanding of the microbiological principles presented in Chapter 8 but also some knowledge of the biological characteristics of water and wastewater. This knowledge begins with an understanding that water may serve as a medium in which thousands of biological species spend part, if not all, of their life cycles. It is important to understand that, to some extent, all members of the biological community are water-quality parameters, because their presence or absence may indicate in general terms the characteristics of a given body of water.

The presence or absence of certain biological organisms—*pathogens*—is of primary importance to the water/wastewater specialist. Pathogens are organisms that are capable of infecting or transmitting diseases in humans and animals. It should be pointed out that these organisms are not native to aquatic systems and usually require an animal host for growth and reproduction. They can, however, be transported by natural water systems. These waterborne pathogens include species of bacteria, viruses, protozoa, and parasitic worms (helminths). The following sections provide a brief review of each of these types of pathogens.

7.5.1 Bacteria

The word *bacteria* (singular: *bacterium*) comes from the Greek word for "rod" or "staff," a shape characteristic of many bacteria. Recall that bacteria are single-celled microscopic organisms that multiply by splitting in two (binary fission). To multiply, autotrophs require carbon dioxide, and heterotrophs require organic compounds (dead vegetation, meat, sewage). Their energy comes from either sunlight, if they are photosynthetic, or chemical reactions, if they are chemosynthetic. Bacteria are present in air, water, earth, rotting vegetation, and the intestines of animals. Human and animal wastes are the primary source of bacteria in water. These sources of bacterial contamination include runoff from feedlots, pastures, dog runs, and other land areas where animal wastes are deposited. Additional sources include seepage or discharge from septic tanks and sewage treatment facilities. Bacteria from these sources can enter wells that are either open at the land surface or do not have watertight casings or caps. Gastrointestinal disorders are common symptoms of most diseases transmitted by waterborne pathogenic bacteria. In wastewater treatment processes, bacteria are fundamental, especially in the degradation of organic matter, which takes place in trickling filters, activated biosolids processes, and biosolids digestion.

7.5.2 Viruses

A *virus* is an entity that carries the information needed for its replication but does not possess the machinery for such replication (Sterritt and Lester, 1988). Thus, viruses are obligate parasites that require a host in which to live. They are the smallest biological structures known, so they can only be seen with the aid of an electron microscope. Waterborne viral infection is usually indicated by disorders with the nervous system rather than of the gastrointestinal tract. Viruses that are excreted by human beings may become a major health hazard to the public. Waterborne viral pathogens are known to cause poliomyelitis and infectious hepatitis.

Testing for viruses in water is difficult because: (1) they are small, (2) they are of low concentrations in natural waters, (3) there are numerous varieties, (4) they are unstable, and (5) only limited identification methods are available. Because of these testing problems and the uncertainty of viral disinfection, direct recycling of wastewater and the practice of land application of wastewater are areas of concern (Peavy et al., 1987).

7.5.3 Protozoa

Protozoa (singular: *protozoan*) are mobile, single-celled, completely self-contained organisms that can be free living or parasitic, pathogenic or nonpathogenic, microscopic or macroscopic. Protozoa range in size from two to several hundred microns in length. They are highly adaptable and widely distributed in natural waters, although only a few are parasitic. Most protozoa are harmless; only a few cause illness in humans (e.g., *Entamoeba histolytica*, which causes an infection of the intestines known as amebiasis). Because aquatic protozoa form cysts during adverse environmental conditions, they are difficult to deactivate by disinfection and must undergo filtration to be removed.

7.5.4 Worms (Helminths)

Worms are the normal inhabitants in organic mud and organic slime. They have aerobic requirements but can metabolize solid organic matter not readily degraded by other microorganisms. Water contamination may result from human and animal waste that contains worms. Worms pose hazards primarily to those persons who come into direct contact with untreated water; thus, swimmers in surface water polluted by sewage or stormwater runoff from cattle feedlots and sewage plant operators are at particular risk.

7.6 CHAPTER REVIEW QUESTIONS

7.1 What are the characteristics or range of characteristics that make water appealing and useful?

7.2 What is the process by which water vapor is emitted by leaves?

7.3 Water we see is known as ________________.

7.4 What is the leading cause of impairment for rivers, lakes, and estuaries?

7.5 All contaminants of water contribute to the ________________.

7.6 The clarity of water is usually measured by its ________________.

7.7 Water has been called the ________________.

7.8 A measure of the ability of water to neutralize acid is referred to as ________________.

7.9 A pH value of 7 represents a ________________.

7.10 There is no safe level for ________________ exposure.

7.11 What is BOD_5?

7.12 Name three sources of wastewater, and give an example of the types of materials associated with each.

7.13 Define *organic* and *inorganic*.

7.14 Name the two types of solids based on physical characteristics.

7.15 What is stormwater runoff, and how can it cause problems for the wastewater treatment plant?

7.16 Name three types of wastewater based on the types of waste carried.

7.17 Give three reasons for treating wastewater.

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CHAPTER 8

MICROBIOLOGY

Scientists picture the primordial Earth as a planet washed by a hot sea and bathed in an atmosphere containing water vapor, ammonia, methane, and hydrogen. Testing this theory, Stanley Miller at the University of Chicago duplicated these conditions in the laboratory. He distilled seawater in a special apparatus; passed the vapor with ammonia, methane, and hydrogen through an electrical discharge at frequent intervals; and condensed the “rain” to return it to the boiling seawater. Within a week, the seawater had turned red. Analysis showed that it contained amino acids, which are the building blocks of protein substances.

Whether this is what really happened early in the Earth’s history is not important; the experiment demonstrated that the basic ingredients of life could have been made in some such fashion, setting the stage for life to come into existence in the sea. The saline fluids in most living things may be an inheritance from such early beginnings (Kemmer, 1979).

8.1 INTRODUCTION

Microorganisms are significant in water and wastewater because of their roles in disease transmission and they are the primary agents of biological treatment in wastewater treatment. Thus, wastewater and other water practitioners must have considerable knowledge of the microbiological characteristics of water and wastewater. Simply put, wastewater operators cannot fully comprehend the principles of effective waste treatment without knowing the fundamental factors concerning microorganisms and their relationships to one another, their effect on the treatment process, and their impact on consumers, animals, and the environment.

Wastewater operators must know the principal groups of microorganisms found in water supplies (surface and groundwater) and wastewater, as well as those pathogenic organisms that must be treated, removed, or controlled during biological treatment processes. They must also be able to identify the organisms used as indicators of pollution and know their significance, as well as the methods used to enumerate the indicator organisms. This chapter provides microbiology fundamentals specifically targeting the needs of wastewater specialists.

Note: To have microbiological activity, the body of wastewater must have the appropriate environmental conditions. The majority of wastewater treatment processes, for example, are designed to operate as aerobic processes. The conditions required for aerobic operation include: (1) sufficient free, elemental oxygen; (2) sufficient organic matter (food); (3) sufficient water; (4) enough nitrogen and phosphorus (nutrients) to permit oxidation of the available carbon materials; (5) proper pH (6.5 to 9.0); and (6) lack of toxic materials.

8.2 MICROBIOLOGY: WHAT IS IT?

Biology is generally defined as the study of living organisms (i.e., the study of life). *Microbiology* is a branch of biology that deals with the study of microorganisms so small in size that they must be studied under a microscope. Microorganisms of interest to the water and wastewater operator include bacteria, protozoa, viruses, algae, and others.

Note: The science and study of bacteria is known as *bacteriology*.

The primary concern of water operators is controlling microorganisms that cause waterborne diseases—waterborne pathogens—to protect the consumer, both human and animal. Wastewater operators have the same microbiological concerns as water operators, but instead of directly purifying water for consumer consumption their focus is on removing harmful pathogens from the wastestream before outfalling it to the environment.

Water operators are concerned with the water supply and water purification through a treatment process. When treating water, the primary concern is producing potable water that is safe to drink (free of pathogens) with no accompanying offensive characteristics such as foul taste or odor. The treatment operator must possess a wide range of knowledge to correctly examine water for pathogenic microorganisms and determine the type of treatment necessary to ensure that the water quality of the end product, potable water, meets regulatory requirements.

Wastewater operators are also concerned with water quality; however, they are not as concerned as water specialists with total removal or reduction of most microorganisms. The wastewater treatment process actually benefits from microorganisms that act to degrade organic compounds, thus stabilizing organic matter in the wastestream. Wastewater operators must be trained to operate the treatment process in a manner that controls the growth of microorganisms and puts them to work.

Moreover, to fully understand wastewater treatment, it is necessary to determine which microorganisms are present and how they function to break down components in the wastewater stream. Then, of course, the operator must ensure that, before outfalling or dumping treated effluent into the receiving body, the microorganisms that worked so hard to degrade organic waste products, especially the pathogenic microorganisms, are not sent from the plant with effluent as viable organisms (Spellman, 1996).

8.3 WASTEWATER MICROORGANISMS

The microorganisms of interest to water and wastewater operators include bacteria, protozoa, rotifers, viruses, algae, fungi, and nematodes. These organisms are the most diverse group of living organisms on Earth, and they occupy important niches in the ecosystem. Their simplicity and minimal survival requirements allow them to exist in diverse situations. Water treatment specialists are primarily concerned with how to control microorganisms that cause *waterborne diseases* carried by *waterborne pathogens* (e.g., bacteria, virus, protozoa). Wastewater operators are concerned with the millions of organisms that arrive at the plant with the influent. The majority of these organisms are nonpathogenic and beneficial to plant operations. From a microbiological standpoint, the predominant species of microorganisms present depends on the characteristics of the influent, environmental conditions, process design, and the mode of plant operation. Pathogenic organisms may be present, including the organisms responsible for diseases such as typhoid, tetanus, hepatitis, dysentery, gastroenteritis, and others.

To understand how to minimize or maximize the growth of microorganisms and control pathogens, one must study the structure and characteristics of the microorganisms. The sections that follow look at each of the major groups of microorganisms (those important to wastewater operators) in relation to their size, shape, types, nutritional needs, and control.

Note: Koren (1991) observed that water is not a medium for the growth of microorganisms but is instead a means of transmission (or a conduit for; hence, the name *waterborne*) for carrying pathogens to places where individuals are able to consume them, thus initiating outbreaks of disease. This is contrary to the view taken by the average person; that is, when the topic of waterborne disease is brought up, many mistakenly assume that waterborne diseases are at home in the water. Nothing could be further from the truth. A water-filled ambience is not the environment in which the pathogenic organism would choose to live, if it had a choice. The point is that microorganisms do not normally grow, reproduce, languish, or thrive in watery surroundings. Pathogenic microorganisms temporarily residing in water are simply biding their time, going with the flow, waiting for their opportunity to meet up with their unsuspecting hosts. To a degree, when pathogenic microorganisms find a host, they are finally home, or may have found their final resting place (Spellman, 1997).

8.3.1 Key Terms

Key terms and basic definitions include the following:

Algae—Simple plants, many microscopic, containing chlorophyll. Freshwater algae are diverse in shape, color, size, and habitat. They are the basic link in the conversion of inorganic constituents in water into organic constituents.

Algae bloom—Sudden spurts of algae growth that can affect water quality adversely and indicate potentially hazardous changes in local water chemistry.

Anaerobic—Refers to the ability to live and grow in the absence of free oxygen.

Autotrophic organisms—Organisms that produce food from inorganic substances.

Bacteria—Single-cell, microscopic living organisms (single-celled microorganisms) that possess rigid cell walls. They may be aerobic, anaerobic, or facultative. They can cause disease, and some are important in pollution control.

Biogeochemical cycle—Chemical interactions among the atmosphere, hydrosphere, and biosphere.

Coliform organisms—Microorganisms found in the intestinal tract of humans and animals. Their presence in water indicates fecal pollution and potentially adverse contamination by pathogens.

Denitrification—Anaerobic biological reduction of nitrate to nitrogen gas.

Fungi—Simple plants lacking the ability to produce energy through photosynthesis.

Heterotrophic organisms—Organisms that are dependent on organic matter for foods.

Prokaryotic cell—A simple cell type characterized by the lack of a nuclear membrane and the absence of mitochondria.

Virus—The smallest form of microorganisms; capable of causing disease.

8.4 MICROORGANISMS (IN GENERAL)

The microorganisms we are concerned with are tiny organisms making up a large and diverse group of free-living forms; they exist as single cells, cell bunches, or clusters. Found in abundance almost anywhere on Earth, the vast majority of microorganisms are not harmful. Many microorganisms, or microbes, occur as single cells (unicellular), others are multicellular, and still others (viruses) do not have a true cellular appearance. A single microbial cell, for the most part, exhibits the characteristic features common to other biological systems, such as metabolism, reproduction, and growth.

8.4.1 Classification

For centuries, scientists classified the forms of life visible to the naked eye as either animal or plant. The Swedish naturalist Carolus Linnaeus organized much of the current knowledge about living things in 1735. The importance of organizing or classifying organisms cannot be overstated, for without a classification scheme it would be difficult to establish criteria for identifying organisms and arrange similar organisms into groups. Probably the most important reason for classifying organisms is to make things less confusing (Wistriech and Lechtman, 1980).

Linnaeus was quite innovative in his classification of organisms. His *binomial system of nomenclature* is still with us today. Under the binomial system, all organisms are generally described by a two-word scientific name, the *genus* and *species.* Genus and species are groups that are part of a hierarchy of groups of increasing size, based on their taxonomy. This hierarchy follows:

Kingdom
Phylum
Class
Order
Family
Genus
Species

Using this system, a *fruit fly* might be classified as:

Kingdom	Animalia
Phylum	Arthropoda
Class	Insecta
Order	Diptera
Family	Drosophilidae
Genus	*Drosophila*
Species	*melanogaster*

This means that this organism is the species *melanogaster* in the genus *Drosophila* in the family Drosophilidae in the order Diptera in the class Insecta in the phylum Arthropoda in the kingdom Animalia.

To further illustrate this hierarchical system, the standard classification of the *mayfly* is provided below:

Kingdom	Animalia
Phylum	Arthropoda
Class	Insecta

Order	Ephermeroptera
Family	Ephemeridae
Genus	*Hexagenia*
Species	*limbata*

Based on this hierarchy and Linnaeus' binomial system of nomenclature, the scientific name of any organism includes both the generic and specific names. To uniquely name a species, it is necessary to supply both the genus and the species; in the above examples, the names would be *Drosophila melanogaster* (fruit fly) and *Hexagenia limbata* (mayfly). The first letter of the generic name is usually capitalized; for example, *Escherichia coli* indicates that *coli* is the species and *Escherichia* (often abbreviated to *E.*) is the genus. The largest, most inclusive category is the plant kingdom. The names are always in Latin, so they are usually printed in italics or underlined. Some organisms also have English common names. Microbe names of particular interest in wastewater treatment include:

- *Escherichia coli* (a coliform bacterium)
- *Salmonella typhi* (the typhoid bacillus)
- *Giardia lamblia* (a protozoan)
- *Shigella* spp.
- *Vibrio cholerae*
- *Campylobacter*
- *Leptospira* spp.
- *Entamoeba histolytica*
- *Cryptosporidium*

Note: *Escherichia coli* is commonly referred to as simply *E. coli*, whereas *Giardia lamblia* is usually referred to by only its genus name, *Giardia.*

Generally, in water science we use a simplified system of microorganism classification, breaking them down into the kingdoms of Animalia, Plantae, and Protista. As a rule, the animal and plant kingdoms contain all of the multicell organisms, and the protists include all single-cell organisms. Along with microorganism classification based on the animal, plant, and protist kingdoms, microorganisms can be further classified as being *eucaryotic* or *prokaryotic* (see Table 8.1).

Note: A *eucaryotic* organism is characterized by a cellular organization that includes a well-defined nuclear membrane. The *prokaryotes* have a structural organization that sets them apart from all other organisms. They are simple cells characterized by a nucleus lacking a limiting membrane, an endoplasmic reticulum, chloroplasts, and mitochondria. They are remarkably adaptable, existing abundantly in the soil, the sea, and freshwater.

TABLE 8.1 SIMPLIFIED CLASSIFICATION OF MICROORGANISMS

Kingdom	Members	Cell Classification
Animal	Rotifers	
	Crustaceans	
	Worms and larvae	Eucaryotic
Plant	Ferns	
	Mosses	
Protista	Protozoa	
	Algae	
	Fungi	
	Bacteria	Prokaryotic
	Lower algae forms	

8.4.2 Differentiation

Differentiation among the higher forms of life is based almost entirely upon morphological (form or structure) differences; however, differentiation (even among the higher forms) is not as easily accomplished as you might expect, because normal variations among individuals of the same species occur frequently. Because of this variation even within a species, it becomes extremely difficult to determine an accurate classification of single-celled microscopic forms that present virtually no visible structural differences. Under these circumstances, it is necessary to consider physiological, cultural, and chemical differences, as well as structure and form. Differentiation among the smaller groups of bacteria is based almost entirely upon chemical differences.

8.5 THE CELL

The structural and fundamental unit of both plants and animals, no matter how complex, is the cell. Since the nineteenth century, scientists have known that all living things, whether animal or plant, are made up of cells. A typical cell is an entity, isolated from other cells by a membrane or cell wall. The cell membrane contains protoplasm and the nucleus (see Figure 8.1). The protoplasm within the cell is a living mass of viscous, transparent material. Within the protoplasm is a dense spherical mass called the *nucleus* or *nuclear material* (which cannot always be observed in bacteria) (see Figure 8.1 and Figure 8.2).

In a typical mature plant cell (see Figure 8.2), the cell wall is rigid and is composed of nonliving material, whereas in the typical animal cell the wall is an elastic, living membrane. Cells come in all sizes and shapes and also have a great variety of functions. Their average size ranges from bacteria too small to be seen with a light microscope to the largest known single cell, the ostrich egg. Microbial cells also have an extensive size range, some being larger than human cells (Kordon, 1993).

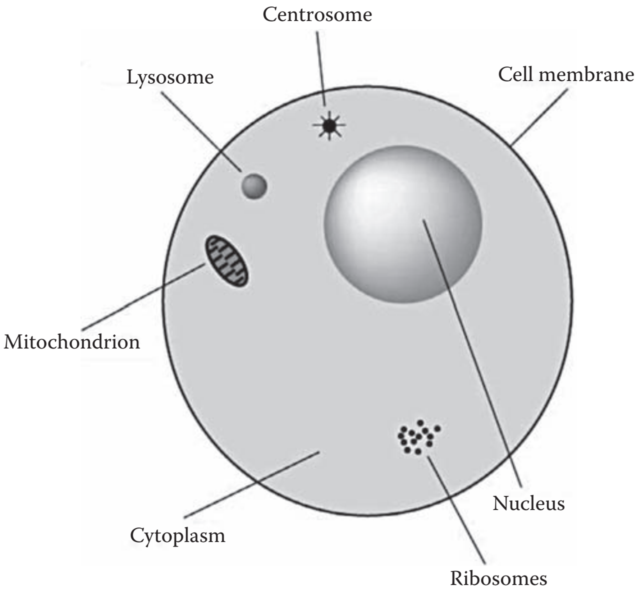

Figure 8.1 Animal cell.

8.5.1 Structure of the Bacterial Cell

The structural form and various components of the bacterial cell are probably best understood by referring to the simplified diagram of a rod-form bacterium shown in Figure 8.3.

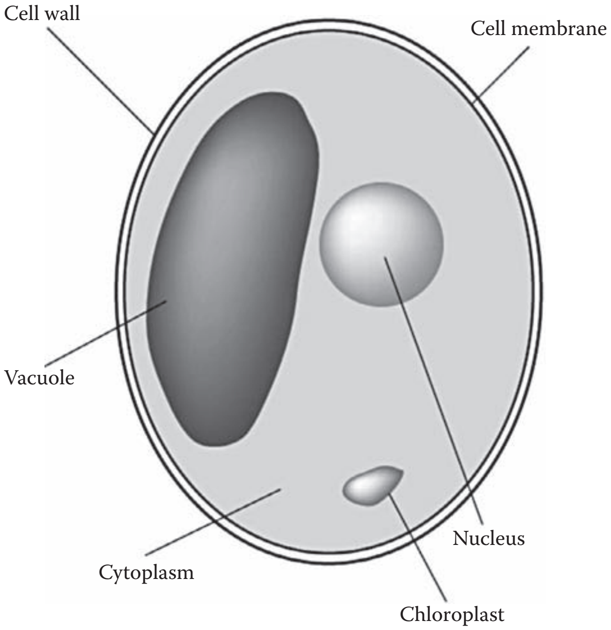

Figure 8.2 Plant cell.

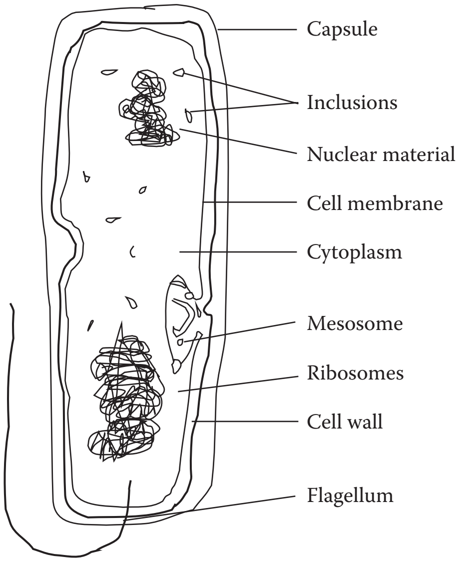

Figure 8.3 Bacterial cell.

Note: When studying Figure 8.3, keep in mind that cells of different species may differ greatly, both in structure and chemical composition; for this reason, no typical bacterium exists. Figure 8.3 shows a generalized bacterium used for the discussion that follows. Not all bacteria have all of the features shown in the figure, and some bacteria have structures not shown in the figure.

8.5.1.1 Capsules

Bacterial capsules (Figure 8.3) are organized accumulations of gelatinous materials on cell walls, in contrast to *slime layers* (a water secretion that adheres loosely to the cell wall and commonly diffuses into the cell), which are unorganized accumulations of similar material. The capsule is usually thick enough to be seen under the ordinary light microscope (macrocapsule), but very thin capsules (microcapsules) can be detected only by electron microscopy (Singleton and Sainsbury, 1994).

The production of capsules is determined largely by genetics as well as environmental conditions and depends on the presence or absence of capsule-degrading enzymes and other growth factors. Varying in composition, capsules are mainly composed of water; the organic contents are made up of complex polysaccharides, nitrogen-containing substance, and polypeptides.

Capsules confer several advantages when bacteria grow in their normal habitat; for example, they: (1) prevent desiccation, (2) resist phagocytosis by host phagocytic cells, (3) prevent infection by bacteriophages, and (4) aid bacterial attachment to tissue surfaces in plant and animal hosts or to surfaces of solids objects in aquatic environments. Capsule formation often correlates with pathogenicity.

8.5.1.2 Flagella

Many bacteria are motile. This ability to move independently is usually attributed to a special structure, the flagella (singular: *flagellum*). A flagellum is a threadlike appendage extending outward from the plasma membrane and cell wall. Flagella are slender, rigid, locomotor structures, about 20 µm across and up to 15 to 20 µm long. Depending on the species, a cell may have a single flagellum (i.e., monotrichous bacteria; *trichous* means "hair") (Figure 8.3); one flagellum at each end (i.e., amphitrichous bacteria; *amphi* means "on both sides"); a tuft of flagella at one or both ends (i.e., lophotrichous bacteria; *lopho* means "tuft"); or flagella that arise all over the cell surface (i.e., peritrichous bacteria; *peri* means "around").

Flagellation patterns are very useful in identifying bacteria and can be seen by light microscopy, but only after the flagella have been stained using special techniques designed to increase their thickness. The detailed structure of flagella can be seen only in the electron microscope.

Bacterial cells benefit from flagella in several ways. They can increase the concentration of nutrients or decrease the concentration of toxic materials near the bacterial surfaces by causing a change in the flow rate of fluids. They can also disperse flagellated organisms to areas where colony formation can take place. The main benefit of flagella to organisms is that they improve the organism's ability to flee from areas that might be harmful.

8.5.1.3 Cell Wall

The main structural component of most prokaryotes is the rigid cell wall (see Figure 8.3). Functions of the cell wall include: (1) providing protection for the delicate protoplast from osmotic lysis (bursting), (2) determining a cell's shape, (3) acting as a permeability layer that excludes large molecules and various antibiotics and plays an active role in regulating the cell's intake of ions, and (4) providing a solid support for flagella. Cell walls of various species may differ greatly in structure, thickness, and composition. The cell wall accounts for about 20 to 40% of the dry weight of a bacterium.

8.5.1.4 Plasma Membrane (Cytoplasmic Membrane)

Surrounded externally by the cell wall and composed of a lipoprotein complex, the *plasma membrane* or cell membrane is the critical barrier separating the inside of the cell from the outside (Figure 8.3). About 7 to 8 µm thick and comprising 10 to 20% of the dry weight of a bacterium, the plasma membrane controls the passage of all material into and out of the cell. The inner and outer faces of the plasma membrane are embedded with water-loving (hydrophilic) lips, whereas the interior is hydrophobic. Control of material into the cell is accomplished by screening, as well as by electric charge. The plasma membrane is the site of the surface charge of the bacteria.

In addition to serving as an osmotic barrier that passively regulates the passage of material into and out of the cell, the plasma membrane participates in the entire active transport of various substances into the bacterial cell. Inside the membrane, many highly reactive chemical groups guide the incoming material to the proper points for further reaction. This active transport system provides bacteria with certain advantages, including the ability to maintain a fairly constant intercellular ionic state in the presence of varying external ionic concentrations. In addition to participating in the uptake of nutrients, the cell membrane transport system participates in waste excretion and protein secretions.

8.5.1.5 Cytoplasm

Within a cell and bounded by the cell membrane is a complicated mixture of substances and structures called the *cytoplasm* (Figure 8.3). The cytoplasm is a water-based fluid containing ribosomes, ions, enzymes, nutrients, storage granules (under certain circumstances), waste products, and various molecules involved in synthesis, energy metabolism, and cell maintenance.

8.5.1.6 Mesosome

A common intracellular structure found in the bacterial cytoplasm is the mesosome (Figure 8.3). Mesosomes are invaginations of the plasma membrane in the shape of tubules, vesicles, or lamellae. Their exact function is unknown. Currently, many bacteriologists believe that mesosomes are artifacts generated during the fixation of bacteria for electron microscopy.

8.5.1.7 Nucleoid (Nuclear Body or Region)

The nuclear region of the prokaryotic cell is primitive and a striking contrast to that of the eucaryotic cell (Figure 8.3). Prokaryotic cells lack a distinct nucleus; the function of the nucleus is carried out by a single, long, double strand of DNA that is efficiently packaged to fit within the nucleoid. The nucleoid is attached to the plasma membrane. A cell can have more than one nucleoid when cell division occurs after the genetic material has been duplicated.

8.5.1.8 Ribosomes

The bacterial cytoplasm is often packed with ribosomes (Figure 8.3). Ribosomes are minute, rounded bodies made of RNA that are loosely attached to the plasma membrane. Ribosomes are estimated to account for about 40% of the dry weight of a bacterium; a single cell may have as many as 10,000 ribosomes. Ribosomes are the site of protein synthesis and are part of the translation process.

8.5.1.9 Inclusions

Inclusions (or storage granules) are often seen within bacterial cells (see Figure 8.3). Some inclusion bodies are not bound by a membrane and lie free in the cytoplasm. A single-layered membrane about 2 to 4 µm thick encloses other inclusion bodies. Many bacteria produce polymers that are stored as granules in the cytoplasm.

8.6 BACTERIA

The simplest wholly contained life systems are bacteria, or prokaryotes, which are the most diverse group of microorganisms. As mentioned, they are among the most common microorganisms in water. They are primitive, unicellular (single-celled) organisms that possess no well-defined nucleus and present a variety of shapes and nutritional needs. Bacteria contain about 85% water and 15% ash or mineral matter. The ash is largely composed of sulfur, potassium, sodium, calcium, and chlorides, with small amounts of iron, silicon, and magnesium. Bacteria reproduce by binary fission.

Note: Binary fission occurs when one organism splits or divides into two or more new organisms.

Bacteria were once considered to be the smallest living organisms, but today it is known that smaller forms of matter exhibit many of the characteristics of life. They range in size from 0.5 to 2 µm in diameter and about 1 to 10 µm long.

Note: A *micron* (µm) is a metric unit of measurement equal to one-thousandth of a millimeter. To visualize the size of bacteria, consider that about 1000 bacteria lying side-by-side would reach across the head of a straight pin.

Bacteria are categorized into three general groups based on their physical form or shape (although almost every variation has been found; see Table 8.2). The simplest form is the sphere. Spherical-shaped bacteria are called *cocci* ("berries"). They are not necessarily perfectly round but may be somewhat elongated, flattened on one side, or oval. Rod-shaped bacteria are called *bacilli*. Spiral-shaped bacteria (*spirilla*) have one or more twists and are never straight (see Figure 8.4). Such formations are usually characteristic of a particular genus or species. Within these three groups are many different arrangements. Some exist as single cells; others as pairs, as packets of four or eight, as chains, or as clumps.

TABLE 8.2 FORMS OF BACTERIA

	Technical Name		
Form	**Singular**	**Plural**	**Example**
Sphere	Coccus	Cocci	*Streptococcus*
Rod	Bacillus	Bacilli	*Bacillus typhosis*
Curved or spiral	Spirillum	Spirilla	*Spirillum cholera*

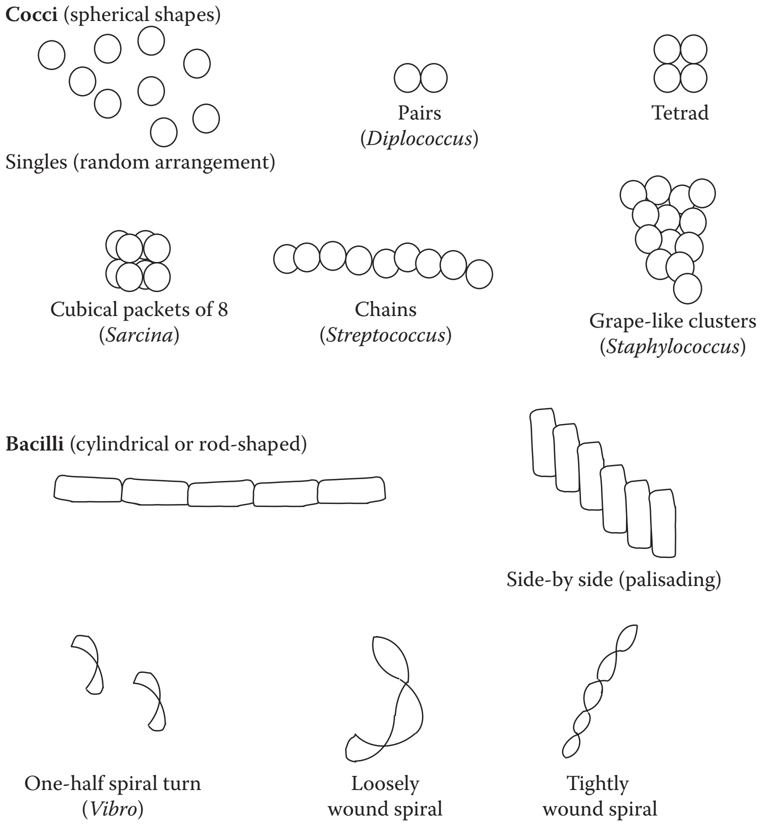

Figure 8.4 Bacterial shapes and arrangements.

Most bacteria require *organic food* to survive and multiply. Plant and animal material that gets into the water provides the food source for bacteria. Bacteria convert the food to energy and use the energy to make new cells. Some bacteria can use inorganics (e.g., minerals such as iron) as an energy source and exist and multiply even when organics (pollution) are not available.

8.6.1 Bacterial Growth Factors

Several factors affect the rate at which bacteria grow, including temperature, pH, and oxygen levels. The warmer the environment, the faster the rate of growth. Generally, for each increase of 10°C, the growth rate doubles. Heat can also be used to kill bacteria. Most bacteria grow best at neutral pH. Extreme acidic or basic conditions generally inhibit growth, although some bacteria may require acidic and some alkaline conditions for growth.

Bacteria are aerobic, anaerobic, or facultative. If *aerobic*, they require free oxygen in the aquatic environment. *Anaerobic* bacteria exist and multiply in environments that lack dissolved oxygen. *Facultative* bacteria (e.g., iron bacteria) can switch from aerobic to anaerobic growth or grow in an anaerobic or aerobic environment.

Under optimum conditions, bacteria grow and reproduce very rapidly. As stated previously, bacteria reproduce by *binary fission*. An important point to consider in connection with bacterial reproduction is the rate at which the process can take place. The total time required for an organism to reproduce and the offspring to reach maturity is the *generation time*. Bacteria growing under optimal conditions can double their number about every 20 to 30 minutes. Obviously, this generation time is very short compared with that of higher plants and animals. Bacteria continue to grow at this rapid rate as long as nutrients hold out—even the smallest contamination can result in a sizable growth in a very short time.

Note: Even though wastewater can contain bacteria counts in the millions per milliliter, in wastewater treatment, under controlled conditions, bacteria can help to destroy and to identify pollutants. In such a process, bacteria stabilize organic matter (e.g., activated sludge processes) and thereby assist the treatment process in producing effluent that does not impose an excessive oxygen demand on the receiving body. Coliform bacteria can be used as an indicator of pollution by human or animal wastes.

8.6.2 Destruction of Bacteria

In water and wastewater treatment, the process of destroying bacteria is usually referred to as *disinfection*. Disinfection does not mean that all microbial forms are killed. That would be *sterilization*. Instead, disinfection reduces the number of disease-causing organisms to an acceptable number. Growing bacteria are easy to control by disinfection; however, bacteria that form spores (survival structures) are much more difficult to destroy.

Key Point: Inhibiting the growth of microorganisms is termed *antisepsis*; destroying them is called *disinfection*.

8.6.3 Waterborne Bacteria

All surface waters contain bacteria. Waterborne bacteria, as we have said, are responsible for infectious epidemic diseases. Bacterial numbers increase significantly during storm events when streams are high. Heavy rainstorms increase stream contamination by washing material from the ground surface into the stream. After the initial washing occurs, few impurities are left to be washed into the stream, which may then carry relatively “clean” water. A river of good quality shows its highest bacterial numbers during rainy periods; however, a much-polluted stream may show the highest numbers during low flows, because of the constant influx of pollutants.

Water and wastewater operators are primarily concerned with bacterial pathogens responsible for disease. These pathogens enter potential drinking water supplies through fecal contamination and are ingested by humans if the water is not properly treated and disinfected.

Note: Regulations require that owners of all public water supplies collect water samples and deliver them to a certified laboratory for bacteriological examination at least monthly. The number of samples required is usually mandated by federal standards, which generally require that one sample per month be collected for each 1000 persons served by the waterworks.

8.7 PROTOZOA

Protozoans ("first animals") are a large group of eucaryotic organisms of more than 50,000 known species belonging to the Protista kingdom; they have adapted a form of cell that serves as the entire body. In fact, protozoans are one-celled animal-like organisms with complex cellular structures. In the microbial world, protozoans are giants, many times larger than bacteria. They range in size from 4 to 500 µm. The largest ones can almost be seen by the naked eye. They can exist as solitary or independent organisms, such as the *Vorticella* sp., a stalked ciliate (Figure 8.5), or they can colonize, such as the sedentary *Carchesium* sp. Protozoa get their name because they employ the same type of feeding strategy as animals; that is, they are heterotrophic, meaning they obtain cellular energy from organic substances such as proteins. Most are harmless, but some are parasitic. Some forms have two life stages: active trophozoites (capable of feeding) and dormant cysts.

The major groups of protozoans are classified based on their method of locomotion (motility). For example, members of the phylum Mastigophora are motile by means of one of more flagella, the whip-like projection that propels the free-swimming organisms (*Giardia lamblia* is a flagellated protozoan). Members of the phylum Ciliophora use shortened modified flagella called *cilia*, short hair-like structures that beat rapidly and propel them through the water. The phylum Sarcodina utilizes amoeboid movement (a streaming or gliding action); the shape of an amoeba changes as it stretches, then contracts, to move from place to place. Sporozoa are nonmotile; they are simply swept along, riding the current of the water.

Key Point: Protozoans not completely resistant to chlorination require higher disinfectant concentrations and longer contact time for disinfection than normally used in water treatment.

Protozoa consume organics to survive; their favorite food is bacteria. Protozoa are mostly aerobic or facultative with regard to oxygen requirements. Toxic materials, pH, and temperature affect protozoan rates of growth in the same way as they affect bacteria. Most protozoan life cycles alternate between an active growth phase (*trophozoites*) and a resting stage (*cysts*). Cysts are extremely resistant structures that protect the organism from destruction when it encounters harsh environmental conditions—including chlorination.

The three protozoans and waterborne diseases associated with them that are of most concern to the waterworks operator are:

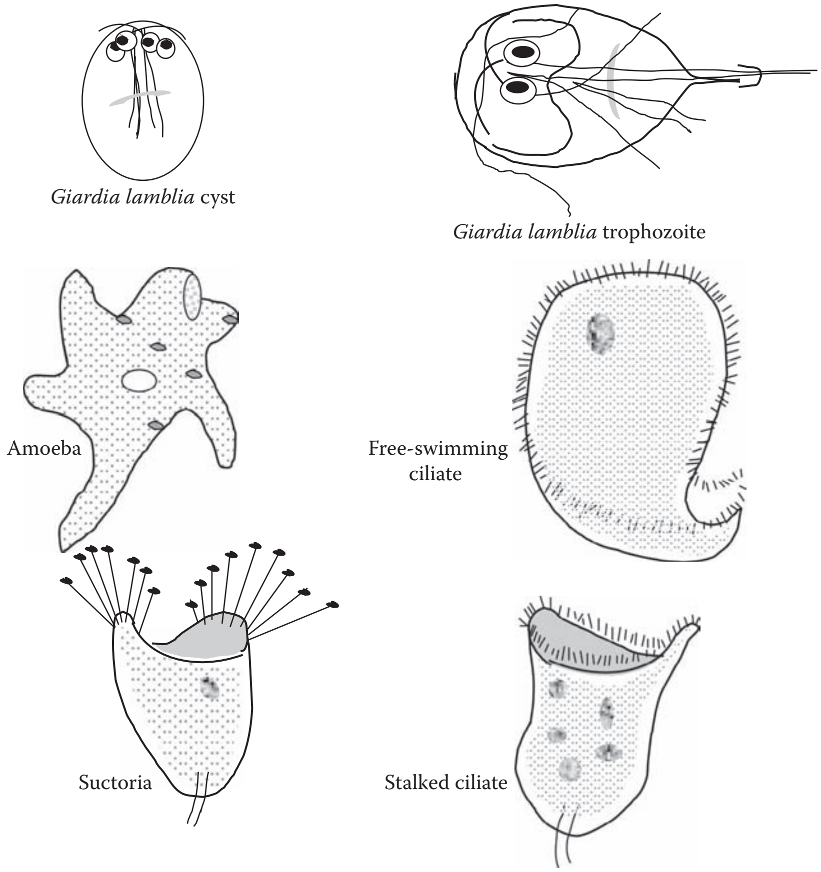

Figure 8.5 Protozoa.

- *Entamoeba histolytica* (amoebic dysentery)
- *Giardia lamblia* (giardiasis)
- *Cryptosporidium* (cryptosporidiosis)

In wastewater treatment, protozoa are a critical component of the purification process and can be used to indicate the condition of treatment processes. Protozoa normally associated with wastewater include amoebae, flagellates, free-swimming ciliates, and stalked ciliates.

The presence of *amoebae* is associated with poor wastewater treatment of a young biosolids mass (Figure 8.5). They move through wastewater by a streaming or gliding motion produced by the movement of liquids stored within the cell wall. They are normally associated with an effluent high in biochemical oxygen demand (BOD) and suspended solids.

Flagellates (flagellated protozoa) have a single, long hair-like or whip-like projection (flagella) that is used to propel the free-swimming organisms through wastewater and to attract food (Figure 8.5). Flagellated protozoans are normally associated with poor treatment and a young biosolids. When the predominate organisms are flagellated protozoa, the plant effluent will contain large amounts of BOD and suspended solids.

The *free-swimming ciliated protozoan* uses its tiny, hair-like projections (cilia) to move itself through the wastewater and to attract food (Figure 8.5). The free-swimming ciliated protozoan is normally associated with a moderate biosolids age and effluent quality. When the free-swimming ciliated protozoan is the predominate organism, the plant effluent will normally be turbid and contain a high amount of suspended solids.

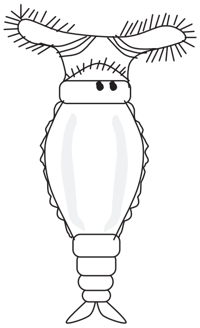

Figure 8.6 Philodina, a common rotifer.

The *stalked ciliated protozoan* attaches itself to the wastewater solids and uses its cilia to attract food (Figure 8.5). The stalked ciliated protozoan is normally associated with a plant effluent that is very clear and contains low amounts of both BOD and suspended solids.

Rotifers are a well-defined group of the smallest, simplest multicellular microorganisms that are found in nearly all aquatic habitats (see Figure 8.6). Rotifers are a higher life form associated with cleaner waters. Normally found in well-operated wastewater treatment plants, they can be used to indicate the performance of certain types of treatment processes.

8.8 MICROSCOPIC CRUSTACEANS

Because they are important members of freshwater zooplankton, microscope *crustaceans* are of interest to water and wastewater operators. These microscopic organisms are characterized by a rigid shell structure. They are multicellular animals that are strict aerobes, and as primary producers they feed on bacteria and algae. They are important as a source of food for fish. Additionally, microscopic crustaceans have been used to clarify algae-laden effluents from oxidation ponds. *Cyclops* and *Daphnia* are two microscopic crustaceans of interest to water and wastewater operators.

8.9 VIRUSES

Viruses are very different from the other microorganisms. Consider their size, for example. Relative to size, if protozoans are the Goliaths of microorganisms, then viruses are the Davids. Stated more specifically and accurately, viruses are intracellular parasitic particles that are the smallest living infectious materials known—the midgets of the microbial world. Viruses are very simple life forms consisting of a central molecule of genetic material surrounded by a protein shell called a *capsid* and sometimes by a second layer called an *envelope*. They contain no mechanisms by which to obtain energy or reproduce on their own; thus, to live, viruses must have a host. After they invade the cells of their specific host (animal, plant, insect, fish, or even bacteria), they take over the host's cellular machinery and force it to make more viruses.

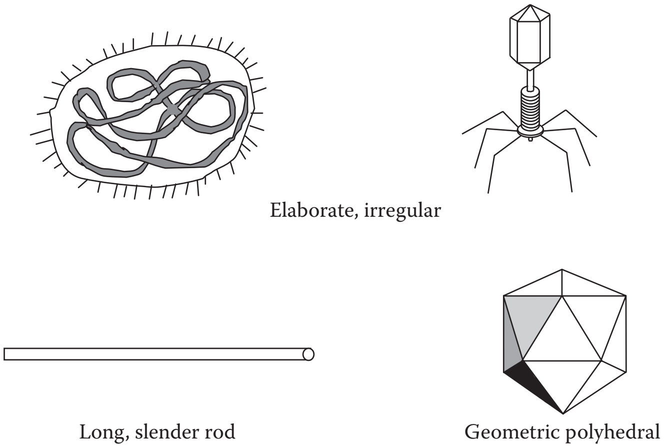

Figure 8.7 Elaborate shapes of virus.

In the process, the host cell is destroyed and hundreds of new viruses are released into the environment. The viruses of most concern to the waterworks operator are the pathogens that cause hepatitis, viral gastroenteritis, and poliomyelitis.

Smaller and different from bacteria, viruses are prevalent in water contaminated with sewage. Detecting viruses in water supplies is a major problem because of the complexity of the nonroutine procedures involved, although experience has shown that the normal coliform index can be used as a rough guide for viruses just as for bacteria. However, more attention must be paid to viruses whenever surface water supplies have been used for sewage disposal. Viruses are difficult to destroy by normal disinfection practices; increased disinfectant concentration and contact time are required for the effective destruction of viruses. Viruses occur in many shapes, including long, slender rods; elaborate, irregular forms; and geometric polyhedrals (see Figure 8.7).

Note: Viruses that infect bacterial cells cannot infect and replicate within cells of other organisms. It is possible to utilize this specificity to identify bacteria, a procedure called *phage typing*.

8.10 ALGAE

You do not have to be a water/wastewater operator to understand that algae can be a nuisance. Many ponds and lakes in the United States are currently undergoing *eutrophication*, the enrichment of an environment with inorganic substances (e.g., phosphorus and nitrogen), causing excessive algae growth and premature aging of the water body. The average person may not know what eutrophication means; however, when eutrophication occurs, and especially when filamentous algae such as *Caldophora* break loose in a pond or lake and wash ashore, algae make their stinking, noxious presence known.

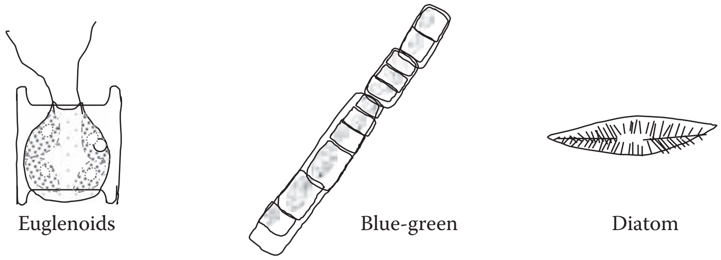

Figure 8.8 Algae.

Algae are a form of aquatic plants and are classified by color (e.g., green algae, blue–green algae, golden–brown algae). Algae come in many shapes and sizes (see Figure 8.8). Although they are not pathogenic, algae do cause problems with water/wastewater treatment plant operations. They grow easily on the walls of troughs and basins, and heavy growth can plug intakes and screens. Additionally, some algae release chemicals that give off undesirable tastes and odors. As mentioned, algae are usually classified by their color; however, they are also commonly classified based on their cellular properties or characteristics, including: (1) cellular organization and cell wall structure; (2) the nature of the chlorophyll; (3) the type of motility, if any; (4) the carbon polymers that are produced and stored; and (5) the reproductive structures and methods.

Many algae (in mass) are easily seen by the naked eye; others are microscopic. They occur in fresh and polluted water, as well as in saltwater. Because they are plants, they are capable of using energy from the sun in photosynthesis. They usually grow near the surface of the water because light cannot penetrate very far through the water.

Algae are controlled in raw waters with chlorine and potassium permanganate. Algae blooms in raw water reservoirs are often controlled with copper sulfate.

Note: By producing oxygen, which is utilized by other organisms including animals, algae play an important role in the balance of nature.

8.11 FUNGI

Fungi are of relatively minor importance in water/wastewater operations (except for biosolids composting, where they are critical). Fungi, like bacteria, are also extremely diverse. They are multicellular, autotrophic, photosynthetic protists. They grow as filamentous, mold-like forms or as yeast-like (single-celled) organisms. They feed on organic material.

Note: Aquatic fungi grow as *parasites* on living plants or animals and as *saprophytes* on those that are dead.

8.12 NEMATODES AND FLATWORMS (WORMS)

Along with inhabiting organic mud, worms also inhabit biological slimes; they have been found in activated sludge and in trickling filter slimes (wastewater treatment processes). Generally microscopic in size, they can range in length from 0.5 to 3 mm and in diameter from 0.01 to 0.05 mm. Most species have a similar appearance. They have a body that is covered by cuticle, cylindrical, nonsegmented, and tapered at both ends.

These organisms continuously enter wastewater treatment systems, primarily through attachment to soils that reach the plant through inflow and infiltration (I&I). They are present in large, often highly variable numbers, but as strict aerobes they are found only in aerobic treatment processes where they metabolize solid organic matter.

Once nematodes are firmly established in the treatment process, they can promote microfloral activity and decomposition. They feed on bacteria in both the activated sludge and trickling filter systems. Their activities in these systems enhance oxygen penetration due to their tunneling through floc particles and biofilm. In activated sludge processes, they are present in relatively small numbers because the liquefied environment is not a suitable habitat for crawling, which they prefer over the free-swimming mode. In trickling filters where the fine stationary substratum is suitable to permit crawling and mating, nematodes are quite abundant.

Not only do nematodes prefer the trickling filter habitat, but they also play a beneficial role in this habitat. For example, they break loose portions of the biological slime coating the filter bed. This action prevents excessive slime growth and filter clogging. They also aid in keeping slime porous and accessible to oxygen by tunneling through the slime. In the activated sludge process, nematodes play an important role as agents of better oxygen diffusion. They accomplish this by tunneling through floc particles. They also act as indicators of operational conditions in the process, such as low dissolved oxygen levels (anoxic conditions) and the presence of toxic wastes.

Environmental conditions have an impact on the growth of nematodes; for example, in anoxic conditions their swimming and growth are impaired. The most important condition they indicate is changes in the wastewater strength or composition. Temperature fluctuations directly affect their growth and survival—their population decreases when temperatures increase.

Aquatic flatworms (improperly named because they are not all flat) feed primarily on algae. Because of their aversion to light, they are found in the lower depths of pools. Two varieties of flatworms are seen in wastewater treatment processes. *Microtubellarians* are more round than flat and average about 0.5 to 5 mm in size, whereas *macrotubellarians* (planarians) are more flat than round and average about 5 to 20 mm in body size. Flatworms are very hardy and can survive wide variations in humidity and temperature. As inhabitants of sewage sludge, they

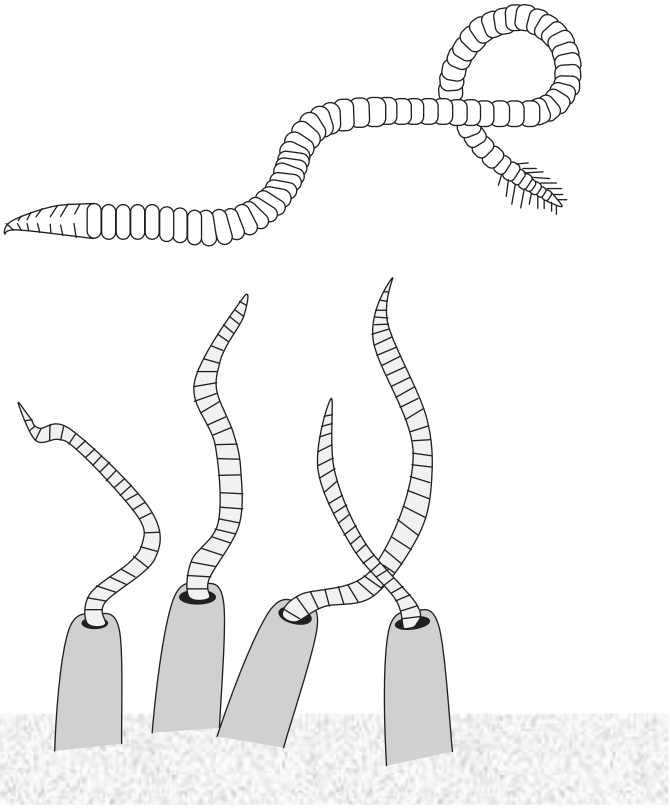

Figure 8.9 Tubificid worms.

play an important role in sludge stabilization and serve as bioindicators or parameters of process problems; as noted earlier, their inactivity or sluggishness might indicate a low dissolved oxygen level or the presence of toxic wastes.

Surface waters grossly polluted with organic matter (especially domestic sewage) have fauna capable of thriving in very low concentrations of oxygen. A few species of tubificid worms dominate this environment. Pennak (1989) reported that the bottoms of severely polluted streams can be literally covered with a "writhing" mass of these tubificids.

Tubifex (commonly known as *sludge worms*) are small, slender, reddish worms that normally range in length from 25 to about 50 mm. They are burrowers; their posterior end protrudes to obtain nutrients (see Figure 8.9). When found in streams, *Tubifex* are indicators of pollution.

8.13 HELMINTHS

Helminths are parasitic worms that grow and multiply in sewage (biological slimes) and wet soil (mud). They multiply in wastewater treatment plants. Strict aerobes, they have been found in activated sludge and particularly in trickling filters and therefore appear in large concentrations in treated domestic liquid waste. They enter via the skin or by ingestion of the worm during one of its many life-cycle phases. Generally, they are not a problem in drinking water supplies in the United States because both their egg and larval forms are large enough to be trapped during conventional water treatment. In addition, most helminths are not waterborne, so chances of infection are minimized (WHO, 1996).

8.14 BIOLOGICAL ASPECTS OF WASTEWATER TREATMENT PROCESSES

Uncontrolled bacteria in industrial water systems produce an endless variety of problems, including disease, equipment damage, and product damage. Unlike the microbiological problems that can occur in water systems, microbiology can be applied in wastewater treatment as a beneficial science for the destruction of pollutants in wastewater (Kemmer, 1979).

It should be noted that all of the biological processes used for the treatment of wastewater (in particular) are derived or modeled from processes occurring naturally in nature. The processes discussed here are typical examples. It also should be noted, “that by controlling the environment of microorganisms, the decomposition of wastes is speeded up. Regardless of the type of waste, the biological treatment process consists of controlling the environment required for optimum growth of the microorganism involved” (Metcalf & Eddy, 2003).

8.14.1 Aerobic Process

In aerobic treatment processes, organisms use free, elemental oxygen and organic matter together with nutrients (nitrogen, phosphorus) and trace metals (iron, etc.) to produce more organisms and stable dissolved and suspended solids and carbon dioxide (see Figure 8.10)

8.14.2 Anaerobic Process

The anaerobic treatment process consists of two steps, occurs completely in the absence of oxygen, and produces a useable byproduct, methane gas. In the first step of the process, facultative microorganisms use the organic matter as food to produce more organisms; volatile (organic) acids; carbon dioxide, hydrogen sulfide, and other gases; and some stable solids (see Figure 8.11). In the second step, anaerobic microorganisms use the volatile acids as their food source. The process produces more organisms, stable solids, and methane gas that can be used to provide energy for various treatment system components (see Figure 8.12).

Oxygen
Bacteria
Organic matter
Nutrients

⇨

More bacteria
Stable solids
Settleable solids
Carbon dioxide

Figure 8.10 Aerobic decomposition.

Facultative bacteria
Organic matter
Nutrients

⇨

More bacteria
Volatile solids
Settleable solids
Hydrogen sulfide

Figure 8.11 Anaerobic decomposition, first step.

Anaerobic bacteria
Volatile acids
Nutrients

⇨

More bacteria
Stable solids
Settleable solids
Methane

Figure 8.12 Anaerobic decomposition, second step.

Nitrate oxygen
Bacteria
Organic matter
Nutrients

⇨

More bacteria
Stable solids
Settleable solids
Nitrogen

Figure 8.13 Anoxic decomposition.

Sun
Algae
Carbon dioxide
Nutrients

⇨

More algae
Oxygen

Figure 8.14 Photosynthesis.

8.14.3 Anoxic Process

In the anoxic (“without oxygen”) treatment process, microorganisms use the fixed oxygen in nitrate compounds as a source of energy. The process produces more organisms and removes nitrogen from the wastewater by converting it to nitrogen gas, which is released into the air (see Figure 8.13).

8.14.4 Photosynthesis

Green algae use carbon dioxide and nutrients in the presence of sunlight and chlorophyll to produce more algae and oxygen (see Figure 8.14).

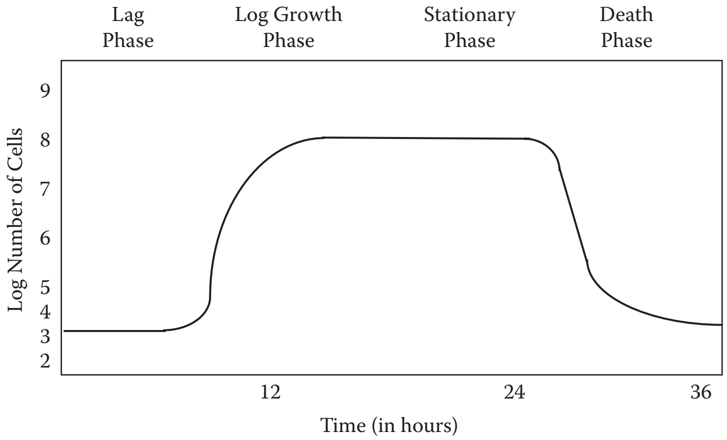

Figure 8.15 Microbe growth curve. The four phases of the growth curve are identified on the curve.

8.15 GROWTH CYCLES

All organisms follow a basic growth cycle that can be shown as a growth curve. This curve occurs when the environmental conditions required for the particular organism are reached. The environmental conditions (i.e., oxygen availability, pH, temperature, presence or absence of nutrients, presence or absence of toxic materials) determine when a particular group of organisms will predominate. Obviously, this information can be very useful in operating a biological treatment process (see Figure 8.15).

8.16 STREAM SELF- (NATURAL) PURIFICATION

Note: It is important for wastewater operators to understand the self-purification process in streams because, as stated earlier, in a sense, wastewater treatment is a stream in a box.

Self- or natural purification refers to the ability of a stream or river (given enough time and distance) to purify itself. For example, when wastewater is discharged to a body of moving water, natural processes occur that will remove some forms of pollution from the water (see Figure 8.16). This process has been ongoing since time immemorial. It is only when the stream becomes overloaded with pollution that the natural cleaning action is retarded. When wastes were less complex than they are today, natural processes could remove the majority of pollutants; however, with increasing population levels (more and larger settlements along rivers and streams), the natural process has much more difficulty doing so.

As shown in Figure 8.16, the natural process consists of four zones or stages (although it is sometimes difficult to distinguish when one zone ends and the next begins). Let's take a look at each of these zones and how the self-purification process actually works.

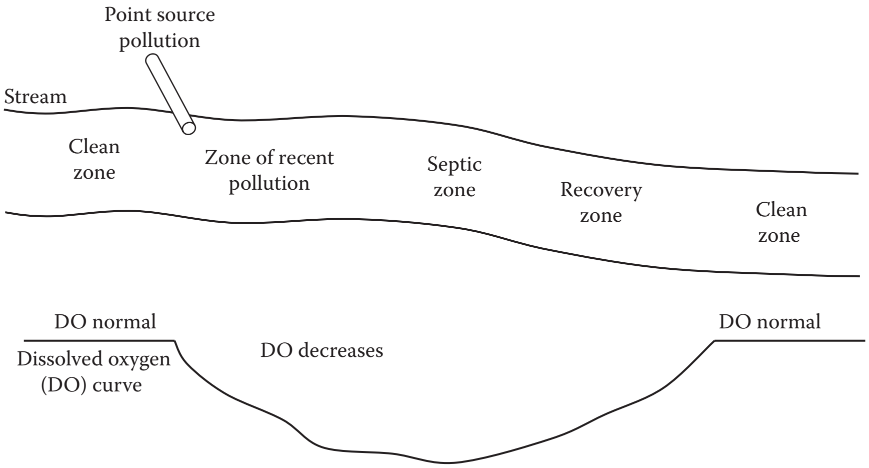

Figure 8.16 Stream zones of pollution.

Zone 1. Degradation

- Wastewater enters the body of water.
- Solids begin to settle, forming sludge banks on the bottom.
- Dissolved oxygen levels in the stream decrease rapidly.
- Water takes on the characteristic color of the wastes.
- Fish population decreases rapidly.
- Bacterial population increases rapidly.

Zone 2. Active decomposition

- Oxygen level is zero.
- Fish life is zero.
- Concentrations of bacteria and other sewage-related organisms are high.
- Color is black.
- Odor is rotten egg odor of hydrogen sulfide.

***Note*:** This zone may not occur if the oxygen demand of the waste discharged does not exceed the aeration rate of the body of water.

Zone 3. Recovery

- Oxygen level begins to increase rapidly.
- Color begins to return to normal.
- Fish population increases.
- Bacterial/microorganism population decreases.
- Odor decreases.

Zone 4. Clean water

- Oxygen levels are at or near saturation.
- Fish populations have returned to normal.
- Color and odor are returning to normal.

Note: The self-purification process removes solids that can settle and organic materials that can be removed by biological activity. It will not remove toxic materials, and it will not remove organic matter when toxic material is present until dilution reduces the concentration of the toxic material enough to eliminate the toxic effect. The process does not remove: (1) disease-causing organisms, (2) dissolved inorganic solids, (3) toxic material, or (4) inorganic dyes. The process can take a long time to complete (up to 30 river miles or more), and the condition of the stream can return to degradation or decomposition due to the addition of more wastes before the process is complete.

8.17 BIOGEOCHEMICAL CYCLES

Several chemicals are essential to life and follow predictable cycles through nature. In these natural cycles, or biogeochemical cycles, the chemicals are converted from one form to another as they progress through the environment. The water/wastewater operator should be aware of the cycles dealing with nutrients (i.e., carbon, nitrogen, and sulfur) because they have a major impact on the performance of the plant and may require changes in operation at various times of the year to keep them functioning properly; this is especially the case in wastewater treatment. The microbiology of each cycle deals with the biotransformation and subsequent biological removal of these nutrients in wastewater treatment plants.

Note: Smith (1974) categorized biogeochemical cycles into two types: *gaseous* and *sedimentary*. Gaseous cycles include the carbon and nitrogen cycles; the main sinks of nutrients in the gaseous cycle are the atmosphere and the ocean. Sedimentary cycles include the sulfur cycle; the main sinks for sedimentary cycles are the soil and rocks of the Earth's crust.

8.17.1 Carbon Cycle

Carbon, which is an essential ingredient of all living things, is the basic building block of the large organic molecules necessary for life. Carbon is cycled into food chains from the atmosphere, as shown in Figure 8.17. From Figure 8.17, it can be seen that green plants obtain carbon dioxide (CO_2) from the air and, through photosynthesis, which was described by Asimov (1989) as the "most important chemical process on Earth," it produces the food and oxygen that all organisms require. Part of the carbon produced remains in living matter; the other part is released as CO_2 in cellular respiration. The carbon dioxide released by cellular respiration in all living organisms is returned to the atmosphere (Miller, 1988).

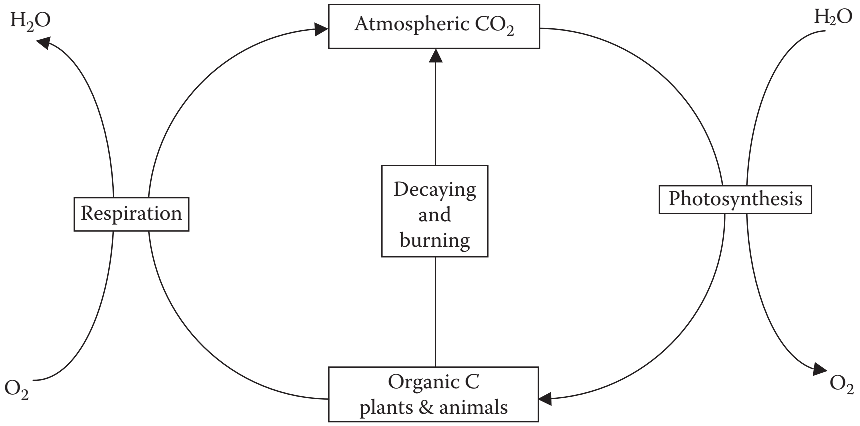

Figure 8.17 Carbon cycle.

Some carbon is contained in buried, dead animal and plant materials. Much of these buried animal and plant materials were transformed into fossil fuels. Fossil fuels—coal, oil, and natural gas—contain large amounts of carbon. When fossil fuels are burned, stored carbon combines with oxygen in the air to form carbon dioxide, which enters the atmosphere. In the atmosphere, carbon dioxide acts as a beneficial heat screen, as it does not allow the Earth's heat to radiate into space. This balance is important. The problem is that, as more carbon dioxide from burning is released into the atmosphere, the balance can and is being altered. Odum (1983) warned that increases in the consumption of fossil fuels "coupled with the decrease in 'removal capacity' of the green belt is beginning to exceed the delicate balance." Massive releases of carbon dioxide into the atmosphere tend to increase the possibility of global warming. The consequences of global warming "would be catastrophic … and the resulting climatic change would be irreversible" (Abrahamson, 1988).

8.17.2 Nitrogen Cycle

Nitrogen is an essential element required by all organisms. In animals, nitrogen is a component of crucial organic molecules, such as proteins and DNA, and it constitutes 1 to 3% dry weight of cells. Our atmosphere contains 78% by volume of nitrogen, yet it is not a common element on Earth. Although nitrogen is an essential ingredient for plant growth, it is chemically very inactive, and it must be *fixed* before the vast majority of the biomass can incorporate it. Special nitrogen-fixing bacteria found in soil and water fix nitrogen; thus, microorganisms play a major role in nitrogen cycling in the environment. These microorganisms (bacteria) have the ability to take nitrogen gas from the air and convert it to nitrate via a process known as *nitrogen fixation.* Some of these bacteria occur as free-living organisms in the soil. Others live in a *symbiotic relationship* with plants. A symbiotic relationship is a close relationship between two organisms of different species where both partners benefit from the association. An example of a symbiotic relationship related to nitrogen can be seen, for example, in the roots of

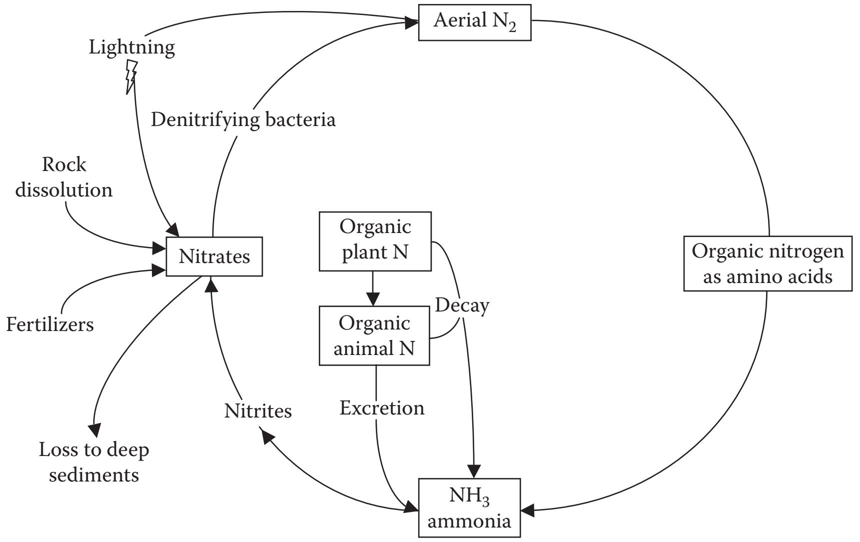

Figure 8.18 Nitrogen cycle.

peas. These roots have small swellings along their length. These contain millions of symbiotic bacteria that have the ability to take nitrogen gas from the atmosphere and convert it to nitrates that can be used by the plant. The plant is then plowed back into the soil after the growing season to improve the nitrogen content.

Price (1984) described the nitrogen cycle as an example "of a largely complete chemical cycle in ecosystems with little leaching out of the system." Simply, the nitrogen cycle provides various bridges between the atmospheric reservoirs and the biological communities (see Figure 8.18).

Atmospheric nitrogen is fixed by either natural or industrial means; for example, nitrogen is fixed by lightning or by soil bacteria that convert it to ammonia, then to nitrite, and finally to nitrates, which plants can use. Nitrifying bacteria make nitrogen from animal wastes. Denitrifying bacteria convert nitrates back to nitrogen and release it as nitrogen gas.

The logical question now is "What does all of this have to do with water?" The best way to answer this question is to ask another question. Have you ever dived into a slow-moving stream and had the noxious misfortune to surface right in the middle of an algae bloom? When this happens to you, the first thought that runs through your mind is, "Where is my nose plug?" Why? Because of the horrendous stench, disablement of the olfactory sense is a necessity.

If too much nitrate, for example, enters the water supply as runoff from fertilizers, it produces an overabundance of algae known as an *algae bloom*. If this runoff from fertilizer gets into a body of water, algae may grow so profusely that they form a blanket over the surface. This usually happens in summer, when the light levels and warm temperatures favor rapid growth.

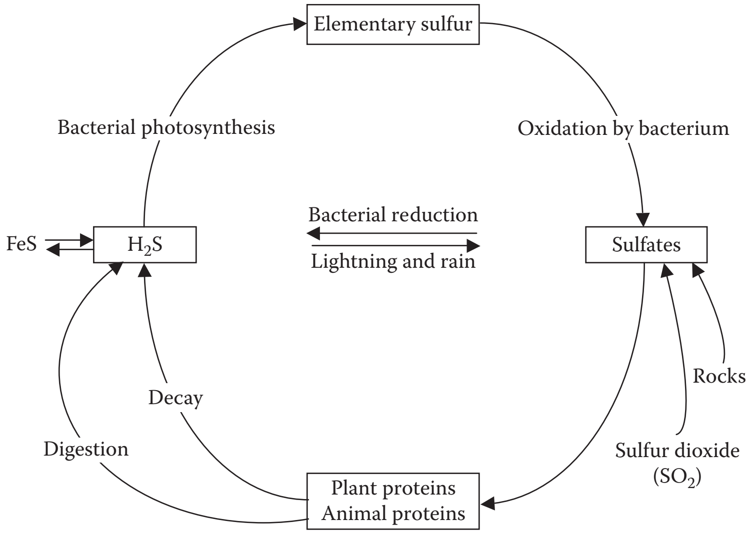

Figure 8.19 Sulfur cycle.

In the voluminous and authoritative text *Wastewater Engineering: Treatment, Disposal, & Reuse* (Metcalf & Eddy, 2003), it is noted that nitrogen is found in wastewater in the form of urea. During wastewater treatment, the urea is transformed into ammonia nitrogen. Because ammonia exerts a BOD and chlorine demand, high quantities of ammonia in wastewater effluents are undesirable. The process of *nitrification* is utilized to convert ammonia to nitrates. Nitrification is a biological process that involves the addition of oxygen to the wastewater. If further treatment is necessary, another biological process called *denitrification* is used. In this process, nitrate is converted into nitrogen gas, which is lost to the atmosphere, as can be seen in Figure 8.18. From the wastewater operator's point of view, nitrogen and phosphorus are both considered limiting factors for productivity. Phosphorus discharged into streams contributes to pollution. Of the two, nitrogen is more difficult to control but is found in smaller quantities in wastewater.

8.17.3 Sulfur Cycle

Sulfur, like nitrogen, is characteristic of organic compounds. The *sulfur cycle* is both sedimentary and gaseous (see Figure 8.19). The principal forms of sulfur that are of special significance in water quality management are organic sulfur, hydrogen sulfide, elemental sulfur, and sulfate (Tchobanoglous and Schroeder, 1985). Bacteria play a major role in the conversion of sulfur from one form to another. In an anaerobic environment, bacteria break down organic matter, thereby producing hydrogen sulfide with its characteristic rotten-egg odor. The bacterium *Beggiatoa* converts hydrogen sulfide into elemental sulfur into sulfates. Other sulfates are contributed by the dissolving of rocks and some sulfur dioxide. Sulfur is incorporated by plants into proteins. Organisms then consume some of these plants. Many heterotrophic anaerobic bacteria liberate sulfur from proteins as hydrogen sulfide.

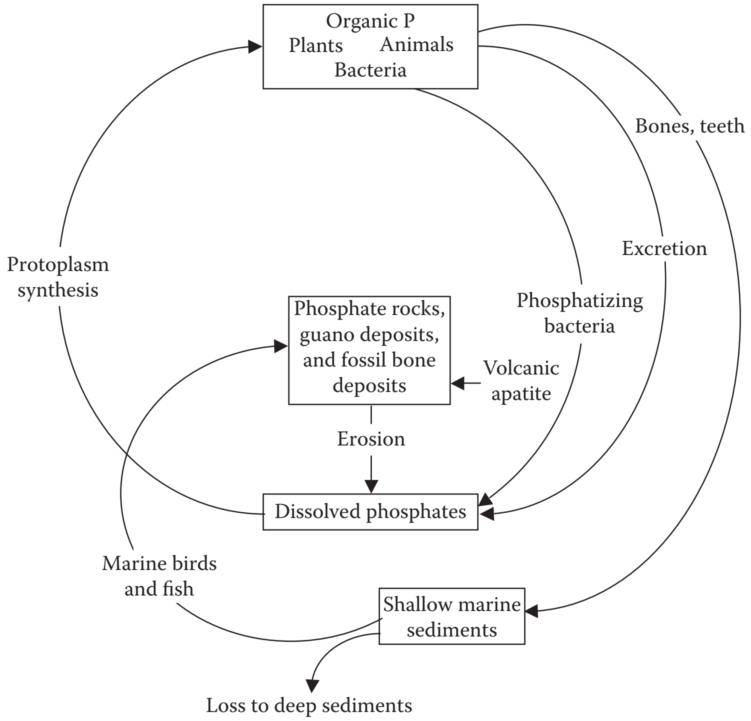

Figure 8.20 Phosphorus cycle.

8.17.4 Phosphorus Cycle

Phosphorus is another chemical element that is common in the structure of living organisms (see Figure 8.20); however, the phosphorus cycle is different from the hydrologic, carbon, and nitrogen cycles because phosphorus is found in sedimentary rock. These massive deposits are gradually eroding and providing phosphorus to ecosystems. A large amount of eroded phosphorus ends up in deep sediments in the oceans and in lesser amounts in shallow sediments. Part of the phosphorus comes to land when marine animals surface. Decomposing plant or animal tissue and animal droppings return organic forms of phosphorus to the water and soil. Fish-eating birds, for example, play a role in the recovery of phosphorus. Guano deposits (bird excreta) on the Peruvian coast are an example. Humans have hastened the rate of phosphorus loss through mining and the production of fertilizers, which are washed away and the phosphorus lost. Odum (1983) suggested, however, that there was no immediate cause for concern, as the known reserves of phosphate are quite large.

Phosphorus has become very important in water quality studies, because it is often found to be a limiting factor. Controlling phosphorus compounds that enter surface waters and contribute to the growth of algae blooms is of considerable interest and has generated much study (Metcalf & Eddy, 2003). Upon entering a stream, phosphorus acts as a fertilizer, promoting the growth of undesirable algae populations or algae blooms. As the organic matter decays, dissolved oxygen levels decrease and fish and other aquatic species die.

Although it is true that phosphorus discharged into streams is a contributing factor to stream pollution, it is also true that phosphorus is not the lone factor. Odum (1975) warned against what he called the *one-factor control hypothesis* (i.e., one-problem/one-solution syndrome). He observed that environmentalists in the past had focused on one of two items, such as phosphorus contamination, and failed to understand that the strategy for pollution control must involve reducing the input of all enriching and toxic materials

8.18 CHAPTER REVIEW QUESTIONS

8.1 Name four types of microorganisms that may be present in wastewater.

8.2 From a human health viewpoint, which type of organism is considered to be the most dangerous?

8.3 What materials are produced when organic matter is decomposed aerobically?

8.4 Describe what occurs in the zone of degradation when wastes are discharged to a stream.

8.5 Which zone many disappear if the strength of the wastes discharged to the stream is reduced?

8.6 What may happen if additional wastes are discharged to a stream before the natural self-purification process is completed?

8.7 Name three materials or contaminants that are not removed by the natural self-purification process.

8.8 List three conditions that must be present for good biological activity in wastewater treatment.

8.9 The three major groups of microorganisms that cause disease in water are ________, ________, and ________.

8.10 When does a river of good quality show its highest bacterial numbers?

8.11 Are coliform organisms pathogenic?

8.12 How do bacteria reproduce?

8.13 The three common shapes of bacteria are ________, ________, and ________.

8.14 Three waterborne disease caused by bacteria are ________, ________, and ________.

8.15 Two protozoa-caused waterborne disease are ________ and ________.

8.16 When a protozoan is in a resting phase, it is called a ________.

8.17 For a virus to live it must have a ________.

8.18 What problems do algae cause in drinking water?

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CHAPTER 9

WATER HYDRAULICS

> Frankly, most of the academic studies [on water] are irrelevant to practical decision-making. But that's okay. They're academicians. They have no responsibility to manage real resources. We have to deal with real things—real dams, real rivers, real demands, real crises.
>
> **Eugene Stakhiv, U.S. Army Corps of Engineers**

9.1 INTRODUCTION

Hydraulics is the study of how liquids act as they move through a channel or pipe. Hydraulics plays an important role in the design and operation of both the wastewater collection system and the treatment plant. This chapter presents information on several basic concepts of water.

9.2 DEFINITIONS

Key terms used in this chapter are defined as follows:

Force—Influence (as a push or pull) that causes motion; in physics, the mass of an object times its acceleration ($F = ma$).

Head—The measure of the pressure of water expressed as the height of water in feet: 1 psi = 2.31 ft of head. Total head includes static head, friction head, and velocity head.

Head loss—The loss of energy, commonly expressed in feet, as a result of friction; the loss is actually a transfer of heat.

Inertia—The tendency of matter to remain at rest or in motion.

Pressure—The force exerted on a unit area. Pressure = weight × height. In water, pressure is usually measured in pounds per square inch (psi). One foot of water exerts a pressure of 0.433 psi.

Static—Nonmoving.

Total dynamic head—The total energy required to move water from the center line of a pump (eye of the first impeller of a lineshaft turbine) to some given elevation or to develop some given pressure. Total dynamic head includes static head, velocity head, and the head loss due to friction.

Velocity head—The amount of energy required to bring a fluid from standstill to its velocity. From a given quantity of flow, the velocity head will vary indirectly with the pipe diameter.

9.3 PRINCIPLES OF HYDRAULICS

Basic characteristics of water include the following:

- One cubic foot of water weighs 62.4 lb and contains 7.48 gal.
- One cubic inch of water weighs 0.0362 lb.
- The specific weight of water is defined relative to a cubic foot; that is, 1 cubic foot of water weighs 62.4 lb. A 1-ft × 1-ft × 1-ft container equals 1 cubic foot; if it were filled with water, the water would weigh approximately 62.4 lb. The total pressure exerted against the bottom of the container is 62.4 lb.
- Water 1 ft deep will exert a pressure of 0.433 psi on the bottom area (12 in. × 0.0362 lb/in.^{3}).

■ ***Example 9.1***

Problem: A column of water 2 ft high exerts 0.86 psi, and a column 10 ft high exerts 4.2 psi. What pressure does a column 55 ft high exert?

Solution:

$$55 \text{ ft} \times 0.433 \text{ ft/psi} = 23.82 \text{ psi}$$

■ ***Example 9.2***

Problem: A column of water 2.31 ft high exerts 10 psi. To produce a pressure of 50 psi requires a water column that is how high?

Solution:

$$50 \text{ psi} \times 2.31 \text{ ft/psi} = 115.5 \text{ ft}$$

- The pressure at the bottom of a container is only affected by the height of water in the container and not by the shape of the container. If we were to take three differently shaped containers and fill them to the same level, the pressure at the bottom of each container would be the same.

- The term *head* is used to designate water pressure in terms of the height of a column of water in feet. For example, a 10-ft column of water exerts 4.33 psi. This can be expressed 4.33 psi pressure or 10 ft of head.

■ *Example 9.3*

Problem: If the static pressure in a pipe leading from an elevated water storage tank is 39 psi, what is the elevation of the water above the pressure gauge?

Solution: Recall that 1 psi = 2.31 ft and the pressure at the gauge is 39 psi, so:

$$39 \text{ psi} \times 2.31 \text{ ft/psi} = 90.1 \text{ ft}$$

The basic relationships between the weight of water and the weight of air can be described as follows:

- If a tube is placed in a body of water at sea level (a lake, a water storage reservoir, a container, or a glass), water will rise in the tube to the same height as the water outside the tube. The atmospheric pressure of 14.7 psi will push down equally on the water surface inside and outside of the tube.
- On the other hand, if the top of the tube is tightly capped and all of the air is removed from the sealed tube above the water surface, forming a *perfect vacuum*, then the pressure on the water surface inside the tube will be 0 psi. The atmospheric pressure of 14.7 psi on the outside of the tube will push the water up into the tube until the weight of the water exerts the same 14.7 psi pressure at a point in the tube even with the water surface outside the tube. The water will rise:

$$14.7 \text{ psi} \times 2.31 \text{ ft/psi} = 34 \text{ ft}$$

- Because it is impossible to create a perfect vacuum in practice, the water will rise somewhat less than 34 ft; the distance it rises depends on the amount of vacuum created.

■ *Example 9.4*

Problem: If enough air was removed from the tube to produce an air pressure of 9.7 psi above the water in the tube, how far will the water rise in the tube?

Solution: To maintain the 14.7 psi at the outside water surface level, the water in the tube must produce a pressure of 14.7 psi – 9.7 psi = 5.0 psi. The height of the column of water that will produce 5 psi is:

$$5.0 \text{ psi} \times 2.31 \text{ ft/psi} = 11.6 \text{ ft}$$

9.4 STATIC WATER (WATER AT REST)

Stevin's law states: "The pressure at any point in a fluid at rest depends on the distance measured vertically to the free surface and the density of the fluid." Stated as a formula this becomes:

$$p = w \times h \tag{9.1}$$

where:

p = pressure in pounds per square foot (psf).
w = density in pounds per cubic foot (lb/ft^3).
h = vertical distance in feet.

■ ***Example 9.5***

Problem: What is the pressure at a point 20 ft below the surface of a reservoir?

Solution: To calculate this, we must know that the density of water (w) is 62.4 lb/ft^3. Thus,

$$p = w \times h = 62.4 \text{ lb/ft}^3 \times 20 \text{ ft} = 1248 \text{ psf}$$

Waterworks operators generally measure pressure in pounds per square *inch* rather than pounds per square *foot*; to convert, divide by 144 in.^{2}/ft^2 (12 in. × 12 in. = 144 in.^{2}):

$$p = \frac{1248 \text{ lb/ft}^2}{144 \text{ in}^2/\text{ft}^2} = 8.7 \text{ lb/in}^2 \text{ or psi}$$

9.5 GAUGE PRESSURE

Recall that head is the height a column of water will rise due to the pressure at its base. Also, a perfect vacuum plus atmospheric pressure of 14.7 psi will lift the water 34 feet. If we now open the top of the sealed tube to the atmosphere and enclose the reservoir and then increase the pressure in the reservoir, the water will again rise in the tube.

Key Point: Gauge pressure + atmospheric pressure = absolute pressure.

In actual pressure measurements, we usually ignore the first 14.7 psi (since atmospheric pressure is essentially universal) and measure only the difference between the water pressure and the atmospheric pressure; we call this *gauge pressure*. For example, water in a lake is subjected to the 14.7 psi of atmospheric pressure, but subtracting this 14.7 psi leaves a gauge pressure of 0 psi. This shows that the water would rise 0 feet above the lake surface. If the gauge pressure in a water main is 120 psi, the water would rise in a tube connected to the main:

$$120 \text{ psi} \times 2.31 \text{ ft/psi} = 277.2 \text{ ft}$$

9.6 DYNAMIC WATER (WATER IN MOTION)

Compared to the study of fluid flow at rest, the study of fluid flow (water in motion) is much more complicated, but it is important to have an understanding of these principles because the water in a water treatment and distribution system is nearly always in motion. *Discharge* is the quantity of water passing a given point in a pipe or channel during a given period of time. It can be calculated by the formula:

$$Q = V \times A \tag{9.2}$$

where:

Q = discharge in cubic feet per second (cfs).

V = water velocity in feet per second (fps or ft/s).

A = cross-section area of the pipe or channel in square feet (ft^2).

The discharge can be converted from cfs to other units such as gallons per minute (gpm) or million gallons per day (MGD) by using the appropriate conversion factors.

■ ***Example 9.6***

Problem: A 12-in.-diameter pipe has water flowing through it at 12 fps. What is the discharge in (a) cfs, (b) gpm, and (c) MGD?

Solution: First, determine the area (A) of the pipe. The formula for the area of a circle is:

$$A = \pi \times \frac{D^2}{4} = \pi \times r^2 \tag{9.3}$$

where:

π = 3.14159, or 3.14.

D = diameter of the circle in feet.

r = radius of the circle in feet.

Thus, the area of the pipe is:

$$A = \pi \times \frac{D^2}{4} = 3.14 \times \frac{(1\text{ ft})^2}{4} = 0.785\text{ ft}^2$$

(a) Determine the discharge in cfs:

$$Q = V \times A = 12\text{ ft/s} \times 0.785\text{ ft}^3\text{/s} = 9.42\text{ ft}^3\text{/s (cfs)}$$

(b) Determine the discharge in gpm. We need to know that 1 cfs = 449 gpm, so 9.42 cfs × 449 gpm/cfs = 4230 gpm.

(c) Determine the discharge in MGD. We know that 1 MGD = 1.55 cfs; thus,

$$9.42\text{ cfs} \div 1.55\text{ cfs/MGD} = 6.1\text{ MGD}$$

The *law of continuity* states that the discharge at each point in a pipe or channel is the same as the discharge at any other point (provided water does not leave or enter the pipe or channel). In equation form, this becomes:

$$Q_1 = Q_2 \text{ or } A_1V_1 = A_2V_2 \tag{9.4}$$

■ ***Example 9.7***

Problem: A 12-in.-diameter pipe is connected to a 6-in.-diameter pipe. The velocity of the water in the 12-in. pipe is 3 fps. What is the velocity in the 6-in. pipe?

Solution: Using the equation $A_1V_1 = A_2V_2$, first determine the area of each pipe:

12-in. diameter:

$$A = \pi \times D^2/4$$

$$A = 3.14 \times (1 \text{ ft})^2/4 = 0.785 \text{ ft}^2$$

6-in. diameter:

$$A = 3.14 \times (0.5 \text{ ft})^2/4 = 0.196 \text{ ft}^2$$

The continuity equation now becomes:

$$0.785 \text{ ft}^2 \times 3 \text{ ft/s} = 0.196 \text{ ft}^2 \times V_2$$

Solving for V_2,

$$V_2 = \frac{0.785 \text{ ft}^2 \times 3 \text{ ft/s}}{0.196 \text{ ft}^2} = 12 \text{ ft/s (fps)}$$

9.7 HEAD LOSS

When water runs through a pipe and the pressure (called *pressure head*) is measured at various points along the flow, pressure decreases with distance from the source. This pressure decrease is the result of *friction loss*. Water flow is retarded by the friction of the water against the inside of the pipe. The resistance to flow offered by pipe friction depends on the size (diameter) of the pipe, the roughness of the pipe wall, and the number and type of fittings (e.g., bends, valves) along the pipe run.

Note: Each type of fitting exerts a specific head loss upon the velocity of water through the fitting. For instance, the head loss through a check valve is 2.25 times greater than through a 90° elbow and 10 times greater than the head loss through an open gate valve.

The resistance to flow offered by friction also depends on the speed of the water through the pipe; the more water you try to pump through a pipe, the more pressure it will take to overcome the friction. The resistance can be expressed in terms of the additional pressure required to push the water through the pipe, in either *psi* or *feet of head*. Because it is a reduction in pressure, it is often referred to as *friction loss* or *head loss*. Head loss is the loss of energy due to friction; the energy is lost as heat. Friction loss is usually measured in feet per 1000 feet of pipe and may easily be converted to pressure loss in pounds per square inch (psi). Factors that affect friction loss include:

- Increased flow rate
- Type of pipe
- Increased pipe length
- Pipe coating
- Decreased pipe diameter
- Constricted pipe
- Addition of bends, fittings, and valves
- Age of pipe
- Smoothness or roughness of the interior surface of pipe

Note: (1) If the flow through a pipe is doubled, the friction loss in the pipe will be decreased by almost four times (obviously, this factor more than any other single factor affects head loss). (2) The diameter of a pipe determines the area of wall in contact with flowing water; for a given discharge, the diameter also determines the velocity of the water.

Pumps are designed to operate under specific head conditions. In addition to the static head, all friction losses and minor losses should be computed in order to determine the total head against which the pump will operate. The total pressure provided at the discharge side of the pump represents the discharge pressure of the discharge head. Head loss from fittings is calculated by substituting the *equivalent length of pipe* from tables.

Basic terms used in pumping hydraulics include the following:

- *Static head* is the distance between the suction and discharge water levels when the pump is not in operation. Static head conditions are often indicated by the letter *Z*:

$$\text{Static Head} = \text{Discharge Elevation} - \text{Supply Elevation} \tag{9.5}$$

- *Suction lift* is the distance between the suction water level and the center of the pump impeller. This term is used only when the pump is in a suction lift condition. In practice, a pump is said to be in a suction lift condition any time the eye (center) of the impeller is above the water being pumped.

- *Suction head* is the distance between the suction water level and the center of the pump impeller when the pump is in a suction head condition (i.e., any time the impeller is below the water level being pumped).
- *Velocity head* is the amount of energy required by the pump and motor to overcome the tendency of water to remain at rest or in motion (inertia):

$$\text{Velocity Head (ft)} = \text{Energy losses to maintain velocity} \tag{9.6}$$

- *Total dynamic head* (TDH) is the static head (the elevation difference) plus the friction head (pressure losses due to the water moving through the pipes) in a given pipe system. Simply, it is the difference in water pressure between the beginning of the pipe (at the pump) and the end of the pipe (i.e., the end point, such as the tank being filled or the consumer's tap). It is the pressure the pumps must overcome to provide water to the consumer:

$$\text{Total Head} = \text{Static Head} + \text{Friction Head} + \text{Velocity Head} \tag{9.7}$$

9.8 PRESSURE AND HEAD CALCULATIONS

The following examples are provided to increase your skill in solving practical calculations for pressure and head. Recall that:

$$\text{Pressure (psi)} = 0.433 \times \text{Head (ft)}$$

and

$$\text{Head (ft)} = 2.31 \text{ ft} \times \text{Pressure (psi)}$$

■ ***Example 9.8***

Problem: Find the pressure (psi) in a 12-ft-deep tank at a point 6 ft below the water surface.

Solution:

$$\text{Pressure} = 0.433 \times 6 \text{ ft} = 2.6 \text{ psi}$$

■ ***Example 9.9***

Problem: A pressure gauge at the bottom of a tank reads 11.3 psi. How deep is the water in the tank?

Solution:

$$\text{Head} = 2.31 \times 11.3 \text{ psi} = 26.1 \text{ ft}$$

9.9 CHAPTER REVIEW QUESTIONS

9.1 Find the number of gallons in a storage tank that has a volume of 669.9 ft^3.

9.2 Suppose a rock weighs 120 lb in air and 85 lb under water. What is the specific gravity?

9.3 There are 1270 gal of a certain liquid in a storage tank. If the specific gravity of the liquid is 0.91, how many pounds of liquid are in the tank?

9.4 A tank is mounted at a height of 65 ft. Find the pressure at the bottom of the tank.

9.5 Find the height of water in a tank if the pressure at the bottom of the tank is 14 psi.

9.6 The elevation of a liquid in the supply tank is 2566 ft. The elevation of the liquid surface of the discharge is 2133 ft. What is the total static head of the system?

REFERENCE AND RECOMMENDED READING

Spellman, F.R. (2008). *The Science of Water*, 2nd ed. Boca Raton, FL: CRC Press.

CHAPTER 10

PUMPS

A hydraulic machine, or pump, is a device that raises, compresses, or transfers fluids.

10.1 INTRODUCTION

"Few engineered artifacts are as essential as pumps in the development of the culture which our Western civilization enjoys" (Garay, 1990). This statement is germane to any discussion about pumps simply because humans have always needed to move water from one place to another against the forces of nature. As the need for potable water increases, the need to pump the water from distant locations to where it is most needed is also increasing.

Initially, humans relied on one of the primary forces of nature—gravity—to move water from one place to another. Gravity only works, of course, if the water is moved downhill on a sloping grade. It was soon discovered that the pressure built up by accumulating water behind the water source (e.g., behind a barricade, levy, or dam) moved the water farther. But, when pressure is dissipated by various losses (e.g., friction loss) or when water in low-lying areas must be moved to higher areas, the energy required to move that water must be created. Simply, some type of pump is needed.

In 287 B.C., Archimedes, a Greek mathematician and physicist, invented the screw pump (see Figure 10.1). It is believed that around 100 A.D. the Roman emperor Nero developed the piston pump. The piston pump displaces volume after volume of water with each stroke. The piston pump has two basic problems: (1) its size limits capacity and (2) it is a high energy consumer. It was not until the 19th century that pumping technology took a leap forward from its rudimentary beginnings. The

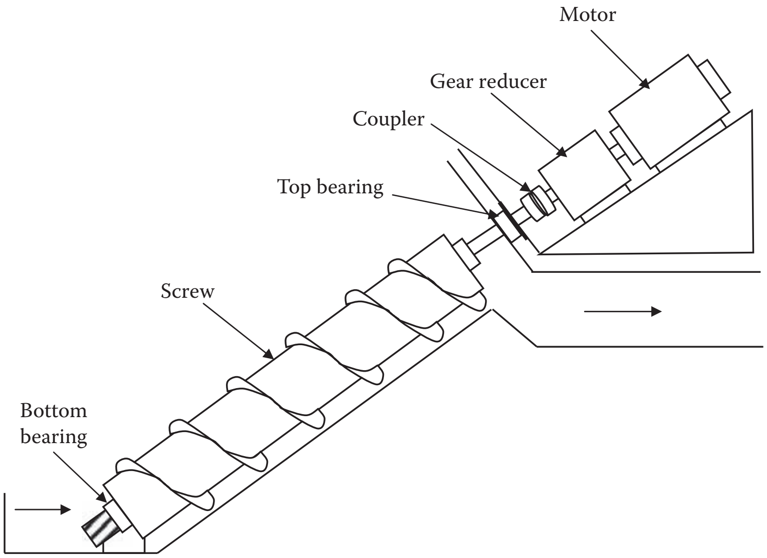

Figure 10.1 Archimedes' screw pump.

first fully functional centrifugal pumps were developed in the 1800s. Centrifugal pumps can move great quantities of water with much smaller units compared to earlier versions of pumps.

The pump is a type of hydraulic machine. Pumps convert mechanical energy into fluid energy. Whether water is being taken from groundwater or a surface water body, from one unit treatment process to another, or to a storage tank for eventual final delivery through various sizes and types of pipes to the customer, *pumps* are the usual source of energy necessary for the conveyance of water. Again, the only exception may be, of course, where the source of energy is supplied entirely by gravity. Waterworks and wastewater maintenance operators must therefore be familiar with pumps, pump characteristics, pump operation, and maintenance.

> There are three general requirements of pump and motor combinations. These requirements are (1) reliability, (2) adequacy, and (3) economy. *Reliability* is generally obtained by installing in duplicate the very best equipment available and by the use of an auxiliary power source. *Adequacy* is obtained by securing liberal sizes of pumping equipment. *Economics* can be achieved by taking into account the life and depreciation, first cost, standby charges, interest and operating costs.
>
> **Texas Utilities Association (1988)**

Over the past several years, it has become more evident that many waterworks and wastewater facilities have been unable to meet their optimum supply or treatment requirements for one of three reasons:

1. Untrained operations and maintenance staff
2. Poor plant maintenance
3. Improper plant design

10.2 BASIC PUMPING CALCULATIONS

Calculations, calculations, calculations, and more calculations! Indeed, we cannot get away from them—not in water/wastewater treatment, collection and distribution operations, licensure certification examinations, nor in real life. Basic calculations are a fact of life that the water/wastewater maintenance operator must accept and should learn well enough to use as required to operate a water/wastewater facility correctly. The following sections address the basic calculations used frequently in water hydraulics and pumping applications. The basic calculations that water and wastewater maintenance operators may be required to know for operational and certification purposes are also discussed. In addition, calculations for pump specific speed, suction specific speed, and affinity, among other advanced calculations, are also covered in the following sections, although at a higher technical level.

10.2.1 Velocity of a Fluid through a Pipeline

The speed or velocity of a fluid flowing through a channel or pipeline is related to the cross-sectional area of the pipeline and the quantity of water moving through the line; for example, if the diameter of a pipeline is reduced, then the velocity of the water in the line must increase to allow the same amount of water to pass through the line.

$$\text{Velocity (fps)} = \frac{\text{Flow (cfs)}}{\text{Cross-Sectional Area (ft}^2\text{)}} = V = \frac{Q}{A} \tag{10.1}$$

■ ***Example 10.1***

Problem: If the flow through a 2-ft-diameter pipe is 9 MGD, what is the velocity?

Solution:

$$\text{Velocity} = \frac{9\text{ MGD} \times 1.55\text{ cfs/MGD}}{0.785 \times 2\text{ ft} \times 2\text{ ft}} = \frac{14\text{ cfs}}{3.14\text{ ft}^2} = 4.5\text{ fps (rounded)}$$

■ ***Example 10.2***

Problem: If the same 9-MGD flow used in Example 10.1 is transferred to a pipe with a 1-ft diameter, what would the velocity be?

Solution:

$$\text{Velocity} = \frac{9\text{ MGD} \times 1.55\text{ cfs/MGD}}{0.785 \times 1\text{ ft} \times 1\text{ ft}} = \frac{14\text{ cfs}}{0.785\text{ ft}^2} = 17.8\text{ fps (rounded)}$$

Based on these sample problems, you can see that if the cross-sectional area is decreased the velocity of the flow must be increased. Mathematically, we can say that the velocity and cross-sectional area are inversely proportional when the amount of flow (Q) is constant.

$$\text{Area}_1 \times \text{Velocity}_1 = \text{Area}_2 \times \text{Velocity}_2 \tag{10.2}$$

Note: The concept just explained is extremely important in the operation of a centrifugal pump and will be discussed later.

10.2.2 Pressure–Velocity Relationship

A relationship similar to that of velocity and cross-sectional area exists for velocity and pressure. As the velocity of flow in a full pipe increases, the pressure of the liquid decreases. This relationship is:

$$\text{Pressure}_1 \times \text{Velocity}_1 = \text{Pressure}_2 \times \text{Velocity}_2 \tag{10.3}$$

■ ***Example 10.3***

Problem: If the flow in a pipe has a velocity of 3 fps and a pressure of 4 psi, and the velocity of the flow increases to 4 fps, what will the pressure be?

Solution:

$$\text{Pressure}_1 \times \text{Velocity}_1 = \text{Pressure}_2 \times \text{Velocity}_2$$

$$4\text{ psi} \times 3\text{ fps} = \text{Pressure}_2 \times 4\text{ fps}$$

Rearranging:

$$P_2 = \frac{4\text{ psi} \times 3\text{ fps}}{4\text{ fps}} = \frac{12\text{ psi}}{4} = 3\text{ psi}$$

Again, this is another important hydraulics principle that is very important to the operation of a centrifugal pump.

10.2.3 Static Head

Pressure at a given point originates from the height, or depth of water above it. It is this pressure, or *head*, that gives the water energy and causes it to flow. By definition, *static head* is the vertical distance the liquid travels from the supply tank to the discharge point. This relationship is shown as:

$$\text{Static Head (ft)} = \text{Discharge Level (ft)} - \text{Supply Level (ft)} \tag{10.4}$$

In many cases, it is desirable to separate the static head into two separate parts: (1) the portion that occurs before the pump (suction head or suction lift), and (2) the portion that occurs after the pump (discharge head). When this is done, the center (or datum) of the pump becomes the reference point.

10.2.3.1 *Static Suction Head*

Static suction head refers to when the supply is located above the pump datum.

$$\text{Static Suction Head (ft)} = \text{Supply Level (ft)} - \text{Pump Level (ft)} \tag{10.5}$$

10.2.3.2 *Static Suction Lift*

Static suction lift refers to when the supply is located below the pump datum.

$$\text{Static Suction Lift (ft)} = \text{Pump Level (ft)} - \text{Supply Level (ft)} \tag{10.6}$$

10.2.3.3 *Static Discharge Head*

$$\text{Static Discharge Head (ft)} = \text{Discharge Level (ft)} - \text{Pump Datum (ft)} \tag{10.7}$$

If the total static head is to be determined after calculating the static suction head or lift and static discharge head individually, two different calculations can be used, depending on whether there is a suction head or a suction lift.

For suction head:

$$\text{Total Static Head (ft)} = \text{Static Discharge Head (ft)} - \text{Static Suction Lift (ft)} \tag{10.8}$$

For suction lift:

$$\text{Total Static Head (ft)} = \text{Static Discharge Head (ft)} + \text{Static Suction Lift (ft)} \tag{10.9}$$

- ***Example 10.4***

Problem: Refer to Figure 10.2 to determine total static head.

Solution:

$$\text{Static Suction Lift} = \text{Pump Level} - \text{Supply Level}$$

$$\text{Static Suction Lift} = 128\text{ ft} - 121\text{ ft} = 7\text{ ft}$$

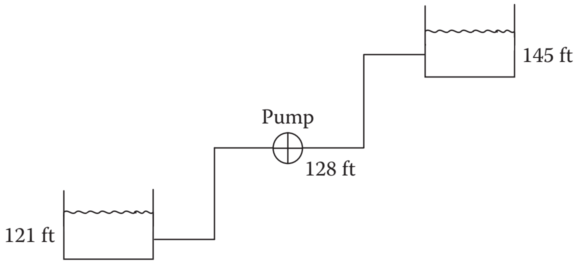

Figure 10.2 Example 10.4.

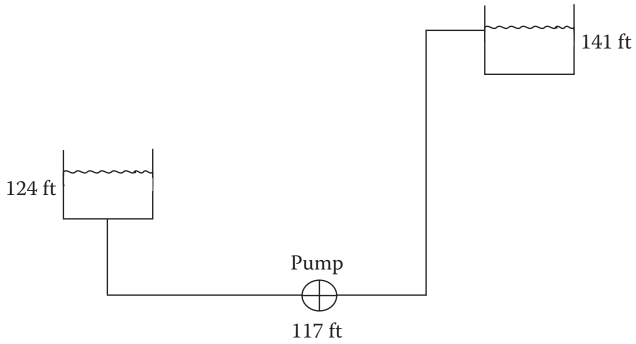

Figure 10.3 Example 10.5.

$$\text{Static Discharge Head} = \text{Discharge Level} - \text{Static Suction Lift}$$

$$\text{Static Discharge Head} = 145\text{ ft} - 128\text{ ft} = 17\text{ ft}$$

$$\text{Total Static Head} = \text{Static Discharge Head} + \text{Static Suction Lift}$$

$$\text{Total Static Head} = 17\text{ ft} + 7\text{ ft} = 24\text{ ft}$$

or

$$\text{Total Static Head} = \text{Discharge Level} - \text{Supply Level}$$

$$\text{Total Static Head} = 145\text{ ft} - 119\text{ ft} = 24\text{ ft}$$

■ *Example 10.5*

Problem: Refer to Figure 10.3 to determine total static head.

Solution:

$$\text{Static Suction Head} = \text{Supply Level} - \text{Pump Level}$$

$$\text{Static Suction Head} = 124\text{ ft} - 117\text{ ft} = 7\text{ ft}$$

$$\text{Static Discharge Head} = \text{Discharge Level} - \text{Pump Level}$$

$$\text{Static Discharge Head} = 141\text{ ft} - 117\text{ ft} = 24\text{ ft}$$

$$\text{Total Static Head} = \text{Static Discharge Head} - \text{Static Suction Head}$$

$$\text{Total Static Head} = 24\text{ ft} - 7\text{ ft} = 17\text{ ft}$$

or

$$\text{Total Static Head} = \text{Discharge Level} - \text{Supply Level}$$

$$\text{Total Static Head} = 141\text{ ft} - 124\text{ ft} = 17\text{ ft}$$

10.2.4 Friction Head

Various formulae calculate friction losses. The Hazen–Williams equation is one of the most common for smooth steel pipe. Usually, we do not need to calculate the friction losses, because handbooks such as the *Hydraulic Institute Pipe Friction Manual* tabulated these long ago.

This important manual also shows velocities in different pipe diameters at varying flows, as well as the resistance coefficient (K) for valves and fittings (Wahren, 1997). Friction head (in feet) is the amount of energy used to overcome resistance to the flow of liquids through the system. It is affected by the length and diameter of the pipe, the roughness of the pipe, and the velocity head. It is also affected by the physical construction of the piping system. The number and types of elbows, valves, T's, etc. will greatly influence the friction head for the system. These must be converted to their equivalent length of pipe and included in the calculation:

Key Point: For centrifugal pumps, good engineering practice is to try to keep velocities in the suction pipe to 3 fps or less. Discharge velocities higher than 11 fps may cause turbulent flow or erosion in the pump casing.

$$\text{Friction Head (ft)} = \text{Roughness Factor} \times \frac{\text{Length}}{\text{Diameter}} \times \frac{\text{Velocity}^2}{2g} \tag{10.10}$$

The *roughness factor* (f) varies with length and diameter as well as the condition of the pipe and the material from which it is constructed; it normally is in the range of .01 to .04. Acceleration due to gravity is denoted as g.

■ *Example 10.6*

Problem: What is the friction head in a system that uses 150 ft of 6-in.-diameter pipe when the velocity is 3 fps? The valving of the system is equivalent to an additional 75 ft of pipe. Reference material indicates a roughness factor (f) of 0.025 for this particular pipe and flow rate.

Solution:

$$\begin{aligned}
\text{Friction Head} &= \text{Roughness Factor} \times \frac{\text{Length}}{\text{Diameter}} \times \frac{\text{Velocity}^2}{2g} \\
&= 0.0025 \times \frac{150\text{ ft} + 75\text{ ft}}{0.5\text{ ft}} \times \frac{(3\text{ fps})^2}{2 \times 32\text{ ft/s}} \\
&= 0.0025 \times \frac{225\text{ ft}}{0.5\text{ ft}} \times \frac{9\text{ ft}^2/\text{s}^2}{64\text{ ft/s}} = 0.025 \times 450 \times 0.140\text{ ft} = 1.58\text{ ft}
\end{aligned}$$

It is also possible to compute friction head using tables. Friction head can also be determined on both the suction side of the pump and the discharge side of the pump. In each case, it is necessary to determine:

1. Length of pipe
2. Diameter of the pipe
3. Velocity
4. Pipe equivalent of valves, elbows, T's, etc.

10.2.5 Velocity Head

Velocity head is the amount of head or energy required to maintain a stated velocity in the suction and discharge lines. The design of most pumps makes the total velocity head for the pumping system zero.

Note: Velocity head only changes from one point to another on a pipeline if the diameter of the pipe changes.

Velocity head and total velocity head are determined by:

$$\text{Velocity Head} = \frac{(\text{Velocity})^2}{2g} \tag{10.11}$$

$$\begin{aligned}\text{Total Velocity Head (ft)} &= \text{Velocity Head Discharge (ft)} \\ &\quad - \text{Velocity Head Suction (ft)}\end{aligned} \tag{10.12}$$

■ ***Example 10.7***

Problem: What is the velocity head in a system with a velocity of 5 fps?

Solution:

$$\begin{aligned}\text{Velocity Head} &= \frac{(\text{Velocity})^2}{2g} \\ &= \frac{(5\text{ fps})^2}{2 \times 32\text{ ft/s}^2} = \frac{25\text{ ft}^2/\text{s}^2}{64\text{ ft/s}^2} = 0.39\text{ ft}\end{aligned}$$

Note: A static system has no velocity head, as the water is not moving.

10.2.6 Total Head

Total head is the sum of the static, friction, and velocity heads:

$$\begin{aligned}\text{Total Head (ft)} &= \text{Static Head (ft)} + \text{Friction Head (ft)} \\ &\quad + \text{Velocity Head (ft)}\end{aligned} \tag{10.13}$$

10.2.7 Conversion of Pressure Head

Pressure is directly related to the head. If liquid in a container subjected to a given pressure is released into a vertical tube, the water will rise 2.31 ft for every pound per square inch of pressure. To convert pressure to head in feet:

$$\text{Head (ft)} = \text{Pressure (psi)} \times 2.31\text{ ft/psi} \tag{10.14}$$

This calculation can be very useful in cases where liquid is moved through another line that is under pressure. Because the liquid must overcome the pressure in the line it is entering, the pump must supply this additional head.

■ *Example 10.8*

Problem: A pump is discharging to a pipe that is full of liquid under a pressure of 20 psi. The pump and piping system has a total head of 97 ft. How much additional head must the pump supply to overcome the line pressure?

Solution:

$$\text{Head} = \text{Pressure (psi)} \times 2.31 \text{ ft/psi} = 20 \text{ psi} \times 2.31 \text{ ft/psi} = 46 \text{ ft (rounded)}$$

The pump must supply an additional head of 46 ft to overcome the internal pressure of the line.

10.2.8 Horsepower

The unit of work is *foot-pound* (ft-lb), which is the amount of work required to lift a 1-lb object 1 ft off the ground. For practical purposes, we consider the amount of work being done. It is more valuable, obviously, to be able to work faster; that is, for economic reasons, we consider the rate at which work is being done (i.e., power or ft-lb/s). At some point, the horse was determined to be the ideal work animal; it could move 550 pounds 1 foot in 1 second, which is considered to be equivalent to 1 horsepower:

$$550 \text{ ft-lb/s} = 1 \text{ horsepower (hp)}$$

or

$$33{,}000 \text{ ft-lb/min} = 1 \text{ horsepower (hp)}$$

A pump performs work while it pushes a certain amount of water at a given pressure. The two basic terms for horsepower are (1) *hydraulic horsepower* and (2) *brake horsepower.*

10.2.8.1 Hydraulic (Water) Horsepower

A pump has power because it does work. A pump lifts water (which has weight) a given distance in a specific amount of time (ft-lb/min). One hydraulic (water) horsepower (WHP) provides the necessary power to lift the water to the required height; it equals the following:

550 ft-lb/s
33,000 ft-lb/min
2545 British thermal units per hour (Btu/hr)
0.746 kW
1.014 metric hp

To calculate the hydraulic horsepower (WHP) using flow in gpm and head in feet, use the following formula for centrifugal pumps:

$$\text{Water Horsepower (WHP)} = \frac{\text{Flow (gpm)} \times \text{Head (ft)} \times \text{Specific Gravity}}{3960} \tag{10.15}$$

Note: 3960 is derived by dividing 33,000 ft/lb by 8.34 lb/gal = 3960.

10.2.8.2 Brake Horsepower

Key Points: (1) *Water horsepower* (WHP) is the power necessary to lift the water to the required height; *brake horsepower* (BHP) is the horsepower applied to the pump; (3) *motor horsepower* is the horsepower applied to the motor; and (4) *efficiency* is the power produced by the unit divided by the power used in operating the unit.

A water pump does not operate alone. It is driven by a motor, and electrical energy drives the motor. Brake horsepower (BHP) is the horsepower applied to the pump. The BHP of a pump equals its hydraulic horsepower divided by the efficiency of the pump. Note that neither the pump nor its prime mover (motor) is 100% efficient. Both of these units experience friction losses, and more horsepower will have to be applied to the pump to achieve the required amount of horsepower to move the water, and even more horsepower must be applied to the motor to get the job done (Hauser, 1993). The formula for BHP is:

$$\text{Brake Horsepower (BHP)} = \frac{\text{Flow (gpm)} \times \text{Head (ft)} \times \text{Specific Gravity}}{3960 \times \text{Efficiency}} \tag{10.16}$$

10.2.9 Specific Speed

The capacity of flow rate of a centrifugal pump is governed by the impeller thickness (Lindeburg, 1986). For a given impeller diameter, the deeper the vanes, the greater the capacity of the pump. Each desired flow rate or desired discharge head will have one optimum impeller design. The impeller that is best for developing a high discharge pressure will have different proportions from an impeller designed to produce a high flow rate. The quantitative index of this optimization is the *specific speed* (N_s). The higher the specific speed of a pump, the higher its efficiency. The specific speed of an impeller is its speed when pumping 1 gpm of water at a differential head of 1 ft. The following formula is used to determine specific speed (where H is at the best efficiency point):

$$N_s = \frac{\text{rpm} \times Q^{0.5}}{H^{0.75}} \tag{10.17}$$

where:

rpm = revolutions per minute.

Q = flow (gpm).

H = head (ft).

Pump specific speeds vary between pumps. Although no absolute rule sets the specific speed for different kinds of centrifugal pumps, the following rule of thumb for N_s can be used:

Volute, diffuser, and vertical turbine	500–5000
Mixed flow	5000–10,000
Propeller pumps	9000–15,000

10.2.10 Suction Specific Speed

Suction specific speed (N_{ss}), another impeller design characteristic, is an index of the suction characteristics of the impeller (i.e., the suction capacities of the pump) (Wahren, 1997). For practical purposes, N_{ss} ranges from about 3000 to 15,000. The limit for the use of suction specific speed impellers in water is approximately 11,000. The following equation expresses N_{ss}:

$$N_{ss} = \frac{\text{rpm} \times Q^{0.5}}{NPSHR^{0.75}} \tag{10.18}$$

where:

rpm = revolutions per minute.

Q = flow in gpm.

NPSHR = net positive suction head required.

Ideally, N_{ss} should be approximately 7900 for single-suction pumps and 11,200 for double-suction pumps. (The value of Q in Equation 10.17 should be halved for double-suction pumps.)

10.2.11 Affinity Laws—Centrifugal Pumps

Most parameters (impeller diameter, speed, and flow rate) determining the performance of a pump can vary. If the impeller diameter is held constant and the speed varied, the following ratios are maintained with no change of efficiency (because of inexact results, some deviations may occur in the calculations):

$$Q_2/Q_1 = D_2/D_1 \tag{10.19}$$

$$H_2/H_1 = (D_2/D_1)^2 \tag{10.20}$$

$$BHP_2/BHP_1 = (D_2/D_1)^3 \tag{10.21}$$

where:

Q = flow.

D_1 = impeller diameter before change.

D_2 = impeller diameter after change.

H_1 = head before change.

H_2 = head after change.

BHP_1 = brake horsepower before change.

BHP_2 = brake horsepower after change.

The relationships for speed (N) changes are as follows:

$$Q_2/Q_1 = N_2/N_1 \tag{10.22}$$

$$H_2/H_1 = (N_2/N_1)^2 \tag{10.23}$$

$$BHP_2/BHP_1 = (N_2/N_1)^3 \tag{10.24}$$

where:

N_1 = initial rpm.

N_2 = changed rpm.

■ *Example 10.9*

Problem: Change an 8-in.-diameter impeller for a 9-in.-diameter impeller, and find the new flow (Q), head (H), and brake horsepower (BHP) for the following 8-in.-diameter impeller data:

Q_1 = 340 rpm

H_1 = 110 ft

BHP_1 = 10

Solution: The 9-in. impeller diameter data would be as follows:

$Q_2 = 340 \times 9/8 = 383$ gpm

$H_2 = 110 \times (9/8)^2 = 139$ ft

$BHP_2 = 10 \times (9/8)^3 = 14$

10.2.12 Net Positive Suction Head

Earlier we referred to the *net positive suction head required* (NPSHR); also important in pumping technology is *net positive suction head* (NPSH) (Lindeburg, 1986; Wahren, 1997). NPSH is different from both suction head and suction pressure. This important point tends to be confusing to those first introduced to the term and to pumping technology in general. When an impeller in a centrifugal pump spins, the motion creates a partial vacuum in the impeller eye. The NPSHA is the height of the column of liquid that will fill this partial vacuum without allowing the vapor pressure of the liquid to drop below its flash point; that is, this is the NPSH required (NPSHR) for the pump to function properly.

The Hydraulic Institute (1994) defines NPSH as "the total suction head in feet of liquid absolute determined at the suction nozzle and referred to datum less the vapor pressure of the liquid in feet absolute." This defines the NPSH available (NPSHA) for the pump. (Note that NPSHA is the actual water energy at the inlet.) The important point here is that a pump will run satisfactorily if the NPSHA equals or exceeds the NPSHR. Most authorities recommend that the NPSHA be at least 2 ft absolute or 10% larger than the NPSHR, whichever number is larger.

Note: With regard to NPSHR, contrary to popular belief water is not sucked into a pump. A positive head (normally atmospheric pressure) must push the water into the impeller (i.e., flood the impeller). NPSHR is the minimum water energy required at the inlet by the pump for satisfactory operation. The pump manufacturer usually specifies NPSHR.

It is important to point out that if NPSHA is less than NPSHR, the water will cavitate. *Cavitation* is the vaporization of fluid within the casing or suction line. If the water pressure is less than the vapor pressure, pockets of vapor will form. As vapor pockets reach the surface of the impeller, the local high water pressure will collapse them, causing noise, vibration, and possible structural damage to the pump.

10.2.12.1 Calculating NPSHA

In the following two examples, we demonstrate how to calculate NPSHA for two real-world situations: (1) determining NPSHA for an open-top water tank or a municipal water storage tank with a roof and correctly sized vent, and (2) determining the NPSHA for a suction lift from an open reservoir.

10.2.12.1.1 NPSHA: Atmospheric Tank

The following calculation may be used for an open-top water tank or a municipal water storage tank with a roof and correctly sized vent, as shown in Figure 10.4 and Figure 10.5. The formula for calculating NPSHA is:

$$\text{NPSHA} = P_a + h - P_v - h_e - h_f \tag{10.25}$$

where:

P_a = atmospheric pressure in absolute or pressure of gases against the surface of the water.

h = weight of the liquid column from the surface of the water to the center of the pump suction nozzle in feet absolute.

P_v = vapor pressure in absolute of water at a given temperature.

h_e = entrance losses in feet absolute.

h_f = friction losses in the suction line in feet absolute.

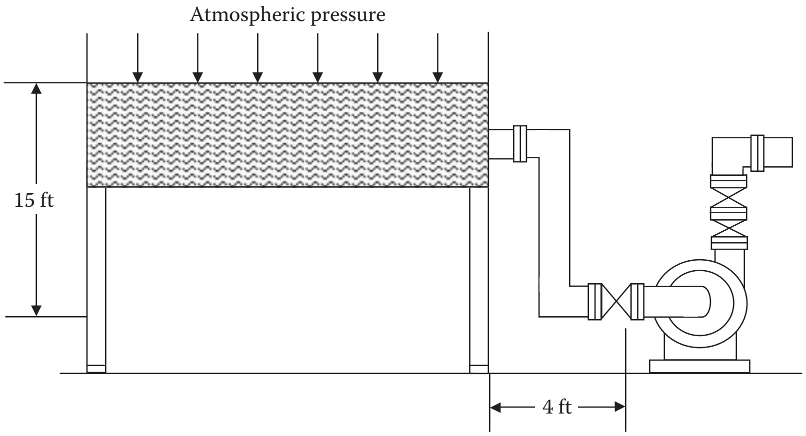

Figure 10.4 Open atmospheric tank.

■ *Example 10.10*

Problem: Given the following, find the NPSHA:

Liquid = water
Temperature (t) = 60°F
Specific gravity = 1.0
P_a = 14.7 psia (34 ft)
h = 15 ft
P_v = 0.256 psia (0.6 ft)
h_e = 0.4 ft
h_f = 2 ft

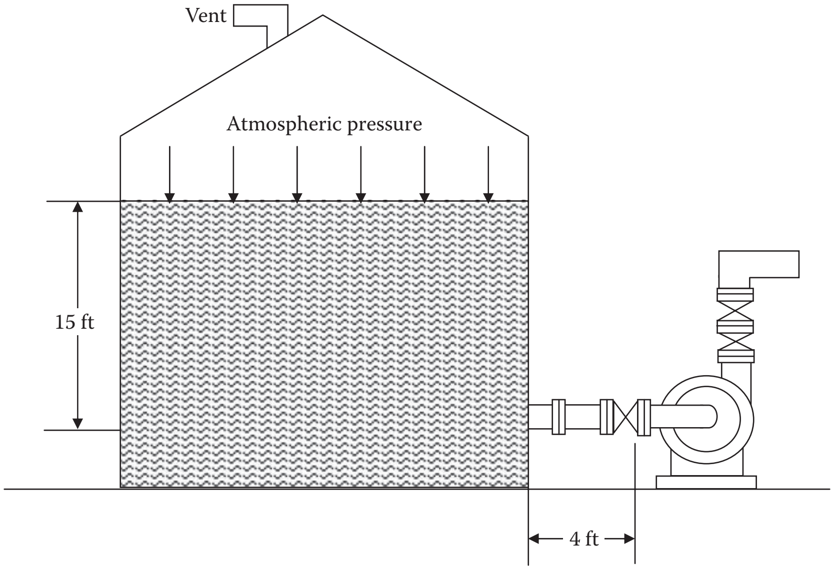

Figure 10.5 Roofed water-storage tank.

Solution:

$$\text{NPSHA} = 34\text{ ft} + 15\text{ ft} - 0.6\text{ ft} - 0.4\text{ ft} - 2\text{ ft} = 46\text{ ft}$$

10.2.12.1.2 NPSHA: Suction Lift from Open Reservoir

■ *Example 10.11*

Problem: Find the NPSHA in Figure 10.6, where:

Liquid = water

Temperature (t) = 60°F

Specific gravity = 1.0

P_a = 14.7 psia (34 ft)

h = –20 ft

P_v = 0.256 psia (0.6 ft)

Q = 120 gpm

h_e = 0.4 ft

h_f = 2 ft

Solution:

$$\text{NPSHA} = 34\text{ ft} + (-20\text{ ft}) - 0.6\text{ ft} - 0.4\text{ ft} - 2\text{ ft} = 11\text{ ft}$$

10.2.13 Pumps in Series and Parallel

Parallel operation occurs when two pumps discharge into a common header. This type of connection is advantageous when the system demand varies greatly. An advantage of operating pumps in parallel

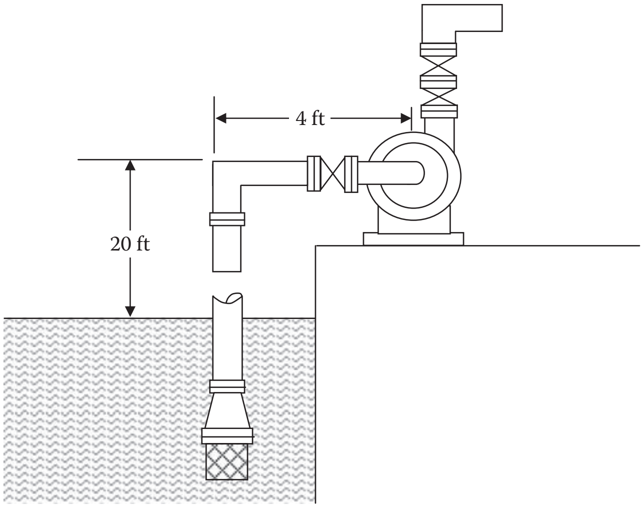

Figure 10.6 Suction lift from open reservoir.

is that when two pumps are online, one can be shut down during low demand. This allows the remaining pump to operate close to its optimum efficiency. *Series* operation is achieved by having one pump discharge into the suction of the next. This arrangement is used primarily to increase the discharge head, although a small increase in capacity also results.

10.3 CENTRIFUGAL PUMPS

The *centrifugal pump* (and its modifications) is the most widely used type of pumping equipment in water/wastewater operations. This type of pump is capable of moving high volumes of water/wastewater (and other liquids) in a relatively efficient manner. The centrifugal pump is very dependable, has relatively low maintenance requirements, and can be constructed out of a wide variety of construction materials. It is considered one of the most dependable systems available for water transfer.

10.3.1 Description

The centrifugal pump consists of a rotating element (*impeller*) sealed in a casing (*volute*). The rotating element is connected to a drive unit (*motor/engine*) that supplies the energy to spin the rotating element. As the impeller spins inside the volute casing, an area of low pressure is created in the center of the impeller. This low pressure allows the atmospheric pressure on the liquid in the supply tank to force the liquid up to the impeller. Because the pump will not operate if no low-pressure zone is created at the center of the impeller, it is important that the casing be sealed to prevent air from entering the casing.

Key Point: A centrifugal pump is a pumping mechanism whose rapidly spinning impeller imparts a high velocity to the water that enters, then converts that velocity to pressure upon exit.

To ensure that the casing is airtight, the pump employs some type of seal (*mechanical* or *conventional packing*) assembly at the point where the shaft enters the casing. This seal also includes lubrication, provided by water, grease, or oil, to prevent excessive wear.

From a hydraulic standpoint, note the energy changes that occur in the moving water. As water enters the casing, the spinning action of the impeller imparts (transfers) energy to the water. This energy is transferred to the water in the form of increased speed or velocity. The liquid is thrown outward by the impeller into the volute casing where the design of the casing allows the velocity of the liquid to be reduced, which, in turn, converts the velocity energy (*velocity head*) to pressure energy (*pressure head*). The process by which this change occurs is described later. The liquid then travels out of the pump through the pump discharge. The major components of the centrifugal pump are shown in Figure 10.7.

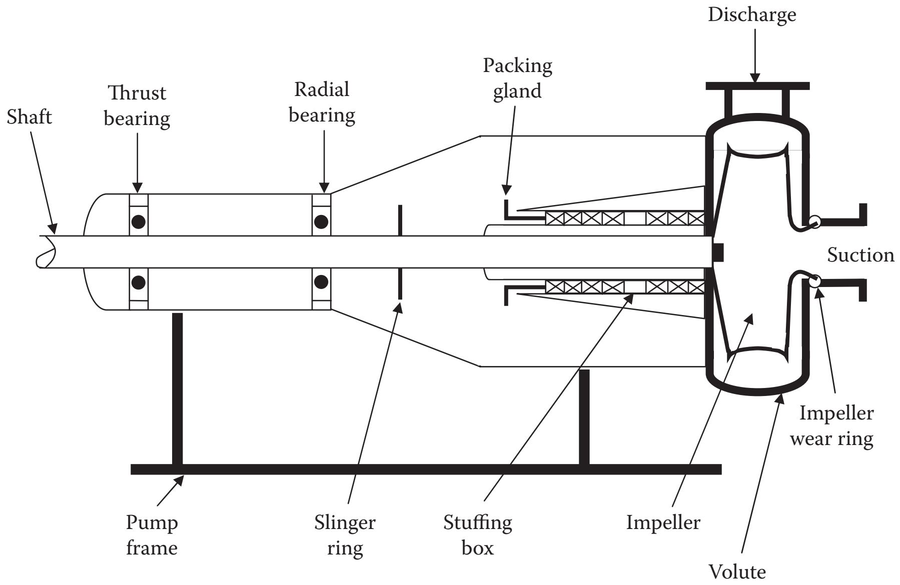

Figure 10.7 Centrifugal pump, major components.

10.3.2 Terminology

To understand centrifugal pumps and their operation, we must understand the terminology associated with centrifugal pumps:

Base plate—The foundation under a pump. It usually extends far enough to support the drive unit. The base plate is often referred to as the *pump frame*.

Bearings—Devices used to reduce friction and to allow the shaft to rotate easily. Bearings may be sleeve, roller, or ball.

- *Radial (line) bearing*—In a single-suction pump, it is the one closest to the pump. It rides free in its own section and takes up and down stresses.
- *Thrust bearing*—In a single-suction pump, it is the bearing located nearest the motor, farthest from the impeller. It takes up the major thrust of the shaft, which is opposite from the discharge direction.

Note: In most cases, where pump and motor are constructed on a common shaft (no coupling), the bearings will be part of the motor assembly.

Casing—The housing surrounding the rotating element of the pump. In the majority of centrifugal pumps, this casing can also be called the *volute*.

- *Split casing*—A pump casing that is manufactured in two pieces fastened together by means of bolts. Split casing pumps may be vertically split (perpendicular to the shaft direction) or horizontally split (parallel to the shaft direction).

Coupling—Device to join the pump shaft to the motor shaft. If the pump and motor are constructed on a common shaft, the assembly is referred to as a *close-coupled arrangement*.

Extended shaft—For a pump constructed on one shaft that must be connected to the motor by a coupling.

Frame—The housing that supports the pump bearing assemblies. In an end-suction pump, it may also be the support for the pump casing and the rotating element.

Impeller—The rotating element in the pump that actually transfers the energy from the drive unit to the liquid. Depending on the pump application, the impeller may be open, semi-open, or closed. It may also be single or double suction.

Impeller eye—The center of the impeller, the area that is subject to lower pressures due to the rapid movement of the liquid to the outer edge of the casing.

Priming—Filling the casing and impeller with liquid. If this area is not completely full of liquid, the centrifugal pump will not pump efficiently.

Seals—Devices used to stop the leakage of air into the inside of the casing around the shaft.

- *Gland*—Also known as the *packing gland*, it is a metal assembly that is designed to apply even pressure to the packing to compress it tightly around the shaft.
- *Lantern ring*—Also known as the *seal cage*, it is positioned between the rings of packing in the stuffing box to allow the introduction of a lubricant (water, oil, or grease) onto the surface of the shaft to reduce the friction between the packing and the rotating shaft.
- *Mechanical seal*—A device consisting of a stationary element, a rotating element, and a spring to supply force to hold the two elements together; may be either single or double units.
- *Packing*—Material that is placed around the pump shaft to seal the shaft opening in the casing and prevent air leakage into the casing.
- *Stuffing box*—The assembly located around the shaft at the rear of the casing. It holds the packing and lantern ring.

Shaft—The rigid steel rod that transmits the energy from the motor to the pump impeller. Shafts may be either vertical or horizontal.

Shaft sleeve—A piece of metal tubing placed over the shaft to protect the shaft as it passes through the packing or seal area. In some cases, the sleeve may also help to position the impeller on the shaft.

Shroud—The metal plate that is used to either support the impeller vanes (open or semi-open impeller) or enclose the vanes of the impeller (closed impeller).

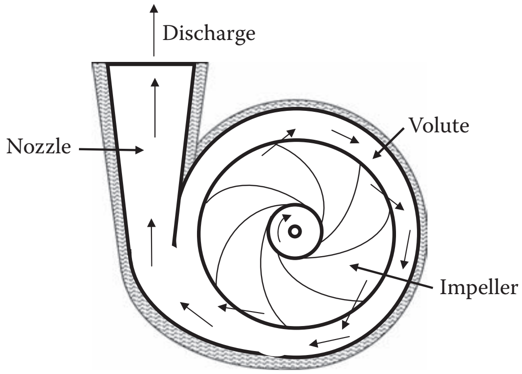

Figure 10.8 Cross-sectional diagram showing the features of a centrifugal pump.

Shut-off head—The head or pressure at which the centrifugal pump will stop discharging. It is also the pressure developed by the pump when it is operated against a closed discharge valve. This is also known as a *cut-off head*.

Slinger ring—A device to prevent pumped liquids from traveling along the shaft and entering the bearing assembly. A slinger ring is also called a *deflector*.

Wearing rings—Devices that are installed on stationary or moving parts within the pump casing to protect the casing and the impeller from wear due to the movement of liquid through points of small clearances.

- *Casing ring*—A wearing ring installed in the casing of the pump. A casing ring is also known as the *suction head ring*.
- *Impeller ring*—A wearing ring installed directly on the impeller.
- *Stuffing box cover ring*—A wearing ring installed at the impeller in an end-suction pump to maintain the impeller clearances and to prevent casing wear.

10.3.3 Pump Theory

The *volute-cased centrifugal pump* (see Figure 10.8) provides the pumping action necessary to transfer liquids from one point to another. First, the drive unit (usually an electric motor) supplies energy to the pump impeller to make it spin. This energy is then transferred to the water by the impeller. The vanes of the impeller spin the liquid toward the outer edge of the impeller at a high rate of speed or velocity. This action is very similar to that which would occur when a bucket full of water with a small hole in the bottom is attached to a rope and spun. When the bucket is sitting still, the water in the bucket will drain out slowly; however, when the bucket is spinning, the water will be forced through the hole at a much higher rate of speed.

Centrifugal pumps may be single stage with a single impeller, or they may be multiple stage with several impellers through which the fluid flows in series. Each impeller in the series increases the pressure of the fluid at the pump discharge. Pumps may have 30 or more stages in extreme cases. In centrifugal pumps, a correlation of pump capacity, head, and speed at optimum efficiency is used to classify the pump impellers with respect to their specific geometry. This correlation is called *specific speed* and is an important parameter for analyzing pump performance (Garay, 1990).

The volute of the pump is designed to convert velocity energy to pressure energy. As a given volume of water moves from one cross-sectional area to another with the volute casing, the velocity or speed of the water changes proportionately. The volute casing has a cross-sectional area that is extremely small at the point in the case that is farthest from the discharge (see Figure 10.8). This area increases continuously to the discharge. As this area increases, the velocity of the water passing through it decreases as it moves around the volute casing to the discharge point.

As the velocity of the water decreases, the velocity head decreases and the energy is converted to pressure head. There is a direct relationship between the velocity of the water and the pressure it exerts; therefore, as the velocity of the water decreases, the excess energy is converted to additional pressure (pressure head). This pressure head supplies the energy to move the water through the discharge piping.

10.3.4 Pump Characteristics

The centrifugal pump operates on the principle of an energy transfer and, therefore, has certain definite characteristics that make it unique. The type and size of the impeller limit the amount of energy that can be transferred to the water, the characteristics of the material being pumped, and the total head of the system through which the water is moving. For any one centrifugal pump, a definite relationship exists between these factors along with head (capacity), efficiency, and brake horsepower.

10.3.4.1 Head (Capacity)

As might be expected, the capacity of a centrifugal pump is directly related to the total head of the system. If the total head on the system is increased, the volume of the discharge will be reduced proportionately. As the head of the system increases, the capacity of the pump decreases proportionately until the discharge stops. The head at which the discharge no longer occurs is known as the *cut-off head*. As pointed out earlier, the total head includes a certain amount of energy to overcome the friction of the system. This friction head can be greatly affected by the size and configuration of the piping and the condition of the valving of the system. If the control valves on the system are closed partially, the friction head can increase dramatically. When this happens, the total head increases and the capacity or volume discharged by the pump decreases. In many cases, this method is employed to reduce the discharge of a centrifugal pump. It should be noted, however, that this does increase the load on the pump and drive system, causing additional energy requirements and additional wear.

The total closure of the discharge control valve increases the friction head to the point where all of the energy supplied by the pump is consumed in the friction head and is not converted to pressure head; consequently, the pump exceeds its cut-off head and the pump discharge is reduced to zero. Again, it is important to note that, although the operation of a centrifugal pump against a closed discharge may not be hazardous (as with other types of pumps), it should be avoided because of the excessive load placed on the drive unit and pump. Our experience has shown that on occasion the pump can produce pressure higher than the pump discharge piping can withstand. Whenever this occurs, the discharge piping may be severely damaged by the operation of the pump against a closed or plugged discharge.

10.3.4.2 Efficiency

Every centrifugal pump will operate with varying degrees of efficiency over its entire capacity and head ranges. The important factor in selecting a centrifugal pump is to select a unit that will perform near its maximum efficiency in the expected application.

10.3.4.3 Brake Horsepower Requirements

In addition to the head capacity and efficiency factors, most pump literature includes a graph showing the amount of energy in horsepower that must be supplied to the pump to obtain optimal performance.

10.3.5 Advantages and Disadvantages of the Centrifugal Pump

The primary reason why centrifugal pumps have become one of the most widely used types of pumps is that they offer several advantages, including:

- *Construction*—The pump consists of a single rotating element and simple casing, which can be constructed using a wide assortment of materials. If the fluids to be pumped are highly corrosive, the pump parts that are exposed to the fluid can be constructed of lead or other material that is not likely to corrode. If the fluid being pumped is highly abrasive, the internal parts can be made of abrasion-resistant material or coated with a protective material. Also, the simple design of a centrifugal pump allows the pump to be constructed in a variety of sizes and configurations. No other pump currently available offers the range of capacities or applications available that the centrifugal pump does.

- *Operation*—"Simple and quiet" best describes the operation of a centrifugal pump. An operator-in-training with a minimum amount of experience may be capable of operating facilities that use centrifugal-type pumps. Even when improperly operated, the rugged construction of the centrifugal pump allows it to operate (in most cases) without major damage.
- *Maintenance*—The amount of wear on the moving parts of a centrifugal pump is reduced and its operating life is extended because its moving parts are not required to be constructed to very close tolerances.
- *Self-limited pressure*—Because of the nature of its pumping action, the centrifugal pump will not exceed a predetermined maximum pressure. Thus, if the discharge valve is suddenly closed, the pump cannot generate additional pressure that might result in damage to the system or could potentially result in a hazardous working condition. The power supplied to the impeller will only generate a specified amount of head (pressure). If a major portion of this head or pressure is consumed in overcoming friction or is lost as heat energy, the pump will have a decreased capacity.
- *Adaptable to high-speed drive systems*—Centrifugal pumps can make use of high-speed, high-efficiency motors. In situations where the pump is selected to match a specific operating condition, which remains relatively constant, the pump drive unit can be used without the need for expensive speed reducers.
- *Small space requirements*—For most pumping capacities, the amount of space required for installation of the centrifugal-type pump is much less than that of any other type of pump.
- *Fewer moving parts*—The rotary rather than reciprocating motion employed in centrifugal pumps reduces space and maintenance requirements due to the fewer number of moving parts required.

Although the centrifugal pump is one of the most widely used pumps, it does have a few disadvantages:

- *Additional equipment is needed for priming*—The centrifugal pump can be installed in a manner that will make it self-priming, but it is not capable of drawing water to the pump impeller unless the pump casing and impeller are filled with water. This can cause problems, because if the water in the casing drains out the pump ceases pumping until it is refilled; therefore, it is normally necessary to start a centrifugal pump with the discharge valve closed. The valve is then gradually opened to its proper operating level. Starting the pump against a closed discharge valve is not hazardous provided the valve is not left closed for extended periods.
- *Air leaks affect pump performance*—Air leaks on the suction side of the pump can cause reduced pumping capacity in several ways. If the leak is not serious enough to result in a total loss of prime, the pump may operate at a reduced head or capacity due to air mixing with the water. This causes the water to be lighter than normal and reduces the efficiency of the energy transfer process.

- *Range of efficiency is narrow*—Centrifugal pump efficiency is directly related to the head capacity of the pump. The highest performance efficiency is available for only a very small section of the head-capacity range. When the pump is operated outside of this optimum range, the efficiency may be greatly reduced.
- *Pump may run backwards*—If a centrifugal pump is stopped without closing the discharge line, it may run backwards, because the pump does not have any built-in mechanism to prevent flow from moving through the pump in the opposite direction (i.e., from discharge side to suction). If the discharge valve is not closed or the system does not contain the proper check valves, the flow that was pumped from the supply tank to the discharge point will immediately flow back to the supply tank when the pump shuts off. This results in increased power consumption due to the frequent start-up of the pump to transfer the same liquid from supply to discharge.

Note: It is sometimes difficult to tell whether a centrifugal pump is running forward or backward because it appears and sounds like it is operating normally when operating in reverse.

- *Pump speed is difficult to adjust*—Centrifugal pump speed cannot usually be adjusted without the use of additional equipment, such as speed-reducing or speed-increasing gears or special drive units. Because the speed of the pump is directly related to the discharge capacity of the pump, the primary method available to adjust the output of the pump other than a valve on the discharge line is to adjust the speed of the impeller. Unlike some other types of pumps, the delivery of the centrifugal pump cannot be adjusted by changing some operating parameter of the pump.

10.3.6 Centrifugal Pump Applications

The centrifugal pump is probably the most widely used pump available at this time because of its simplicity of design and wide-ranging diversity (it can be adjusted to suit a multitude of applications). Proper selection of the pump components (e.g., impeller, casing) and construction materials can produce a centrifugal pump capable of transporting not only water but also other materials ranging from material or chemical slurries to air (centrifugal blowers). To attempt to list all of the various applications for the centrifugal pump would exceed the limitations of this handbook; therefore, our discussion of pump applications is limited to those that frequently occur in water/wastewater operations.

- *Large-volume pumping*—In water/wastewater operations, the primary use of centrifugal pumps is large-volume pumping. Generally, in large-volume pumping, low-speed, moderate-head, vertically shafted pumps are used. Centrifugal pumps are well suited for water/wastewater system operations because they can be used in conditions where high volumes are required and a change in flow is not a problem. As the discharge pressure on a centrifugal pump is increased, the quantity of water/wastewater pumped is reduced. Also, centrifugal pumps can be operated for short periods with the discharge valve closed.

- *Nonclog pumping*—Specifically designed centrifugal pumps utilize closed impellers with, at most, two to three vanes. They are usually designed to pass solids or trash up to 3 inches in diameter.
- *Dry-pit pump*—Depending on the application, the dry-pit pump may be either a large-volume pump or a nonclog pump. It is located in a dry pit that shares a common wall with the wet well. This pump is normally placed in such a position as to ensure that the liquid level in the wet well is sufficient to maintain the prime of the pump.
- *Wet-pit or submersible pump*—This type of pump is usually a nonclog pump that can be submerged, with its motor, directly in the wet well. In a few instances, the pump may be submerged in the wet well while the motor remains above the water level. In these cases, the pump is connected to the motor by an extended shaft.
- *Underground pump stations*—Utilizing a wet-well/dry-well design, these pumps are located in an underground facility. Wastes are collected in a separate wet well, then pumped upward and discharged into another collector line or manhole. This system normally uses a nonclog type of pump and is designed to add sufficient head to water/wastewater flow to allow gravity to move the flow to the plant or the next pump station.
- *Recycle or recirculation pumps*—Because the liquids being transferred by the recycle or recirculation pump normally do not contain any large solids, the use of the nonclog type of centrifugal pump is not always required. A standard centrifugal pump may be used to recycle trickling filter effluent, return activated sludge, or digester supernatant.
- *Service water pumps*—The wastewater plant effluent may be used for many purposes, such as to clean tanks, water lawns, provide the water to operate the chlorination system, and backwash filters. Because the plant effluent used for these purposes is normally clean, the centrifugal pumps used in this case closely parallel the units used for potable water. In many cases, the double-suction, closed-impeller, or turbine type of pump will be used.

10.3.7 Pump Control Systems

> Pump operations usually control only one variable: flow, pressure, or level. All pump control systems have a measuring device that compares a measured value with a desired one. This information relays to a control element that makes the changes. ...The user may obtain control with manually operated valves or sophisticated microprocessors. Economics dictate the accuracy and complication of a control system.
>
> **Wahren (1997)**

Most centrifugal pumps require some form of pump control system. The only exception to this practice is when the plant pumping facilities are designed to operate continuously at a constant rate of discharge. The

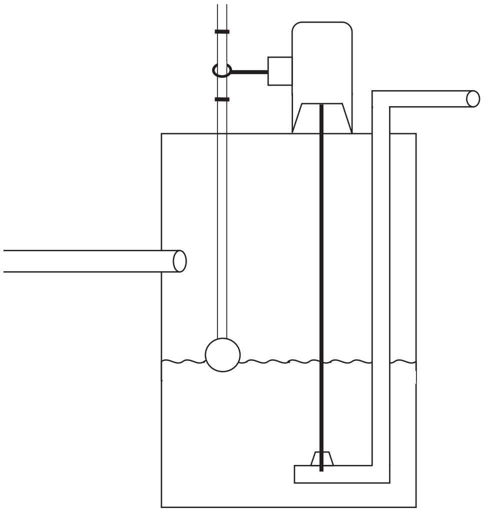

Figure 10.9 Float system for pump motor control.

typical pump control system includes a sensor to determine when the pump should be turned on or off and the electrical/electronic controls to actually start and stop the pump. The control systems currently available for the centrifugal pump range from a very simple on/off float control to an extremely complex system capable of controlling several pumps in sequence. The following sections briefly describe the operation of various types of control devices/systems used with centrifugal pumps.

10.3.7.1 Float Control System

Currently, the float control system is the simplest of the centrifugal pump controls (see Figure 10.9). In the float control system, the float rides on the surface of the water in the well, storage tank, or clear well and is attached to the pump controls by a rod with two collars. One collar activates the pump when the liquid level in the well or tank reaches a preset level, and a second collar shuts the pump off when the level in the well reaches a minimum level. This type of control system is simple to operate and relatively inexpensive to install and maintain. The system has several disadvantages; for example, it operates at one discharge rate, which can result in: (1) extreme variations in the hydraulic loading on succeeding units, and (2) long periods of not operating due to low flow periods or maintenance activities.

10.3.7.2 Pneumatic Control System

The pneumatic control system (also called a *bubbler tube control system*) is a relatively simple system that can be used to control one or more pumps. The system consists of an air compressor; a tube extending into the well, clear well, or storage tank/basin; and pressure-sensitive switches with varying on/off set points and a pressure relief valve (see Figure 10.10). The system works on the basic principle of measuring the depth of the water in the well or tank by determining the air pressure

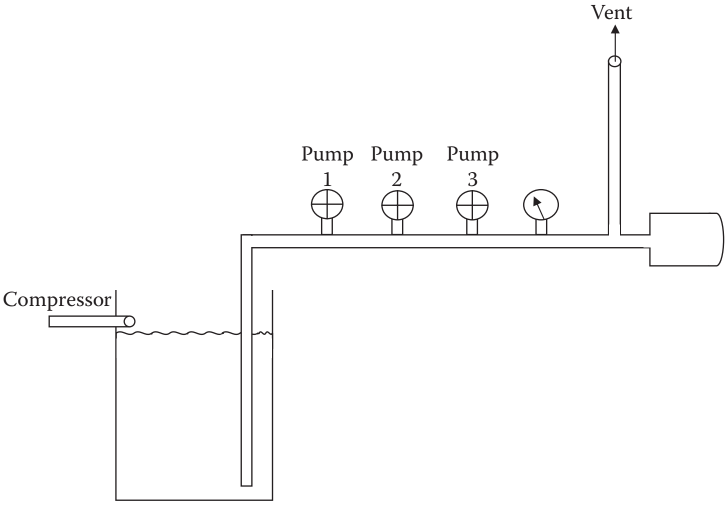

Figure 10.10 Pneumatic system for pump motor control.

necessary to just release a bubble from the bottom of the tube (see Figure 10.10)—hence, the name *bubbler tube*. The air pressure required to force a bubble out of the tube is determined by the liquid pressure, which is directly related to the depth of the liquid (1 psi = 2.31 ft). By installing a pressure switch on the air line to activate the pump starter at a given pressure, the level of the water can be controlled by activating one or more pumps.

Installation of additional pressure switches with slightly different pressure settings allows several pumps to be activated in sequence. As an example, the first pressure switch can be adjusted to activate a pump when the level in the well or tank is 3.8 ft (1.6 psi) and shut off at 1.7 ft (0.74 psi). If the flow into the pump well or tank varies greatly, and additional pumps are available to ensure that the level in the well or tank does not exceed the design capacity, additional pressure switches may be installed. These additional pressure switches are set to activate a second pump when the level in the well or tank reaches a preset level (e.g., 4.5 ft/1.95 psi) and cut off when the well or tank level is reduced to a preset level (e.g., 2.7 ft/1.2 psi).

If the capacity of the first pump is less than the rate of flow into the well or tank, the level of the well or tank continues to rise. When the preset level (e.g., 4 ft) is reached, the second pump will be activated. If necessary, a third pump can be added to the system set to activate at a third preset well or tank depth (e.g., 4.6 ft or 1.99 psi) and to cut off a preset depth (e.g., 3.0 ft or 1.3 psi).

The pneumatic control system is relatively simple and has minimal operation and maintenance requirements. The major operational problem involved with this control system is clogging of the bubbler tube. If, for some reason, the tube becomes clogged, the pressure on the system can increase and may activate all pumps to run even when the well or tank is low. This can result in excessive power consumption, which, in turn, may damage the pumps.

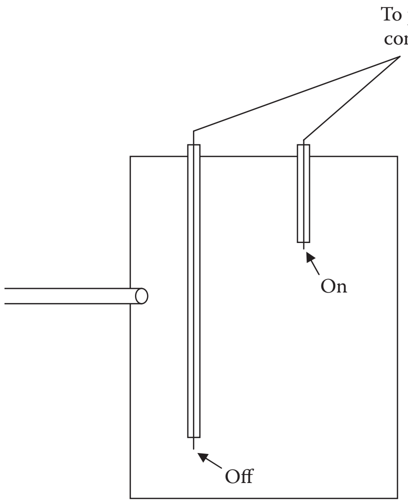

Figure 10.11 Electrode system for pump motor control.

10.3.7.3 Electrode Control System

The electrode control system uses a probe or electrode to control the pump on and off cycle. A relatively simple control system, it consists of two electrodes extending into the clear well, storage tank, or basin. One electrode activates the pump starter when it is submerged in the water; the second electrode extends deeper into the well or tank and is designed to open the pump circuit when the water drops below the electrode (see Figure 10.11). The major maintenance requirement of this system is keeping the electrodes clean.

Key Point: Because the electrode control system uses two separate electrodes, the unit may be locked into an on cycle or off cycle, depending on which electrode is compromised.

10.3.7.4 Other Control Systems

Several other systems that use electrical energy are available for control of the centrifugal pump. These include a *tube-like device* that has several electrical contacts mounted inside (see Figure 10.12). As the water level rises in the clear well, storage tank, or basin, the water rises in the tube, making contact with the electrical contacts and activating the motor starter. Again, this system can be used to activate several pumps in series by installation of several sets of contact points. As the water level drops in the well or tank, the level in the tube drops below a second contact that deactivates the motor and stops the pumping. Another control system uses a *mercury switch* (or a similar type of switch) enclosed in a protective capsule. Again, two units are required per pump. One switch activates the pump when the liquid level rises, and the second switch shuts the pump off when the level reaches the desired minimum depth.

10.3.8 Electronic Control Systems

Several centrifugal pump control systems are available that use electronic systems for control of pump operation. A brief description of some of these systems is provided in the sections that follow.

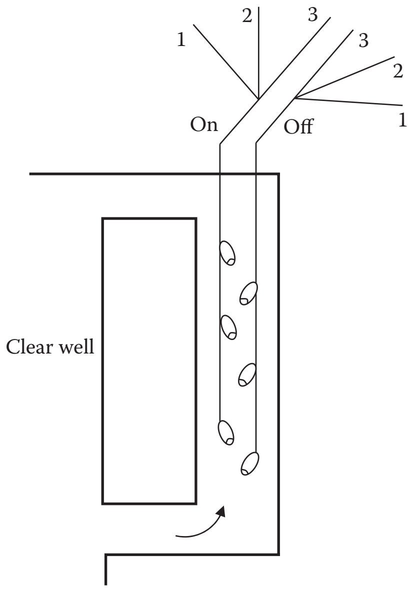

Figure 10.12 Electrical contacts for pump motor control.

10.3.8.1 Flow Equalization System

In any multiple pump operation, the flow delivered by each pump will vary due to the basic hydraulic design of the system. To obtain equal loads on each pump when two or more are in operation, the flow equalization system electronically monitors the delivery of each pump and adjusts the speed of the pumps to obtain similar discharge rates for each pump.

10.3.8.2 Sonar or Other Transmission Type Controllers

A *sonar* or *low-level radiation system* can be used to control centrifugal pumps. This type of system uses a transmitter and receiver to locate the level of the water in a tank, clear well, or basin. When the level reaches a predetermined set point, the pump is activated; when the level is reduced to a predetermined set point, the pump is shut off. Basically, the system is very similar to a radar unit. The transmitter sends out a beam that travels to the liquid, bounces off the surface, and returns to the receiver. The time required for this is directly proportional to the distance from the liquid to the instrument. The electronic components of the system can be adjusted to activate the pump when the time interval corresponds to a specific depth in the well or tank. The electronic system can also be set to shut off the pump when the time interval corresponds to a preset minimum depth.

10.3.8.3 Motor Controllers

Several types of controllers are available that protect the motor not only from overloads but also from short-circuit conditions. Many motor controllers also function to adjust motor speed to increase or decrease

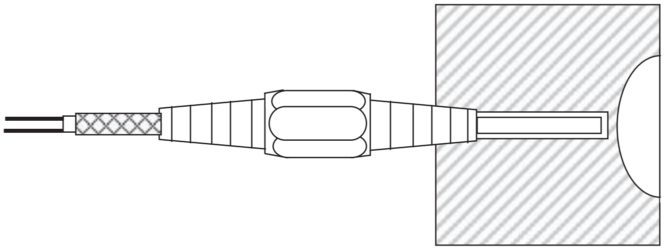

Figure 10.13 Thermocouple installation in journal bearing.

the discharge rate for a centrifugal pump. This type of control may use one of the previously described controls to start and stop the pump and, in some cases, adjust the speed of the unit. As the depth of the water in a well or tank increases, the sensor automatically increases the speed of the motor in predetermined steps to the maximum design speed. If the level continues to increase, the sensor may be designed to activate an additional pump.

10.3.8.4 Protective Instrumentation

Protective instrumentation of some type is normally employed in pump or motor installation. (Note that the information provided in this section applies to the centrifugal pump as well as to many other types of pumps.) Protective instrumentation for centrifugal pumps (or most other types of pumps) is dependent on pump size, application, and the amount of operator supervision; that is, pumps under 500 hp often only come with pressure gauges and temperature indicators. These gauges or transducers may be mounted locally (on the pump itself) or remotely (in suction and discharge lines immediately upstream and downstream of the suction and discharge nozzles). If transducers are employed, readings are typically displayed and taken (or automatically recorded) at a remote operating panel or control center.

10.3.8.5 Temperature Detectors

Resistance temperature devices (RTDs) and *thermocouples* (see Figure 10.13) (Grimes, 1976) are commonly used as temperature detectors on the pump prime movers (motors) to indicate temperature problems. In some cases, dial thermometers, armored glass-stem thermometers, or bimetallic-actuated temperature indicators are used. Whichever device is employed, it typically monitors temperature variances that may indicate a possible source of trouble. On electric motors greater than 250 hp, RTD elements are used to monitor temperatures in stator winding coils. Two RTDs per phase are standard. One RTD element is usually installed in the shoe of the loaded area employed on journal bearings in pumps and motors. Normally, tilted-pad thrust bearings have an RTD element in the active, as well as the inactive, side. RTDs are used when remote indication, recording, or automatic logging of temperature readings is required. Because of their smaller size, RTDs provide more flexibility in locating the measuring device near the measuring point. When dial thermometers are installed, they monitor oil thrown from bearings. Sometimes temperature detectors also monitor bearings with water-cooled jackets to warn against water supply failure. Pumps with heavy wall casings may also have casing temperature monitors.

10.3.8.6 Vibration Sensors

Vibration sensors are available to measure either bearing vibration or shaft vibration direction directly. Direct measurement of shaft vibration is desirable for machines with stiff bearing supports where bearing-cap measurements will be only a fraction of the shaft vibration. Pumps and motors 1000 hp and larger may have the following vibration monitoring equipment (Wahren, 1997):

- A seismic pickup with double set points installed on the pump outboard housing
- Proximators with *x–y* vibration probes complete with interconnecting coaxial cables at each radial and thrust journal bearing
- Key phasor with proximator and interconnecting coaxial cables

10.3.8.7 Supervisory Instrumentation

Supervisory instruments are used to monitor the routine operation of pumps, their prime movers, and their accessories to sustain a desired level of reliability and performance. Generally, these instruments are not used for accurate performance tests or for automatic control, although they may share connections or functions. Supervisory instruments consist of annunciators and alarms that provide operators with warnings of abnormal conditions that, unless corrected, will cause pump failure. Annunciators used for both alarm and pre-alarm have both visible and audible signals.

10.3.9 Centrifugal Pump Modifications

The centrifugal pump can be modified to meet the needs of several different applications. If it is necessary to produce higher discharge heads, the pump may be modified to include several additional impellers. If the material being pumped contains a large amount of material that could clog the pump, the pump construction may be modified to remove a major portion of the impeller from direct contact with the material being pumped. Although numerous modifications of the centrifugal pump are available, the scope of this text covers only those that have found wide application in the water distribution and wastewater collection and treatment fields. Modifications presented in this section include:

- Submersible pumps
- Recessed impeller or vortex pumps
- Turbine pumps

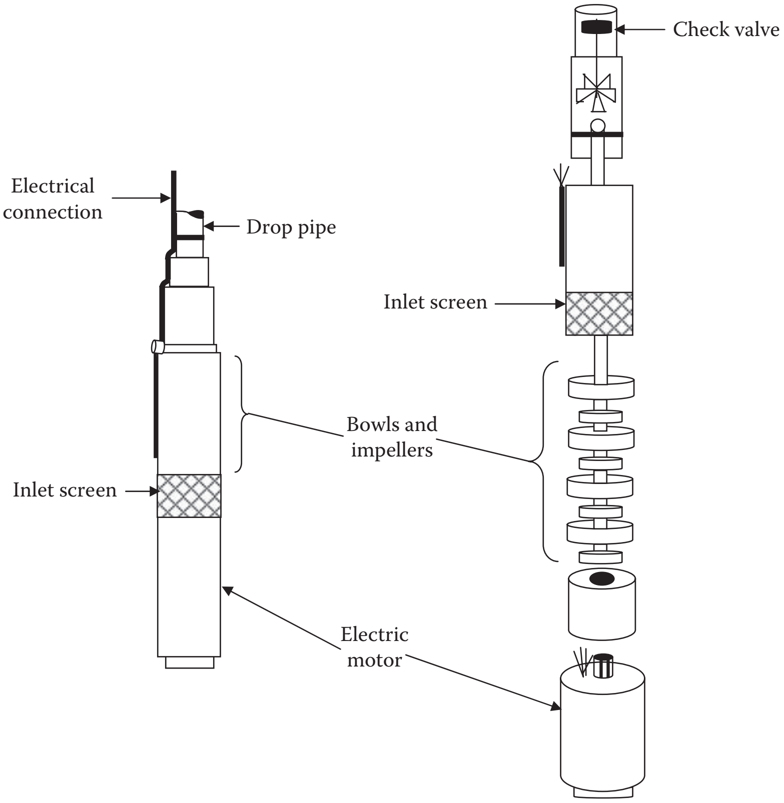

Figure 10.14 Submersible pump.

10.3.9.1 Submersible Pumps

The submersible pump is, as the name suggests, placed directly in the wet well or groundwater well. It uses a waterproof electric motor located below the static level of the well to drive a series of impellers. In some cases, only the pump is submerged, while in other cases the entire pump–motor assembly is submerged. Figure 10.14 illustrates this system.

The submersible pump may be either a close-coupled centrifugal pump or an extended-shaft centrifugal pump. If the system is a close-coupled system, then both motor and pump are submerged in the liquid being pumped. Seals prevent water and wastewater from entering the inside of the motor, protecting the electric motor in a close-coupled pump from shorts and motor burnout. In the extended-shaft system, the pump is submerged and the motor is mounted above the pump wet well. In this situation, an extended shaft assembly must connect the pump and motor.

The submersible pump has wide applications in the water/wastewater treatment industry. It generally can be substituted in any application of other types of centrifugal pumps; however, it has found its widest application in distribution or collector system pump stations. In addition to the advantages discussed earlier for a conventional centrifugal pump, the submersible pump has additional advantages:

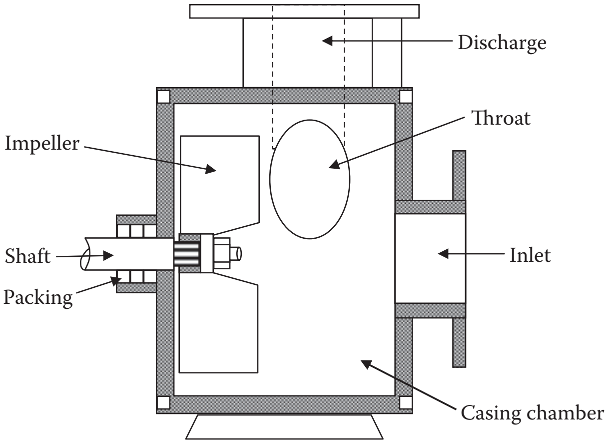

Figure 10.15 Schematic of a recessed impeller or vortex pump.

- It is located below the surface of the liquid, so it is not as likely that the pump will lose its prime, develop air leaks on the suction side of the pump, or require initial priming.
- The pump or the entire assembly is located in the well, so costs associated with the construction and operation of this system are reduced. It is not necessary to construct a dry well or a large structure to hold the pumping equipment and necessary controls.

The major disadvantage associated with the submersible pump is the lack of access to the pump or pump and motor. The performance of any maintenance requires either drainage of the wet well or extensive lift equipment to remove the equipment from the wet well, or both. This may be a major factor in determining if a pump receives the attention it requires. Also, in most cases, all major maintenance on close-coupled submersible pumps must be performed by outside contractors due to the need to reseal the motor to prevent leakage.

10.3.9.2 Recessed Impeller or Vortex Pumps

The recessed impeller or vortex pump uses an impeller that is either partially or wholly recessed into the rear of the casing (see Figure 10.15). The spinning action of the impeller creates a vortex or whirlpool. This whirlpool increases the velocity of the material being pumped. As in other centrifugal pumps, this increased velocity is then converted to increased pressure or head. The recessed impeller or vortex pump is used widely in applications where the liquid being pumped contains large amounts of solids or debris and slurries that could clog or damage the impeller of the pump. It has found increasing use as a sludge pump in facilities that withdraw sludge continuously from their primary clarifiers.

The major advantage of this modification is the increased ability to handle materials that would normally clog or damage the pump impeller. Because the majority of the flow does not come in direct contact with the impeller, the potential for problems is reduced. Because of the reduced direct contact between the liquid and the impeller, the energy transfer is less efficient. This results in somewhat higher power costs and limits application of the pump to low to moderate capacities. Objects that might have clogged a conventional type of centrifugal pump are able to pass through the pump. Although this is very beneficial in reducing pump maintenance requirements, it has, in some situations, allowed material to pass into a less accessible location before becoming an obstruction. To be effective, the piping and valving must be designed to pass objects of a size equal to that which the pump will discharge.

10.3.9.3 Turbine Pumps

The turbine pump consists of a motor, drive shaft, discharge pipe of varying lengths, and one or more impeller–bowl assemblies (see Figure 10.16). It is normally a vertical assembly, where water enters at the bottom, passes axially through the impeller–bowl assembly where the energy transfer occurs, then moves upward through additional impeller–bowl assemblies to the discharge pipe. The length of this discharge pipe will vary with the distance from the wet well to the desired point of discharge. Due to the construction of the turbine pump, the major applications have traditionally been for pumping of relatively clean water. The lineshaft turbine pump has been used extensively for drinking water pumping, especially in those situations where water is withdrawn from deep wells. The main wastewater plant application has been pumping plant effluent back into the plant for use as service water.

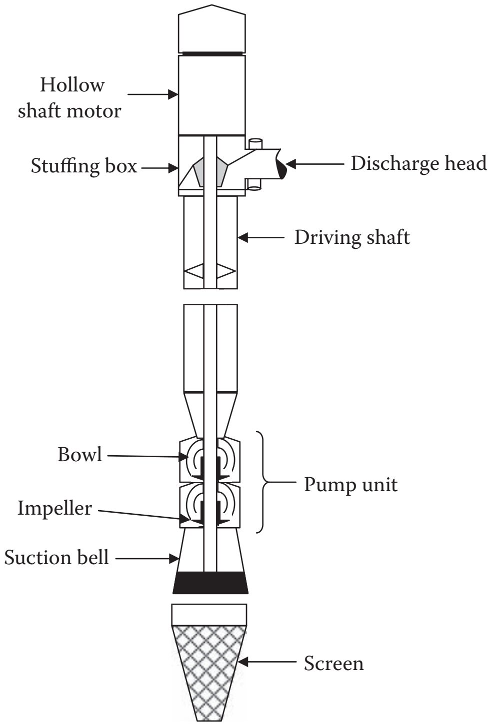

Figure 10.16 Vertical turbine pump.

The turbine pump has a major advantage in the amount of head it is capable of producing. By installing additional impeller–bowl assemblies, the pump is capable of even greater production. Moreover, the turbine pump has simple construction and a low noise level and is adaptable to several drive types—motor, engine, or turbine. High initial costs and high repair costs are two of the major disadvantages of turbine pumps. In addition, the presence of large amounts of solids within the liquid being pumped can seriously increase the amount of maintenance the pump requires; consequently, the unit has not found widespread use in any situation other than service water pumping.

10.4 POSITIVE DISPLACEMENT PUMPS

Positive displacement pumps force or displace water through the pumping mechanism. Most have a reciprocating element that draws water into the pump chamber on one stroke and pushes it out on the other. Unlike centrifugal pumps that are meant for low-pressure, high-flow applications, positive displacement pumps can achieve greater pressures but are slower moving, low-flow pumps. Types of positive displacement pumps include piston pumps, diaphragm pumps, and peristaltic pumps. In the wastewater industry, positive displacement pumps are most often found as chemical feed pumps. It is important to remember that positive displacement pumps *cannot* be operated against a closed discharge valve. As the name indicates, something must be displaced with each stroke of the pump. Closing the discharge valve can cause rupturing of the discharge pipe, the pump head, the valve, or some other component.

10.4.1 Piston Pump or Reciprocating Pump

The piston or reciprocating pump is one type of positive displacement pump. This pump works just like the piston in an automobile engine—on the intake stroke, the intake valve opens, filling the cylinder with liquid. As the piston reverses direction, the intake valve is pushed closed and the discharge valve is pushed open; the liquid is pushed into the discharge pipe. With the next reversal of the piston, the discharge valve is pulled closed and the intake valve pulled open, and the cycle repeats. A piston pump is usually equipped with an electric motor and a gear and cam system that drives a plunger connected to the piston. Again, just like an automobile engine piston, the piston must have packing rings to prevent leakage and must be lubricated to reduce friction. Because the piston is in contact with the liquid being pumped, only good-grade lubricants can be used for pumping materials that will be added to drinking water. The valves must be replaced periodically, as well.

10.4.2 Diaphragm Pump

A diaphragm pump is composed of a chamber used to pump the fluid, a diaphragm that is operated by either electric or mechanical means, and two valve assemblies—a suction and a discharge valve assembly (see Figure

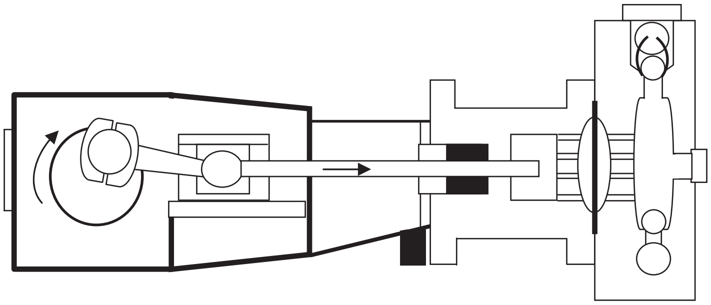

Figure 10.17 Diaphragm pump.

10.17). A diaphragm pump is a variation of the piston pump in which the plunger is isolated from the liquid being pumped by a rubber or synthetic diaphragm. As the diaphragm is moved back and forth by the plunger, liquid is pulled into and pushed out of the pump. This arrangement provides better protection against leakage of the liquid being pumped and allows the use of lubricants that otherwise would not be permitted. Care must be taken to ensure that diaphragms are replaced before they rupture. Diaphragm pumps are appropriate for discharge pressures up to about 125 psi but do not work well if they must lift liquids more than about 4 feet. Diaphragm pumps are frequently used for chemical feed pumps. By adjusting the frequency of the plunger motion and the length of the stroke, extremely accurate flow rates can be metered. The pump may be driven hydraulically by an electric motor or by an electronic driver in which the plunger is operated by a solenoid. Electronically driven metering pumps are extremely reliable (few moving parts) and inexpensive.

10.4.3 Peristaltic Pumps

Peristaltic pumps (sometimes called *tubing pumps*) use a series of rollers to compress plastic tubing to move the liquid through the tubing. A rotary gear turns the rollers at a constant speed to meter the flow. Peristaltic pumps are mainly used as chemical feed pumps. The flow rate is adjusted by changing the speed at which the roller or gear rotates (to push the waves faster) or by changing the size of the tubing (so there is more liquid in each wave). As long as the appropriate type of tubing is used, peristaltic pumps can operate at discharge pressures up to 100 psi. Note that the tubing must be resistant to deterioration from the chemical being pumped. The principle item of maintenance is periodic replacement of the tubing in the pump head. This type of pump has no check valves or diaphragms.

10.5 CHAPTER REVIEW QUESTIONS

10.1 Applications in which chemicals must be metered under high pressure require high-powered __________ pumps.

10.2 __________ materials are materials that resist any flow-producing force.

10.3 What type of pump is usually used for pumping high-viscosity materials?

10.4 High-powered positive-displacement pumps are used to pump chemicals that are under __________ pressure.

10.5 __________ viscosity materials are thick.

10.6 When the __________ of a pump impeller is above the level of the pumped fluid, the condition is called *suction lift*.

10.7 When a pump is not running, conditions are referred to as __________; when a pump is running, the conditions are __________.

10.8 With the __________, the difference in elevation between the suction and discharge liquid levels is called *static head*.

10.9 Velocity head is expressed mathematically as __________.

10.10 The sum of total static head, head loss, and dynamic head is called __________.

10.11 What are the three basic types of curves used for centrifugal pumps?

10.12 What liquid is used to rate pump capacity?

10.13 Because of the reduced amount of air pressure at high altitudes, less __________ is available for the pump.

10.14 With the pump shut off, the difference between the suction and discharge liquid levels is called __________.

10.15 __________ and __________ are the greatest contributing factors to the reduction of pressure at a pump impeller.

10.16 The operation of a centrifugal pump is based on __________.

10.17 The casing of a pump encloses the pump impeller, the shaft, and the __________.

10.18 What part of the pump supplies energy to the fluid?

10.19 If wearing rings are used only on the volute case, we must replace the __________ and __________ at the same time.

10.20 Which part of the end-suction pump directs water flow into and out of the pump?

10.21 What is the function of the pump's impeller?

10.22 What type of pump has no bearings?

10.23 __________ split casings split perpendicular to the pump shaft.

10.24 Name three types of impellers.

10.25 A __________ casing adds a guiding vane to the fluid passage.

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CHAPTER 11

WASTEWATER COLLECTION

In this chapter, we discuss the basics of wastewater collection systems. In Volume II of this handbook series, as you might expect, wastewater collection and conveyance systems are discussed in greater detail. Wastewater collection systems collect and convey used or spent water (wastewater) to the treatment plant. Wastewater collected from homes, businesses, and industries and conveyed to a wastewater treatment plant comprise a *sanitary sewer system*. A similar system known as a *stormwater collection system* conveys water resulting from the runoff of rain and snow from buildings and paved and unpaved areas to a natural watercourse or body of water, usually without treatment. This type of system is also known as a *storm sewer*. In the past, some sanitary sewers and storm sewers were combined into one system; however, during heavy rain events the wastewater treatment plants served by combined sewers often became hydraulically overloaded and washed out into the receiving stream, causing complete treatment system failure. For this reason, combined sewers are now uncommon. The complexity of the system depends on the size of the community and the type of system selected. Methods of collection and conveyance of wastewater include gravity systems, force main systems, vacuum systems, and combinations of all three types of systems.

11.1 GRAVITY COLLECTION SYSTEM

In a gravity collection system, the collection lines are sloped to permit the flow to move through the system with as little pumping as possible. The slope of the lines must keep the wastewater moving at a velocity (speed) of 2 to 4 feet per second; otherwise, at lower velocities, solids will settle out, causing clogged lines, overflows, and offensive odors. To keep collection system lines at a reasonable depth, wastewater must be lifted (pumped) periodically so it can continue flowing "downhill" to the treatment plant. Pumping stations are installed at selected points within the system for this purpose.

11.2 FORCE MAIN COLLECTION SYSTEM

In a typical force main collection system, wastewater is collected to central points and pumped under pressure to the treatment plant. The system is normally used for conveying wastewater long distances. A force main system allows wastewater to flow to the treatment plant at the desired velocity without using sloped lines. It should be noted that the pump station discharge lines in a gravity system are considered to be force mains, as the contents of the lines are under pressure.

Note: Extra care must be taken when performing maintenance on force main systems because the contents of these collection systems are under pressure.

11.3 VACUUM COLLECTION SYSTEM

In a vacuum collection system, wastewaters are collected to central points and then drawn toward the treatment plant under vacuum. The system consists of a large amount of mechanical equipment and requires considerable maintenance to perform properly. Generally, vacuum-type collection systems are not economically feasible.

11.4 PUMPING STATIONS

Pumping stations provide the motive force (energy) to keep the wastewater moving at the desired velocity. They are used in both force main and gravity systems and are designed in several different configurations that may rely on different sources of energy to move the wastewater (i.e., pumps, air pressure, or vacuum). One of the more commonly used pumping station designs is the wet-well/dry-well design.

11.4.1 Wet-Well/Dry-Well Pumping Stations

The wet-well/dry-well pumping station consists of two separate spaces or sections separated by a common wall. Wastewater is collected in one section (wet-well section) and the pumping equipment (and, in many cases, the motors and controllers) is located in a second section known as the dry well. Many different designs are available for this type of system, but in most cases the pumps selected for this system are of a centrifugal design. Two major factors to consider when selecting the centrifugal design are that: (1) it allows for the separation of mechanical equipment (e.g., pumps, motors, controllers, wiring) from the potentially corrosive atmosphere (sulfides) of the wastewater, and (2) it is usually safer for workers because they can monitor, maintain, operate, and repair equipment without entering the pumping station wet well.

Note: Most pumping station wet wells are confined spaces. To ensure safe entry into such spaces, compliance with Occupational Safety and Health Administration (OSHA) 29 CFR 1910.146 (Confined Space Entry Standard) is required.

11.4.2 Wet-Well Pumping Stations

Another type of pumping station is the wet-well type, which consists of a single compartment that collects the wastewater flow. The pump is submerged in the wastewater with motor controls located in the space, or it has a weatherproof motor housing located above the wet well. In this type of station, a submersible centrifugal pump is normally used.

11.4.3 Pneumatic Pumping Stations

The pneumatic pumping station consists of a wet well and a control system that controls the inlet and outlet valve operations and provides pressurized air to force or push the wastewater through the system. The exact method of operation depends on the system design. When the pump is operating, wastewater in the wet well reaches a predetermined level, activating an automatic valve that closes the influent line. The tank (wet well) is then pressurized to a predetermined level. When the pressure reaches the predetermined level, the effluent line valve is opened and the pressure pushes the wastestream out of the discharge line.

11.4.4 Pumping Station Wet-Well Calculations

Calculations normally associated with pumping station wet-well design (such as determining design lift or pumping capacity) are usually left up to design and mechanical engineers. On occasion, however, wastewater operators or interceptor technicians may be called upon to make certain basic calculations. Usually these calculations deal with determining either pump capacity without influent (e.g., checking the pumping rate of the constant-speed pump) or pump capacity with influent (e.g., checking how many gallons per minute the pump is discharging). This section provides examples of how and where these two calculations are made.

■ *Example 11.1. Determining Pump Capacity without Influent*

Problem: A pumping station wet well is 10 ft × 9 ft. The operator needs to check the pumping rate of the station's constant speed pump. To do this, the influent valve to the wet well was closed for a 5-minute test, and the level in the well dropped 2.2 ft. What is the pumping rate in gallons per minute?

Solution: Using the length and width of the well, we can find the area of the water surface.

$$10 \text{ ft} \times 9 \text{ ft} = 90 \text{ ft}^2$$

The water level dropped 2.2 ft. From this, we can determine the volume of water removed by the pump during the test:

$$\text{Area} \times \text{Depth} = \text{Volume} \tag{11.1}$$

$$90 \text{ ft}^2 \times 2.2 \text{ ft} = 198 \text{ ft}^3$$

One cubic foot of water holds 7.48 gal. We can convert this volume in cubic feet to gallons:

$$198 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 = 1481 \text{ gal}$$

The test was done for 5 minutes. From this information, a pumping rate can be calculated:

$$\frac{1481 \text{ gal}}{5 \text{ min}} = \frac{296.2}{1 \text{ min}} = 296.2 \text{ gpm}$$

■ *Example 11.2. Determining Pump Capacity with Influent*

Problem: A wet well is 8.2 ft × 9.6 ft. The influent flow to the well, measured upstream, is 365 gpm. If the wet well rises 2.2 in. in 5 minutes, how many gallons per minute is the pump discharging?

Solution:

$$\text{Influent} = \text{Discharge} + \text{Accumulation} \tag{11.2}$$

$$365 \text{ gpm} = \text{Discharge} + \text{Accumulation}$$

We want to calculate the discharge. Influent is known, and we have enough information to calculate the accumulation:

$$\text{Volume Accumulated} = 8.2 \text{ ft} \times 9.6 \text{ ft} \times 2.2 \text{ in.} \times \frac{1 \text{ ft}}{12 \text{ in.}} \times \frac{7.48 \text{ gal}}{1 \text{ ft}^3} = 108 \text{ gal}$$

$$\text{Accumulation} = \frac{108 \text{ gal}}{5 \text{ min}} = \frac{21.6 \text{ gal}}{1 \text{ min}} = 21.6 \text{ gpm}$$

Using Equation 11.2:

$$\text{Influent} = \text{Discharge} + \text{Accumulation}$$

$$365 \text{ gpm} = \text{Discharge} + 21.6$$

Subtracting from both sides:

$$365 \text{ gpm} - 21.6 \text{ gpm} = \text{Discharge} + 21.6 \text{ gpm} - 21.6 \text{ gpm}$$

$$343.4 \text{ gpm} = \text{Discharge}$$

The wet well pump is discharging 343.4 gpm.

11.5 CHAPTER REVIEW QUESTION

11.1 Why are pumping stations required in gravity collection systems?

CHAPTER 12

PRELIMINARY TREATMENT

12.1 INTRODUCTION

The initial stage in the wastewater treatment process (following collection and influent pumping) is *preliminary treatment*. Raw influent entering the treatment plant may contain many kinds of materials, including trash, garbage, and other debris, such as roots, rocks, rubber and plastic products, rags, bottles, and building materials (e.g., drywall, wood waste). The purpose of preliminary treatment is to protect plant equipment by removing these materials, which could cause clogs, jams, or excessive wear to plant machinery. In addition, the removal of various materials at the beginning of the treatment process saves valuable space within the treatment plant.

Preliminary treatment may include many different processes, each designed to remove specific types of coarse material that have the potential to cause problems within the treatment process. Processes include wastewater collection, influent pumping, screening, shredding, grit removal, flow measurement, preaeration, chemical addition, and flow equalization. This chapter describes and discusses these processes and their importance in the treatment process.

Note: Not all treatment plants will include all of the processes discussed herein. The specific processes included here facilitate discussion of the major potential problems inherent in each process, information that may be important to the wastewater operator.

12.2 SCREENING

The purpose of screening is to remove large solids such as rags, cans, rocks, branches, leaves, or roots from the flow before the flow moves on to downstream processes.

Note: Typically, a treatment plant will remove anywhere from 0.5 to 12 ft^3 of screenings for each million gallons of influent received.

A *bar screen* traps debris as wastewater influent passes through. Typically, a bar screen consists of a series of parallel, evenly spaced bars or a perforated screen placed in a channel (see Figure 12.1). The wastestream passes through the screen and the large solids (*screenings*) are trapped on the bars for removal.

Note: The screenings must be removed frequently enough to prevent accumulation that could block the screen and cause the water level in front of the screen to build up.

The bar screen may be coarse (2- to 4-in. openings) or fine (0.75- to 2.0-in. openings). The bar screen may be manually cleaned, in which case bars or screens are placed at an angle of 30° for easier solids removal (Figure 12.1), or it may be mechanically cleaned, in which case the bars are placed at a 45° to 60° angle to improve mechanical cleaner operation. The screening method employed depends on the design of the plant, the amount of solids expected, and whether the screen is for constant or emergency use only.

12.2.1 Manually Cleaned Screens

Manually cleaned screens are cleaned at least once per shift (or often enough to prevent buildup that could lead to reduced flow into the plant) using a long tooth rake. Solids are manually pulled to the drain platform and allowed to drain before storage in a covered container. The area around the screen should be cleaned frequently to prevent a buildup of grease or other materials that can cause odors, slippery conditions, and insect and rodent problems. Because screenings may contain organic matter as well as large amounts of grease, they should be stored in a covered container. Screenings can be disposed of by burial in approved landfills or by incineration. Some treatment facilities grind the screenings into small particles, which are then returned to the wastewater flow for further processing and for removal later in the process.

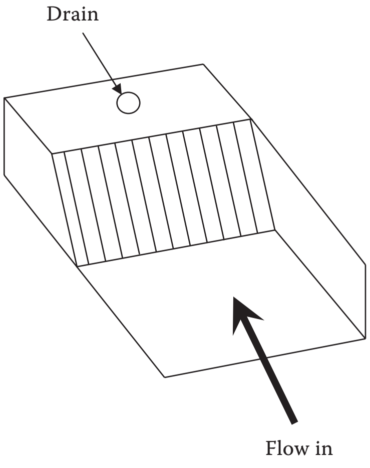

Figure 12.1 Basic bar screen.

12.2.1.1 Operational Considerations

Manually cleaned screens require a certain amount of operator attention to maintain optimum operation. Failure to clean the screen frequently can lead to septic wastes entering the primary, surge flows after cleaning, or low flows before cleaning. On occasion, when such operational problems occur, it becomes necessary to increase the frequency of the cleaning cycle. Another operational problem is excessive grit in the bar screen channel. Improper design or construction or insufficient cleaning may cause this problem. The corrective action required is either to correct the design problem or to increase cleaning frequency and flush the channel regularly. Another common problem with manually cleaned bar screens is their tendency to clog frequently. This may be caused by excessive debris in the wastewater or the screen being too fine for its current application. The operator should locate the source of the excessive debris and eliminate it. If the screen is the problem, a coarser screen may have to be installed. If the bar screen area is filled with obnoxious odors or flies and other insects, it may be necessary to dispose of screenings more frequently.

12.2.2 Mechanically Cleaned Screens

Mechanically cleaned screens use a mechanized rake assembly to collect the solids and move them out of the wastewater flow for discharge to a storage hopper. The screen may be continuously cleaned or cleaned on a time- or flow-controlled cycle. As with the manually cleaned screen, the area surrounding the mechanically operated screen must be cleaned frequently to prevent a buildup of materials that can cause unsafe conditions. As with all mechanical equipment, operator vigilance is required to ensure proper operation and that proper maintenance is performed. Maintenance includes lubricating the equipment and maintaining it in accordance with the manufacturer’s recommendations or the plant’s operations and maintenance (O&M) manual. Screenings from mechanically operated bar screens are disposed of in the same manner as screenings from manually operated screens: landfill disposal, incineration, or being ground into smaller particles for return to the wastewater flow.

12.2.2.1 Operational Considerations

Many of the operational problems associated with mechanically cleaned bar screens are the same as those for manual screens: septic wastes entering the primary, surge flows after cleaning, excessive grit in the bar screen channel, and frequent screen clogging. Basically, the same corrective actions employed for manually operated screens would be applied for these problems in mechanically operated screens. In addition to these problems, however, mechanically operated screens can have other problems; for example, the cleaner might not operate at all, or the rake might not operate but the motor does. Obviously, these are mechanical problems that could be caused by a jammed cleaning mechanism, broken chain, broken cable, or broken shear pin. Authorized and fully trained maintenance operators should be called in to handle these types of problems.

12.2.3 Screening Safety

The screening area is the first location where the operator is exposed to the wastewater flow. Any toxic, flammable, or explosive gases present in the wastewater can be released at this point. Operators who frequently enter enclosed bar screen areas should be equipped with personal air monitors, and adequate ventilation must be provided. It is also important to remember that, due to the grease attached to the screenings, this area of the plant can be extremely slippery. Routine cleaning is required to minimize this problem.

Key Point: Never override safety devices on mechanical equipment. Overrides can result in dangerous conditions and injuries, as well as mechanical failure.

12.2.4 Screenings Removal Computations

Operators responsible for screenings disposal are typically required to keep a record of the amount of screenings removed from the wastewater flow. To keep and maintain accurate screening records, the volume of screenings withdrawn must be determined. Two methods are commonly used to calculate the volume of screenings withdrawn:

$$\text{Screenings Removed (ft}^3\text{/day)} = \frac{\text{Screenings (ft}^3\text{)}}{\text{Days}} \tag{12.1}$$

$$\text{Screenings Removed (ft}^3\text{/MG)} = \frac{\text{Screenings (ft}^3\text{)}}{\text{Flow (MG)}} \tag{12.2}$$

■ *Example 12.1*

Problem: A total of 65 gal of screenings is removed from the wastewater flow during a 24-hr period. What is the screenings removal reported as cubic feet per day?

Solution: First, convert gallons screenings to cubic feet:

$$\frac{\text{65 gal}}{\text{7.48 gal/ft}^3} = \text{8.7 ft}^3 \text{ screenings}$$

Next, calculate screenings removed as ft^3/day:

$$\text{Screenings Removed (ft}^3\text{/day)} = \frac{\text{8.7 ft}^3}{\text{1 day}} = \text{8.7 ft}^3\text{/day}$$

■ *Example 12.2*

Problem: During one week, a total of 310 gal of screenings was removed from the wastewater screens. What is the average screening removal in ft^3/day?

Solution: First, gallons of screenings must be converted to cubic feet of screenings:

$$\frac{310 \text{ gal}}{7.48 \text{ gal/ft}^3} = 41.4 \text{ ft}^3 \text{ screenings}$$

$$\text{Screenings removed (ft}^3\text{/day)} = \frac{41.4 \text{ ft}^3}{7} = 5.9 \text{ ft}^3\text{/day}$$

12.3 SHREDDING

As an alternative to screening, shredding can be used to reduce solids to a size that can enter the plant without causing mechanical problems or clogging. Shredding processes include comminution (*comminute* means "cut up") and barminution devices.

12.3.1 Comminution

The *comminutor* is the most common shredding device used in wastewater treatment. In this device, all the wastewater flow passes through the grinder assembly. The grinder consists of a screen or slotted basket, a rotating or oscillating cutter, and a stationary cutter. Solids pass through the screen and are chopped or shredded between the two cutters. The comminutor will not remove solids that are too large to fit through the slots, and it will not remove floating objects. These materials must be removed manually. Maintenance requirements for comminutors include aligning, sharpening, and replacing cutters and corrective and preventive maintenance performed in accordance with plant's O&M manual.

12.3.1.1 Operational Considerations

Common operational problems associated with comminutors include output containing coarse solids. When this occurs it is usually a sign that the cutters are dull or misaligned. If the system does not operate at all, then the unit is clogged or jammed, a shear pin or coupling is broken, or electrical power is shut off. If the unit stalls or jams frequently, this usually indicates cutter misalignment, excessive debris in the influent, or dull cutters.

Note: Only qualified maintenance operators should perform maintenance of shredding equipment.

12.3.2 Barminution

In barminution, the *barminutor* uses a bar screen to collect solids, which are then shredded and passed through the bar screen for removal at a later process. In operation, the cutter alignment and sharpness of each device are critical factors in effective operation. Cutters must be sharpened or replaced, and alignment must be checked in accordance with manufacturer's recommendations. Solids that are not shredded must be removed daily, stored in closed containers, and disposed of by burial or incineration. Barminutor operational problems are similar to those listed above for comminutors. Preventive and corrective maintenance as well as lubrication must be performed by qualified personnel and in accordance with the plant's O&M manual. Because of its higher maintenance requirements, the barminutor is less frequently used.

12.4 GRIT REMOVAL

The purpose of grit removal is to remove the heavy inorganic solids that could cause excessive mechanical wear. Grit is heavier than inorganic solids and includes sand, gravel, clay, egg shells, coffee grounds, metal filings, seeds, and other similar materials. Several processes or devices are used for grit removal. All of the processes are based on the fact that grit is heavier than organic solids, which should be kept in suspension for treatment in subsequent processes. Grit removal may be accomplished in grit chambers or by centrifugal separation of sludge. Processes use gravity and velocity, aeration, or centrifugal force to separate the solids from the wastewater.

12.4.1 Gravity-/Velocity-Controlled Grit Removal

Gravity-/velocity-controlled grit removal is normally accomplished in a channel or tank where the speed or velocity of the wastewater is controlled, ideally, to about 1 foot per second (fps), so the grit will settle while organic matter remains suspended. As long as the velocity is controlled in the range of 0.7 to 1.4 feet per second (fps), the grit removal will remain effective. Velocity is controlled by the amount of water flowing through the channel, the depth of the water in the channel, the width of the channel, or the cumulative width of channels in service.

12.4.1.1 Process Control Calculations

Velocity of the flow in a channel can be determined either by the float-and-stopwatch method or by channel dimensions.

■ ***Example 12.3. Velocity by Float and Stopwatch***

$$\text{Velocity (fps)} = \frac{\text{Distance traveled (ft)}}{\text{Time required (seconds)}} \tag{12.3}$$

Problem: A float takes 25 s to travel 34 ft in a grit channel. What is the velocity of the flow in the channel?

Solution:

$$\text{Velocity} = \frac{34\text{ ft}}{25\text{ s}} = 1.4\text{ fps}$$

■ *Example 12.4. Velocity by Flow and Channel Dimensions*

This calculation can be used for a single channel or tank or multiple channels or tanks with the same dimensions and equal flow. If the flows through each unit of the unit dimensions are unequal, the velocity for each channel or tank must be computed individually.

$$\text{Velocity (fps)} = \frac{\text{Flow (MGD)} \times 1.55 \text{ cfs/MGD}}{\text{No. of Channels} \times \text{Channel Width (ft)} \times \text{Water Depth (ft)}} \quad (12.4)$$

Problem: The plant is currently using two grit channels. Each channel is 3 ft wide and has a water depth of 1.2 ft. What is the velocity when the influent flow rate is 3.0 MGD?

Solution:

$$\text{Velocity} = \frac{3.0 \text{ MGD} \times 1.55 \text{ cfs/MGD}}{2 \text{ Channels} \times 3 \text{ ft} \times 1.2 \text{ ft}} = \frac{4.65 \text{ cfs}}{7.2 \text{ ft}^2} = .65 \text{ fps}$$

Note: The channel dimensions must always be in feet; convert inches to feet by dividing by 12 inches per foot.

■ *Example 12.5. Required Settling Time*

This calculation can be used to determine the time required for a particle to travel from the surface of the liquid to the bottom at a given settling velocity. To compute the settling time, the settling velocity in feet per second must be provided or determined experimentally in a laboratory.

$$\text{Settling Time (s)} = \frac{\text{Liquid Depth (ft)}}{\text{Settling Velocity (fps)}} \quad (12.5)$$

Problem: The plant's grit channel is designed to remove sand that has a settling velocity of 0.085 fps. The channel is currently operating at a depth of 2.2 ft. How many seconds will it take for a sand particle to reach the channel bottom?

Solution:

$$\text{Settling Time} = \frac{2.2 \text{ ft}}{0.085 \text{ fps}} = 25.9 \text{ seconds}$$

■ *Example 12.6. Required Channel Length*

This calculation can be used to determine the length of a channel required to remove an object with a specified settling velocity:

$$\text{Required Channel Length} = \frac{\text{Channel Depth (ft)} \times \text{Flow Velocity (fps)}}{\text{Settling Velocity (fps)}} \quad (12.6)$$

Problem: The plant's grit channel is designed to remove sand that has a settling velocity of 0.070 fps. The channel is currently operating at a depth of 3 ft. The calculated velocity of flow through the channel is 0.80 fps. The channel is 35 feet long. Is the channel long enough to remove the desired sand particle size?

Solution:

$$\text{Required Channel Length} = \frac{3\text{ ft} \times 0.80\text{ fps}}{0.070\text{ fps}} = 34.3\text{ ft}$$

Yes, the channel is long enough to ensure that all of the sand will be removed.

12.4.1.2 Cleaning

Gravity-type systems may be manually or mechanically cleaned. Manual cleaning normally requires that the channel be taken out of service, drained, and manually cleaned. Mechanical cleaning systems are operated continuously or on a time cycle. Removal should be frequent enough to prevent grit carryover into the rest of the plant.

Key Point: Before and during cleaning activities always ventilate the area thoroughly.

12.4.1.3 Operational Considerations

Gravity-/velocity-controlled grit removal normally occurs in a channel or tank where the speed or the velocity of the wastewater is controlled to about 1 fps (ideal), so the grit settles while organic materials remain suspended. As long as the velocity is controlled in the range of 0.7 to 1.4 fps, the grit removal remains effective. Velocity is controlled by the amount of water flowing through the channel, by the depth of the water in the channel, by the width of the channel, or by the cumulative width of channels in service. During operation, the operator must pay particular attention to grit characteristics for evidence of organic solids in the channel, grit carryover into the plant, and mechanical problems, as well as to grit storage and disposal (housekeeping).

Aerated grit removal systems use aeration to keep the lighter organic solids in suspension while allowing the heavier grit articles to settle out. Aerated grit removal systems may be manually or mechanically cleaned; however, the majority of the systems are mechanically cleaned. During normal operation, adjusting the aeration rate produces the desired separation. This requires observation of mixing and aeration and sampling of fixed suspended solids. Actual grit removal is controlled by the rate of aeration. If the rate is too high, all of the solids remain in suspension. If the rate is too low, both grit and organics will settle out. The operator observes the same kinds of conditions as those listed for the gravity-/velocity-controlled system but must also pay close attention to the air distribution system to ensure proper operation.

The *cyclone degritter* uses a rapid spinning motion (centrifugal force) to separate the heavy inorganic solids or grit from the light organic solids. This unit process is normally used on primary sludge rather than the entire wastewater flow. The critical control factor for the process is the inlet pressure. If the pressure exceeds the recommendations of the manufacturer, the unit will flood, and grit will carry through with the flow. Grit is separated from flow, washed, and discharged directly to a storage container. Grit removal performance is determined by calculating the percent removal for inorganic (fixed) suspended solids. The operator observes the same kinds of conditions listed for the gravity-/velocity-controlled and aerated grit removal systems, with the exception of the air distribution system. Typical problems associated with grit removal include mechanical malfunctions and a rotten-egg odor in the grit chamber (hydrogen sulfide formation), which can lead to metal and concrete corrosion problems. A low grit recovery rate is another typical problem; bottom scour, overaeration, or not enough detention time can normally cause this. When these problems occur, the operator must make the required adjustments or repairs.

12.4.2 Grit Removal Calculations

Wastewater systems typically average 1 to 15 ft^3 of grit per million gallons of flow (sanitary systems, 1 to 4 ft^3/MG; combined wastewater systems, 4 to 15 ft^3/MG), with higher ranges during storm events. Because grit is generally disposed of in sanitary landfills, operators must keep accurate records of grit removal. Most often, the data are reported as cubic feet of grit removed per million gallons of flow:

$$\text{Grit Removed (ft}^3\text{/MG)} = \frac{\text{Grit Volume (ft}^3\text{)}}{\text{Flow (MG)}} \tag{12.7}$$

Over a given period, the average grit removal rate at a plant (at least a seasonal average) can be determined and used for planning purposes. Typically, grit removal is calculated as cubic yards, because excavation is normally expressed in terms of cubic yards.

$$\text{Grit Removed (yd}^3\text{)} = \frac{\text{Total Grit (ft}^3\text{)}}{27\ \text{ft}^3\text{/yd}^3} \tag{12.8}$$

■ ***Example 12.7***

Problem: A treatment plant removes 10 ft^3 of grit in one day. How many cubic feet of grit were removed per million gallons if the plant flow was 9 MGD?

Solution:

$$\text{Grit Removed} = \frac{\text{Grit Volume (ft}^3\text{)}}{\text{Flow (MG)}} = \frac{10\ \text{ft}^3}{9\ \text{MG}} = 1.1\ \text{ft}^3\text{/MG}$$

■ *Example 12.8*

Problem: The total daily grit removed for a plant is 250 gal. If the plant flow is 12.2 MGD, how many cubic feet of grit are removed per million gallons of flow?

Solution: First, convert gallon grit removed to cubic feet:

$$\frac{250 \text{ gal}}{7.48 \text{ gal/ft}^3} = 33 \text{ ft}^3$$

Next, complete the calculation of cubic feet per million gallons:

$$\text{Grit Removed} = \frac{\text{Grit Volume (ft}^3\text{)}}{\text{Flow (MG)}} = \frac{33 \text{ ft}^3}{12.2 \text{ MG}} = 2.7 \text{ ft}^3\text{/MG}$$

■ *Example 12.9*

Problem: The monthly average grit removal is 2.5 ft^3/MG. If the monthly average flow is 2,500,000 gpd, how many cubic yards must be available for the grit disposal pit to have a 90-day capacity?

Solution: First, calculate the grit generated each day:

$$\frac{2.5 \text{ ft}^3}{\text{MG}} \times 2.5 \text{ MGD} = 6.25 \text{ ft}^3 \text{ each day}$$

The cubic feet of grit generated for 90 days would be:

$$\frac{6.25 \text{ ft}^3}{\text{day}} \times 90 \text{ days} = 562.5 \text{ ft}$$

Convert cubic feet of grit to cubic yards of grit:

$$\frac{562.5 \text{ ft}^3}{27 \text{ ft}^3\text{/yd}^3} = 21 \text{ yd}^3$$

12.5 PREAERATION

In the preaeration process (diffused or mechanical), we aerate wastewater to achieve and maintain an aerobic state (to freshen septic wastes), to strip off hydrogen sulfide (to reduce odors and corrosion), to agitate solids (to release trapped gases and improve solids separation and settling), and to reduce BOD_5. All of this can be accomplished by aerating the wastewater for 10 to 30 minutes. To reduce BOD_5, preaeration must be conducted for 45 to 60 minutes.

12.5.1 Operational Considerations

In preaeration grit removal systems, the operator is concerned with maintaining proper operation and must be alert to any possible mechanical problems. In addition, the operator monitors dissolved oxygen levels and the impact of preaeration on influent.

12.6 CHEMICAL ADDITION

Chemical addition is made (either via dry chemical metering or solution feed metering) to the wastestream to improve settling, reduce odors, neutralize acids or bases, reduce corrosion, reduce BOD_5, improve solids and grease removal, reduce loading on the plant, add or remove nutrients, add organisms, or aid subsequent downstream processes. The particular chemical and amount used depend on the desired result. Chemicals must be added at a point where sufficient mixing will occur to obtain maximum benefit. Chemicals typically used in wastewater treatment include chlorine, peroxide, acids and bases, mineral salts (e.g., ferric chloride, alum), and bioadditives and enzymes.

12.6.1 Operational Considerations

When adding chemicals to the wastestream to remove grit, the operator monitors the process for evidence of mechanical problems and takes proper corrective actions when necessary. The operator also monitors the current chemical feed rate and dosage, ensures that mixing at the point of addition is accomplished in accordance with standard operating procedures, and monitors the impact of chemical addition on influent.

12.7 EQUALIZATION

The purpose of flow equalization (whether by surge, diurnal, or complete methods) is to reduce or remove the wide swings in flow rates normally associated with wastewater treatment plant loading; it minimizes the impact of storm flows. The process can be designed to prevent flows above maximum plant design hydraulic capacity, to reduce the magnitude of diurnal flow variations, and to eliminate flow variations. Flow equalization is accomplished using mixing or aeration equipment, pumps, and flow measurement. Normal operation depends on the purpose and requirements of the flow equalization system. Equalized flows allow the plant to perform at optimum levels by providing stable hydraulic and organic loading. The downside to flow equalization is the additional costs associated with construction and operation of the flow equalization facilities.

12.7.1 Operational Considerations

During normal operations, the operator must monitor all mechanical systems involved with flow equalization and must watch for mechanical problems and take the appropriate corrective action. The operator also monitors dissolved oxygen levels, the impact of equalization on influent, and water levels in equalization basins and makes necessary adjustments.

12.8 AERATED SYSTEMS

Aerated grit removal systems use aeration to keep the lighter organic solids in suspension while allowing the heavier grit particles to settle out. Aerated grit removal systems may be manually or mechanically cleaned; however, the majority of the systems are mechanically cleaned. In normal operation, the aeration rate is adjusted to produce the desired separation, which requires observation of mixing and aeration and sampling of fixed suspended solids. Actual grit removal is controlled by the rate of aeration. If the rate is too high, all of the solids remain in suspension. If the rate is too low, both the grit and the organics will settle out.

12.9 CYCLONE DEGRITTER

The cyclone degritter uses a rapid spinning motion (centrifugal force) to separate the heavy inorganic solids or grit from the light organic solids. This unit process is normally used on primary sludge rather than the entire wastewater flow. The critical control factor for the process is the inlet pressure. If the pressure exceeds the recommendations of the manufacturer, the unit will flood and grit will carry through with the flow. Grit is separated from the flow and discharged directly to a storage container. Grit removal performance is determined by calculating the percent removal for inorganic (fixed) suspended solids.

12.10 PRELIMINARY TREATMENT SAMPLING AND TESTING

During normal operation of grit removal systems (with the exception of the screening and shredding processes), the plant operator is responsible for sampling and testing as shown in Table 12.1.

12.10.1 Other Preliminary Treatment Process Control Calculations

The desired velocity in sewers in approximately 2 fps at peak flow, because this velocity normally prevents solids from settling from the lines; however, when the flow reaches the grit channel, the velocity should decrease to about 1 fps to permit the heavy inorganic solids to settle. In the example calculations that follow, we describe how the velocity of the flow in a channel can be determined by the float-and-stopwatch method and by channel dimensions.

■ ***Example 12.10. Velocity by Float-and-Stopwatch***

$$\text{Velocity (fps)} = \frac{\text{Distance traveled (ft)}}{\text{Time required (s)}} \tag{12.9}$$

TABLE 12.1 SAMPLING AND TESTING GRIT REMOVAL SYSTEMS

Process	Location	Test	Frequency
Grit removal (velocity)	Influent	Suspended solids (fixed)	Variable
	Channel	Depth of grit	Variable
	Grit	Total solids (fixed)	Variable
	Effluent	Suspended solids (fixed)	Variable
Grit removal (aerated)	Influent	Suspended solids (fixed)	Variable
	Channel	Dissolved oxygen	Variable
	Grit	Total solids (fixed)	Variable
	Effluent	Suspended solids (fixed)	Variable
Chemical addition	Influent	Jar test	Variable
Preaeration	Influent	Dissolved oxygen	Variable
	Effluent	Dissolved oxygen	Variable
Equalization	Effluent	Dissolved oxygen	Variable

Problem: A float takes 30 s to travel 37 ft in a grit channel. What is the velocity of the flow in the channel?

Solution:

$$\text{Velocity} = \frac{37\text{ ft}}{30\text{ s}} = 1.2\text{ fps}$$

■ *Example 12.11. Velocity by Flow and Channel Dimensions*

This calculation can be used for a single channel or tank or for multiple channels or tanks with the same dimensions and equal flow. If the flow through each of the unit dimensions is unequal, the velocity for each channel or tank must be computed individually.

$$\text{Velocity (fps)} = \frac{\text{Flow (MGD)} \times 1.55\text{ cfs/MGD}}{\text{No. Channels} \times \text{Channel Width (ft)} \times \text{Water Depth (ft)}} \quad (12.10)$$

Problem: The plant is currently using two grit channels. Each channel is 3 ft wide and has a water depth of 1.3 ft. What is the velocity when the influent flow rate is 4.0 MGD?

Solution:

$$\text{Velocity} = \frac{40\text{ MGD} \times 1.55\text{ cfs/MGD}}{2\text{ Channels} \times 3\text{ ft} \times 1.3\text{ ft}} = \frac{6.2\text{ cfs}}{7.8\text{ ft}^3} = 0.79\text{ fps}$$

Because 0.79 is within the 0.7 to 1.4 level, the operator of this unit would not make any adjustments.

Note: The channel dimensions must always be in feet; convert inches to feet by dividing by 12 inches per foot.

■ *Example 12.12. Required Settling Time*

This calculation can be used to determine the time required for a particle to travel from the surface of the liquid to the bottom at a given settling velocity. To compute the settling time, the settling velocity in feet per second must be provided or determined by experiment in a laboratory.

$$\text{Settling Time (s)} = \frac{\text{Liquid Depth (ft)}}{\text{Settling, Velocity (fps)}} \tag{12.11}$$

Problem: The plant's grit channel is designed to remove sand that has a settling velocity of 0.080 fps. The channel is currently operating at a depth of 2.3 ft. How many seconds will it take for a sand particle to reach the channel bottom?

Solution:

$$\text{Settling Time} = \frac{2.3\ \text{ft}}{0.080\ \text{fps}} = 28.7\ \text{s}$$

■ *Example 12.13. Required Channel Length*

Note: This calculation can be used to determine the length of channel required to remove an object with a specified settling velocity.

$$\text{Required Channel Length} = \frac{\text{Channel Depth (ft)} \times \text{Flow Velocity (fps)}}{0.080\ \text{fps}} \tag{12.12}$$

Problem: The plant's grit channel is designed to remove sand that has a settling velocity of 0.080 fps. The channel is currently operating at a depth of 3 ft. The calculated velocity of flow through the channel is 0.85 fps. The channel is 36 ft long. Is the channel long enough to remove the desired sand particle size?

Solution:

$$\text{Required Channel Length} = \frac{3\ \text{ft} \times 0.85\ \text{fps}}{0.080\ \text{fps}} = 31.9\ \text{ft}$$

Yes, the channel is long enough to ensure that all of the sand will be removed.

Caution: Before and during cleaning activities, always ventilate the area thoroughly.

12.11 CHAPTER REVIEW QUESTIONS

12.1 What is the purpose of preliminary treatment?

12.2 What is the purpose of the bar screen?

12.3 What two methods are available for cleaning a bar screen?

12.4 Name two ways to dispose of screenings.

12.5 What must be done to the cutters in a comminutor to ensure proper operation?

12.6 What controls the velocity in a gravity-type grit channel?

12.7 A plant has three channels in service. Each channel is 3 ft wide and has a water depth of 2 ft. What is the velocity in the channel when the flow rate is 8.0 MGD?

12.8 List three reasons why you might wish to include preaeration in the preliminary treatment portion of your plant.

12.9 Name two reasons why we would want to remove grit.

12.10 How slow should the flow of wastewater be to settle the grit?

12.11 Below what velocity will grit settle in the screening channel?

12.12 An empty screenings hopper 4 ft by 5 ft is filled to an even depth of 24 in. over the course of 84 hr. If the average plant flow rate was 4.5 MGD during this period, how many cubic feet of screenings were removed per million gallons of wastewater received?

12.13 The decomposition process that results in the production of methane gas is know as ______________ decomposition.

12.14 A V-notch weir is normally used to measure ______________.

12.15 If untreated organic wastes are discharged to a stream, the dissolved oxygen level of the stream will ______________.

12.16 The main purpose of the grit chamber is to ______________.

12.17 The main purpose of primary treatment is to ______________.

REFERENCE AND RECOMMENDED READING

Qasim, S.R. (1999). *Wastewater Treatment Plants: Plant, Design, and Operation*, 2nd ed. Lancaster, PA: Technomic.

CHAPTER **13**

SEDIMENTATION (PRIMARY TREATMENT)

13.1 INTRODUCTION

The purpose of primary treatment (primary sedimentation or primary clarification) is to remove settleable organic and floatable solids. Normally, each primary clarification unit can be expected to remove 90 to 95% settleable solids, 40 to 60% total suspended solids, and 25 to 35% biochemical oxygen demand (BOD_5).

Note: Performance expectations for settling devices used in other areas of plant operation are normally expressed as overall unit performance rather than settling unit performance.

Sedimentation may be used throughout the plant to remove settleable and floatable solids. It is used in primary treatment, secondary treatment, and advanced wastewater treatment processes. This chapter focuses on primary treatment, or primary clarification, which achieves primary settling through the use of large basins under relatively quiescent conditions. Within these basins, mechanical scrapers collect the primary settled solids into a hopper from which they are pumped to a sludge-processing area. Oil, grease, and other floating materials (scum) are skimmed from the surface. The effluent is discharged over weirs into a collection trough.

13.1.1 Process Description

In primary sedimentation, wastewater enters a settling tank or basin. Velocity is reduced to approximately 1 foot per minute (fpm). Solids that are heavier than water settle to the bottom, while solids that are lighter than water float to the top. Settled solids are removed as sludge, and floating solids are removed as scum. Wastewater leaves the sedimentation tank over an effluent weir and moves on to the next step in the treatment process. Detention time, temperature, tank design, and condition of the equipment control the efficiency of the process.

Note: The velocity is based on minutes instead of seconds, as was the case in the grit channels. A grit channel velocity of 1 fps would be 60 fpm.

13.1.1.1 Overview of Primary Treatment

- Primary treatment reduces the organic loading on downstream treatment processes by removing a large amount of settleable, suspended, and floatable materials.
- Primary treatment reduces the velocity of the wastewater through a clarifier to approximately 1 to 2 fpm, so settling and flotation can take place. Slowing the flow enhances removal of suspended solids in wastewater.
- Primary settling tanks remove floated grease and scum, remove the settled sludge solids, and collect them for pumped transfer to disposal or further treatment.
- The clarifiers may be rectangular or circular. In *rectangular* clarifiers, wastewater flows from one end to the other, and the settled sludge is moved to a hopper at one end, either by flights set on parallel chains or by a single bottom scraper set on a traveling bridge. Floating material (mostly grease and oil) is collected by a surface skimmer. In *circular* tanks, the wastewater usually enters at the middle and flows outward. Settled sludge is pushed to a hopper in the middle of the tank bottom, and a surface skimmer removes floating material.
- Factors affecting primary clarifier performance include:
    - Rate of flow through the clarifier
    - Wastewater characteristics (strength, temperature, amount and type of industrial waste, and density, size, and shape of the particles)
    - Performance of pretreatment processes
    - Nature and amount of any wastes recycled to the primary clarifier

13.1.1.2 Clarifier Operation Calculations

Key factors in primary clarifier operation include the following concepts:

$$\text{Retention Time (hr)} = \frac{\text{Volume (gal)} \times 24\text{ hr/day}}{\text{Flow (gpd)}}$$

$$\text{Surface Loading Rate (gpd/ft}^2\text{)} = \frac{Q\text{ (gpd)}}{\text{Surface Area (ft}^2\text{)}}$$

$$\text{Solids Loading Rate (lb/day/ft}^2\text{)} = \frac{\text{Solids into Clarifier (lb/day)}}{\text{Surface Area (ft}^2\text{)}}$$

$$\text{Weir Overflow Rate (gpd/linear ft)} = \frac{Q\text{ (gpd)}}{\text{Weir Length (linear ft)}}$$

13.1.2 Types of Sedimentation Tanks

Sedimentation equipment includes septic tanks, two-story tanks, and plain settling tanks or clarifiers. All three devices may be used for primary treatment, while plain settling tanks are normally used for secondary or advanced wastewater treatment processes.

13.1.2.1 Septic Tanks

Septic tanks are prefabricated tanks that serve as a combined settling and skimming tank and as an unheated, unmixed anaerobic digester. Septic tanks provide long settling times (6 to 8 hr or more) but do not separate decomposing solids from the wastewater flow. When the tank becomes full, solids will be discharged with the flow. The process is suitable for small facilities (e.g., schools, motels, homes), but, due to the long detention times and lack of control, it is not suitable for larger applications.

13.1.2.2 Two-Story (Imhoff) Tank

The *two-story* or *Imhoff tank* is similar to a septic tank with regard to the removal of settleable solids and the anaerobic digestion of solids. The difference is that the two-story tank consists of a settling compartment, where sedimentation is accomplished; a lower compartment, where settled solids digestion takes place; and gas vents. Solids removed from the wastewater by settling pass from the settling compartment into the digestion compartment through a slot in the bottom of the settling compartment. The design of the slot prevents solids from returning to the settling compartment. Solids decompose anaerobically in the digestion section. Gases produced as a result of the solids decomposition are released through the gas vents running along each side of the settling compartment.

13.1.2.3 Plain Settling Tanks (Clarifiers)

The *plain settling tank* or *clarifier* optimizes the settling process. Sludge is removed from the tank for processing in other downstream treatment units. Flow enters the tank, is slowed and distributed evenly across the width and depth of the unit, passes through the unit, and leaves over the effluent weir. Detention time within the primary settling tank is from 1 to 3 hr (2-hr average).

Sludge removal is accomplished frequently on either a continuous or an intermittent basis. Continuous removal requires additional sludge treatment processes to remove the excess water resulting from removal of sludge containing less than 2 to 3% solids. Intermittent sludge removal requires that the sludge be pumped from the tank on a schedule frequent enough to prevent large clumps of solids rising to the surface but infrequent enough to obtain 4 to 8% solids in the sludge withdrawn.

Scum must be removed from the surface of the settling tank frequently. This is normally a mechanical process but may require manual start-up. The system should be operated frequently enough to prevent excessive buildup and scum carryover but not so frequent as to cause hydraulic overloading of the scum removal system.

Settling tanks require housekeeping and maintenance. Baffles, which prevent floatable solids (scum) from leaving the tank; scum troughs; scum collectors; effluent troughs; and effluent weirs require frequent cleaning to prevent heavy biological growth and solids accumulations. Mechanical equipment must be lubricated and maintained as specified in the manufacturer's recommendations or in accordance with procedures listed in the plant's operations and maintenance (O&M) manual.

Process control sampling and testing are used to evaluate the performance of the settling process. Settleable solids, dissolved oxygen, pH, temperature, total suspended solids, and BOD_5, as well as sludge solids and volatile matter, testing is routinely accomplished.

13.1.3 Operator Observations

Before identifying a primary treatment problem and proceeding with appropriate troubleshooting effort, the operator must be cognizant of what constitutes "normal" operation (is the system operating as per design or is there a problem?). Several important items of normal operation can have a strong impact on performance. The following sections discuss the important operational parameters and "normal" observations.

13.1.3.1 Primary Clarification: Normal Operation

Again, as mentioned earlier, in primary clarification, wastewater enters a settling tank or basin. Velocity is reduced to approximately 1 foot per minute. Solids that are heavier than water settle to the bottom, while solids that are lighter than water float to the top. Settled solids are removed as sludge, and floating solids are removed as scum. Wastewater leaves the sedimentation tank over an effluent weir and moves on to the next step in the treatment process. Detention time, temperature, tank design, and condition of the equipment control the efficiency of the process.

13.1.3.2 Operational Parameters for Primary Clarification

- *Flow distribution*—Normal flow distribution is indicated by the flow to each in-service unit being equal and uniform. There is no indication of short-circuiting. The surface-loading rate is within design specifications.
- *Weir condition*—Weirs are level, flow over the weir is uniform, and the weir overflow rate is within design specifications.
- *Scum removal*—The surface is free of scum accumulations, and the scum removal does not operate continuously.
- *Sludge removal*—No large clumps of sludge appear on the surface, the system operates as designed, the pumping rate is controlled to prevent coning or buildup, and the sludge blanket depth is within desired levels.
- *Performance*—The unit is removing expected levels of BOD_5, total suspended solids, and settleable solids.
- *Unit maintenance*—Mechanical equipment is maintained in accordance with planned schedules, and equipment is available for service as required.

To assist the operator in judging primary treatment operation, several process control tests can be used for process evaluation and control. These tests include the following:

- pH (6.5 to 9.0)
- Dissolved oxygen (<1.0 mg/L)
- Temperature (varies with climate and season)
- Settleable solids (influent, 5 to 15 mL/L; effluent, 0.3 to 5 mL/L)
- BOD_5 (influent, 150 to 400 mg/L; effluent, 50 to 150 mg/L)
- Percent solids (4 to 8%)
- Percent volatile matter (40 to 70%)
- Heavy metals (as required)
- Jar tests (as required)

Note: Testing frequency should be determined on the basis of the process influent and effluent variability and the available resources. All of these tests should be performed periodically to provide reference information for evaluation of performance.

13.1.4 Process Control Calculations

As with many other wastewater treatment plant unit processes, process control calculations aid in determining the performance of the sedimentation process. Process control calculations are used in the sedimentation process to determine:

- Percent removal
- Hydraulic detention time
- Surface loading rate (surface settling rate)
- Weir overflow rate (weir loading rate)
- Sludge pumping
- Percent total solids (%TS)

In the following sections we take a closer look at a few of these process control calculations and example problems.

Note: The calculations presented in the following sections allow you to determine values for each function performed. Keep in mind that an optimally operated primary clarifier should have values in an expected range.

13.1.4.1 Percent Removal

The expected ranges of percent removal for a primary clarifier are:

Settleable solids	90–95%
Suspended solids	40–60%
BOD_5	25–35%

13.1.4.2 Detention Time

The primary purpose of primary settling is to remove settleable solids. This is accomplished by slowing the flow down to approximately 1 fpm. The flow at this velocity will stay in the primary tank from 1.5 to 2.5 hr. The length of time the water stays in the tank is called the *hydraulic detention time*.

13.1.4.3 Surface Loading Rate (Surface Settling Rate) and Surface Overflow Rate

The surface loading rate is the number of gallons of wastewater passing over 1 ft^2 of tank per day. This can be used to compare actual conditions with design. Plant designs generally use a surface loading rate of 300 to 1200 gpd/ft^2. Other terms used synonymously with surface loading rate are *surface settling rate* and *surface overflow rate*.

$$\text{Surface Settling Rate (gpd/ft}^2\text{)} = \frac{\text{Flow (gpd)}}{\text{Settling Tank Area (ft}^2\text{)}} \qquad (13.1)$$

■ ***Example 13.1***

Problem: A settling tank is 120 ft in diameter, and flow to the unit is 4.5 MGD. What is the surface loading rate in gpd/ft^2?

Solution:

$$\text{Surface Loading Rate} = \frac{4.5\text{ MGD} \times 1{,}000{,}000\text{ gal/MGD}}{0.785 \times 120\text{ ft} \times 120\text{ ft}} = 398\text{ gpd/ft}^2$$

■ ***Example 13.2***

Problem: A circular clarifier has a diameter of 50 ft. If the primary effluent flow is 2,150,000 gpd, what is the surface overflow rate in gpd/ft^2?

Solution:

$$\text{Surface Overflow Rate} = \frac{2{,}150{,}000}{0.785 \times 50\text{ ft} \times 50\text{ ft}} = 1096\text{ gpd/ft}^2$$

13.1.4.4 Weir Overflow Rate

Weir overflow rate (weir loading rate) is the amount of water leaving the settling tank per linear foot of weir. The result of this calculation can be compared with design. Normally, weir overflow rates of 10,000 to 20,000 gpd/ft are used in the design of a settling tank.

■ ***Example 13.3***

Problem: The circular settling tank is 90 ft in diameter and has a weir along its circumference. The effluent flow rate is 2.55 MGD. What is the weir overflow rate in gallons per day per foot?

Solution:

$$\text{Weir Overflow Rate (gpd/ft)} = \frac{\text{Flow (gpd)}}{\text{Weir Length (ft)}} \tag{13.2}$$

$$\text{Weir Overflow Rate} = \frac{2.55\text{ MGD} \times 1{,}000{,}000\text{ gal/MG}}{3.14 \times 90\text{ ft}} = 9023\text{ gpd/ft}$$

13.1.4.5 Sludge Pumping

Determination of sludge pumping (the quantity of solids and volatile solids removed from the sedimentation tank) provides the accurate information required for process control of the sedimentation process.

$$\text{Solids (lb/day)} = \text{Pump Rate} \times \text{Pump Time} \times 8.34\ \text{lb/gal} \times \%\ \text{Solids} \qquad (13.3)$$

$$\text{Volatile Matter (lb/day)} = \text{Pump Rate} \times \text{Pump Time} \times 8.34\ \text{lb/gal} \times \%\ \text{Solids} \times \%\ \text{Volatile Matter} \qquad (13.4)$$

■ ***Example 13.4***

Problem: The sludge pump operates 20 minutes per hour. The pump delivers 20 gpm of sludge. Laboratory tests indicate that the sludge is 5.2% solids and 66% volatile matter. How many pounds of volatile matter are transferred from the settling tank to the digester?

Solution:

Pump time = 20 min/hr

Pump rate = 20 gpm

Percent solids = 5.2%

Percent volatile matter = 66%

$$\begin{aligned}\text{Volatile matter} &= 20\ \text{gpm} \times (20\ \text{min/hr} \times 24\ \text{hr/day}) \times 8.34\ \text{lb/gal} \times 0.052 \times 0.66 \\ &= 2748\ \text{lb/day}\end{aligned}$$

13.1.4.6 Percent Total Solids (%TS)

■ ***Example 13.5***

Problem: A settling tank sludge sample is tested for solids. The sample and dish weighed 74.69 g. The dish alone weighs 21.2 g. After drying, the dish with dry solids weighed 22.3 g. What is the percent total solids (%TS) of the sample?

Solution:

Dry solids + dish = 22.3 g

Dry solids weight = 22.3 g – 21.2 g = 1.1 g

Sample + dish = 74.69 g

Sample weight = 74.69 g – 1.2 g = 53.49 g

(1.1 g)/(53.49 g) × 100% = 2%

13.1.4.7 BOD and SS Removal (lb/day)

To calculate the pounds of biochemical oxygen demand (BOD) or suspended solids removed each day, we need to know the mg/L BOD or SS removed and the plant flow. Then, we can use the following equation:

$$\text{SS Removed (lb/day)} = \text{SS (mg/L)} \times \text{MGD} \times 8.34\ \text{lb/gal} \qquad (13.5)$$

■ ***Example 13.6***

Problem: If 120 mg/L suspended solids are removed by a primary clarifier, how many lb/day suspended solids are removed when the flow is 6,250,000 gpd?

Solution:

$$\text{SS Removed} = 120\text{ mg/L} \times 6.25\text{ MGD} \times 8.34\text{ lb/gal} = 6255\text{ lb/day}$$

■ ***Example 13.7***

Problem: The flow to a secondary clarifier is 1.6 MGD. If the influent BOD concentration is 200 mg/L and the effluent BOD concentration is 70 mg/L, how many pounds of BOD are removed daily?

Solution:

$$\text{BOD Removed} = 200\text{ mg/L} - 70\text{ mg/L} = 130\text{ mg/L}$$

After calculating mg/L BOD removed, calculate lb/day BOD removed:

$$\text{BOD Removed} = 130\text{ mg/L} \times 1.6\text{ MGD} \times 8.34\text{ lb/gal} = 1735\text{ lb/day}$$

13.1.5 Effluent from Settling Tanks

Upon completion of screening, degritting, and settling in sedimentation basins, large debris, grit, and many settleable materials have been removed from the wastestream. What is left is referred to as *primary effluent*. Usually cloudy and frequently gray in color, primary effluent still contains large amounts of dissolved food and other chemicals (nutrients). These nutrients are treated in the next step in the treatment process (secondary treatment), discussed in the next chapter.

Note: Two of the most important nutrients left to remove are phosphorus and ammonia. Although we want to remove these two nutrients from the wastestream, we do not want to remove too much. Carbonaceous microorganisms in secondary treatment (biological treatment) need both phosphorus and ammonia.

13.2 CHAPTER REVIEW QUESTIONS

13.1 What is the purpose of sedimentation?

13.2 The sludge pump operates 20 min every 3 hr. The pump delivers 75 gpm. If the sludge is 5.5% solids and has a volatile matter content of 66%, how many pounds of volatile solids are removed from the settling tank each day?

13.3 The circular settling tank is 80 ft in diameter and has a depth of 12 ft. The flow rate is 2.6 MGD. What is the detention time in hours, surface loading rate in gal/day/ft^2, and weir overflow rate in gal/day/ft?

13.4 What is the recommended procedure to follow when removing sludge intermittently from a primary settling tank?

13.5 Why is there normally a baffle at the effluent end of the primary settling tank?

13.6 How much of the settleable solids are removed by primary settling?

13.7 What is an average detention time in a primary clarifier?

13.8 A settling tank is 80 ft long × 20 ft wide × 10 ft deep and receives a flow rate of 1.5 MGD. What is the surface overflow rate in gpd/ft^2?

13.9 A settling tank with a total weir length of 80 ft receives a flow rate of 1.25 MGD. What is the weir overflow rate in gpd/ft?

13.10 A wastewater treatment plant has 6 primary tanks. Each tank is 80 ft long × 20 ft wide, with a side water depth of 12 ft and a total weir length of 86 ft. The flow rate to the plant is 5 MGD. Three tanks are currently in service. Calculate the detention time in minutes, the surface overflow rate in gpd/ft^2, and the weir overflow rate in gpd/ft.

13.11 A primary settling tank is 80 ft in diameter and 10 ft deep. What is the detention time when the flow rate is 3.25 MGD?

REFERENCE AND RECOMMENDED READING

Metcalf & Eddy. (1991). *Wastewater Engineering: Treatment, Disposal, Reuses*, 3rd ed. New York: McGraw-Hill.

CHAPTER 14

SECONDARY TREATMENT

14.1 INTRODUCTION

The main purpose of secondary treatment (sometimes referred to as *biological treatment*) is to remove suspended solids and provide biochemical oxygen demand (BOD) removal of 90% or more, beyond what is achievable by primary treatment. The three commonly used approaches all take advantage of the ability of microorganisms to convert organic wastes (via biological treatment) into stabilized, low-energy compounds. Two of these approaches, the *trickling filter*—or its variation, the *rotating biological contactor* (*RBC*)—and the *activated sludge process*, sequentially follow normal primary treatment. The third approach, *ponds* (oxidation ponds or lagoons), can provide equivalent results without preliminary treatment.

In this chapter, we present a brief overview of the secondary treatment process followed by a detailed discussion of wastewater treatment ponds (used primarily in smaller treatment plants), trickling filters, and RBCs. In Chapter 15, we focus on the activated sludge process—the secondary treatment process that is used primarily in large installations and is the main focus of the handbook.

Secondary treatment refers to those treatment processes that use biological processes to convert dissolved, suspended, and colloidal organic wastes to more stable solids, which can be either removed by settling or discharged to the environment without causing harm. Exactly what is secondary treatment? As defined by the Clean Water Act (CWA), secondary treatment produces an effluent with no more than 30 mg/L BOD_5 and 30 mg/L total suspended solids.

Note: The CWA also states that ponds and trickling filters will be included in the definition of secondary treatment even if they do not meet the effluent quality requirements continuously.

Most secondary treatment processes decompose solids aerobically, producing carbon dioxide, stable solids, and more organisms. Because solids are produced, all of the biological processes must include some form of solids removal (e.g., settling tank, filter).

Secondary treatment processes can be separated into two large categories: fixed-film systems and suspended growth systems. *Fixed-film systems* are processes that use a biological growth (biomass or slime) that is attached to some form of media. Wastewater passes over or around the media and the slime. When the wastewater and slime are in contact, the organisms remove and oxidize the organic solids. The media may be stone, redwood, synthetic materials, or any other substance that is durable (capable of withstanding weather conditions for many years), provides a large area for slime growth and open space for ventilation, and is not toxic to the organisms in the biomass. Fixed-film devices include trickling filters and rotating biological contactors. *Suspended growth systems* are processes that use a biological growth mixed with the wastewater. Typical suspended growth systems consist of various modifications of the activated sludge process.

14.2 TREATMENT PONDS

Wastewater treatment can be accomplished using ponds. Shallow ponds (3 to 5 feet) are relatively easy to build and manage, they accommodate large fluctuations in flow, and they can also provide treatment that approaches the effectiveness of conventional systems (producing a highly purified effluent) at much lower cost. It is the cost advantage (the economics) that drives many managers to decide on the pond option. The actual degree of treatment provided depends on the type and number of ponds used. Ponds can be used as the sole type of treatment, or they can be used in conjunction with other forms of wastewater treatment—that is, other treatment processes followed by a pond or a pond followed by other treatment processes.

As with any other wastewater treatment process, each type of treatment has its advantages and disadvantages. As a completer process, and for areas where land is not costly and the location is isolated from residential, commercial, and recreational areas, the ponding of wastewater offers many advantages for smaller installations, including:

- Does not require expensive equipment
- Does not require highly trained operation personnel
- Is economical to construct
- Provides treatment that is equal or superior to some convention processes
- Is adaptable to changing loads

- Is adaptable to land application
- Consumes little energy
- Has an increased potential design life
- Serves as a wildlife habitat
- Is usually the most trouble free of any treatment process
- Has few sludge handling and disposal problems

Treatment ponds also have limitations; for example, they:

- Require a large area of land
- May contaminate ground waters unless properly lined
- May emit odors
- Treat wastes inconsistently, depending on climatic conditions
- Can have high suspended solids levels in the effluent

14.2.1 Types of Ponds

Ponds can be classified (named) based on their location in the system, by the type wastes they receive, and by the main biological process occurring in the pond. This section takes a look at the types of ponds classified according to their location and the type wastes they receive: *raw sewage stabilization ponds* (see Figure 14.1), *oxidation ponds*, and *polishing ponds*. In the following section, ponds are classified by the type of processes occurring within the pond: *aerobic ponds*, *anaerobic ponds*, *facultative ponds*, and *aerated ponds*.

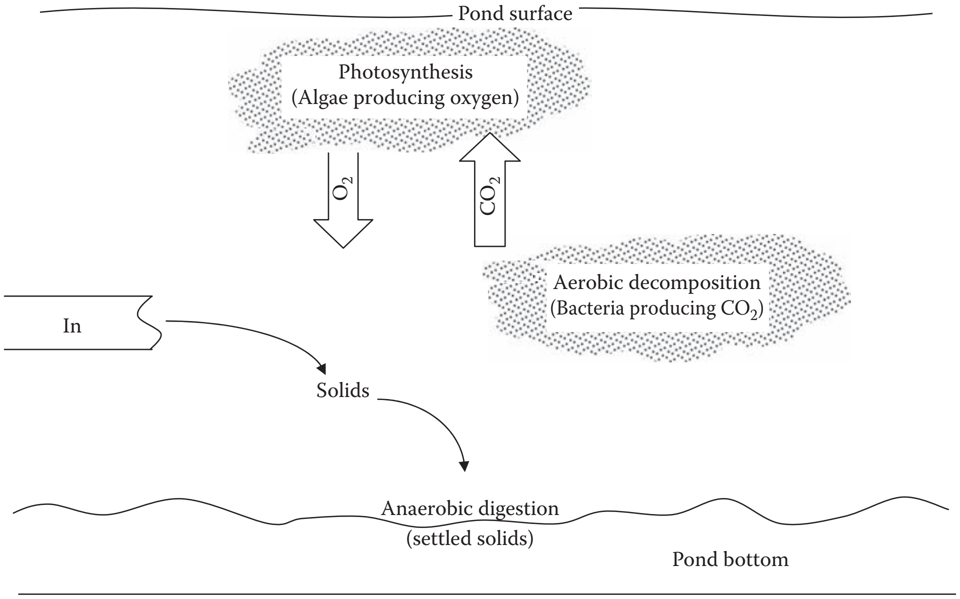

Figure 14.1 Stabilization pond processes.

14.2.1.1 Ponds Based on Location and Types of Wastes They Receive

14.2.1.1.1 Raw Sewage Stabilization Pond

The raw sewage stabilization pond is the most common type of pond. With the exception of screening and shredding, this type of pond receives no prior treatment. Generally, raw sewage stabilization ponds are designed to provide a minimum of 45 days' detention time and to receive no more than 30 pounds of BOD_5 per day per acre. The quality of the discharge is dependent on the time of the year. Summer months produce high BOD_5 removal but excellent suspended solids removals.

The pond consists of an influent structure, pond berm, or walls and an effluent structure designed to allow selection of the best quality effluent. Normal operating depth of the pond is 3 to 5 feet. The process occurring in the pond involves bacteria decomposing the organics in the wastewater (aerobically and anaerobically) and algae using the products of the bacterial action to produce oxygen (photosynthesis). Because this type of pond is the most commonly used in wastewater treatment, the process that occurs within the pond is described in greater detail in the following.

When wastewater enters the stabilization pond, several processes begin to occur. These include settling, aerobic decomposition, anaerobic decomposition, and photosynthesis (refer to Figure 19.3). Solids in the wastewater will settle to the bottom of the pond. In addition to the solids in the wastewater entering the pond, solids produced by the biological activity will also settle to the bottom. Eventually, this will reduce the detention time and the performance of the pond. When this occurs (20 to 30 years is normal), the pond will have to be replaced or cleaned.

Bacteria and other microorganisms use the organic matter as a food source. They use oxygen (aerobic decomposition), organic matter, and nutrients to produce carbon dioxide, water, stable solids (which may settle out), and more organisms. The carbon dioxide is an essential component of the photosynthesis process occurring near the surface of the pond.

Organisms also use the solids that settle out as food material; however, the oxygen levels at the bottom of the pond are extremely low so the process used is anaerobic decomposition. The organisms use the organic matter to produce gases (e.g., hydrogen sulfide, methane), which are dissolved in the water; stable solids; and more organisms. Near the surface of the pond, a population of green algae will develop which can use the carbon dioxide produced by the bacterial population, nutrients, and sunlight to produce more algae and oxygen, which is dissolved into the water. The dissolved oxygen is then used by organisms in the aerobic decomposition process.

When compared with other wastewater treatment systems involving biological treatment, a stabilization pond treatment system is the simplest to operate and maintain. Operation and maintenance activities include collecting and testing samples for dissolved oxygen (DO) and pH, removing weeds and other debris (scum) from the pond, mowing the berms, repairing erosion, and removing burrowing animals.

Note: When operating properly, the stabilization pond will exhibit a wide variation in both DO and pH due to the photosynthesis occurring in the system. Normal operation, however, will result in very high DO and pH levels.

14.2.1.1.2 Oxidation Pond

An oxidation pond, which is normally designed using the same criteria as the stabilization pond, receives flows that have passed through a stabilization pond or primary settling tank. This type of pond provides biological treatment, additional settling, and some reduction in the number of fecal coliform present.

14.2.1.1.3 Polishing Pond

A polishing pond, which uses the same equipment as a stabilization pond, receives flow from an oxidation pond or from other secondary treatment systems. Polishing ponds remove additional BOD_5, solids, and fecal coliform and some nutrients. They are designed to provide 1 to 3 days' detention time and normally operate at a depth of 5 to 10 feet. Excessive detention time or too shallow a depth will result in algae growth, which increases influent suspended solids concentrations.

14.2.1.2 Ponds Based on the Type of Processes Occurring Within

Ponds may also be classified based on the type of processes occurring within the pond, including aerobic, anaerobic, facultative, and aerated processes.

14.2.1.2.1 Aerobic Ponds

Aerobic ponds are 3 to 5 feet deep; aeration is not widely used, and dissolved oxygen is present throughout the pond. These ponds usually require an additional source of oxygen to supplement the rather minimal amount that can be diffused from the atmosphere at the water surface. All biological activity is aerobic decomposition. The additional oxygen may be supplied by algae during daylight hours.

14.2.1.2.2 Anaerobic Ponds

Anaerobic ponds are normally used to treat high-strength industrial wastes. No oxygen is present in the pond, and all biological activity is anaerobic decomposition.

14.2.1.2.3 Facultative Pond

The facultative pond is the most common type of pond (based on processes occurring). Oxygen is present in the upper portions (supernatant) of the pond, and aerobic processes are occurring. No oxygen is present in the lower levels of the pond where processes occurring are anoxic and anaerobic. Facultative ponds are usually 4 to 8 feet deep.

14.2.1.2.4 Aerated Pond

In the aerated pond, oxygen is provided through the use of mechanical or diffused air systems. When aeration is used, the depth of the pond and the acceptable loading levels may increase. Mechanical or diffused aeration is often used to supplement natural oxygen production or to replace it.

14.2.1.3 Process Control Calculations (Stabilization Ponds)

Process control calculations are an important part of wastewater treatment operations, including pond operations. More significantly, process control calculations are an important part of state wastewater licensing examinations—you simply cannot master the licensing examinations without being able to perform the required calculations. Thus, as with previous sections (and with sections to follow), whenever possible, example process control problems are provided to enhance your knowledge and skill.

14.2.1.3.1 Determining Pond Area in Acres

$$\text{Area (acres)} = \frac{\text{Area (ft}^2\text{)}}{43{,}560\ \text{ft}^2/\text{ac}} \tag{14.1}$$

14.2.1.3.2 Determining Pond Volume in Acre-Feet

$$\text{Volume (ac-ft)} = \frac{\text{Volume (ft}^3\text{)}}{43{,}560\ \text{ft}^3/\text{ac-ft}} \tag{14.2}$$

14.2.1.3.3 Determining Flow Rate in Acre-Feet/Day

$$\text{Flow (ac-ft/day)} = \text{Flow (MGD)} \times 3.069\ \text{ac-ft/MG} \tag{14.3}$$

Note: Acre-feet (ac-ft) is a unit that can cause confusion, especially for those not familiar with pond or lagoon operations. 1 ac-ft is the volume of a box with a 1-acre top and 1 ft of depth—but the top does not have to be an even number of acres in size to use acre-feet.

14.2.1.3.4 Determining Flow Rate in Acre-Inches/Day

$$\text{Flow (ac-in./day)} = \text{Flow (MGD)} \times 36.8 \text{ ac-in./MG} \tag{14.4}$$

14.2.1.3.5 Hydraulic Detention Time in Days

$$\text{Hydraulic Detention Time (days)} = \frac{\text{Pond Volume (ac-ft)}}{\text{Influent Flow (ac-ft/day)}} \tag{14.5}$$

Note: Normally, hydraulic detention time ranges from 30 to 120 days for stabilization ponds.

■ *Example 14.1*

Problem: A stabilization pond has a volume of 53.5 ac-ft. What is the detention time in days when the flow is 0.30 MGD?

Solution:

$$\text{Flow (ac-ft/day)} = 0.30 \text{ MGD} \times 3.069 = 0.92 \text{ ac-ft/day}$$

$$\text{Detention Time (days)} = \frac{53.5 \text{ ac}}{0.92 \text{ ac-ft/day}} = 58.2 \text{ days}$$

14.2.1.3.6 Hydraulic Loading in Inches/Day (Overflow Rate)

$$\text{Hydraulic Loading (in./day)} = \frac{\text{Influent Flow (ac-in./day)}}{\text{Pond Area (ac)}} \tag{14.6}$$

$$\text{Population Loading} = \frac{\text{Population served by system (people)}}{\text{Pond Area (ac)}} \tag{14.7}$$

Note: Population loading normally ranges from 50 to 500 people per acre.

14.2.1.3.7 Organic Loading

Organic loading can be expressed as pounds of BOD_5 per acre per day (most common), pounds BOD_5 per acre-foot per day, or people per acre per day:

$$\begin{array}{c}\text{Organic Loading}\\ \text{(lb BOD}_5\text{/day/ac)}\end{array} = \frac{\text{BOD}_5 \text{ (mg/L)} \times \text{Influent Flow (MGD)} \times 8.34}{\text{Pond Area (ac)}} \tag{14.8}$$

Note: Normal range is 10 to 50 lb BOD_5 per acre per day.

■ ***Example 14.2***

Problem: A wastewater treatment pond has an average width of 380 ft and an average length of 725 ft. The influent flow rate to the pond is 0.12 MGD with a BOD concentration of 160 mg/L. What is the organic loading rate to the pond in pounds per acre per day (lb/ac/day)?

Solution:

$$725\text{ ft} \times 380\text{ ft} \times \frac{1\text{ acre}}{43{,}560\text{ ft}^2} = 6.32\text{ acre}$$

$$0.12\text{ MGD} \times 160\text{ mg/L} \times 8.34\text{ lb/gal} = 160.1\text{ lb/day}$$

$$\frac{160.1\text{ lb/day}}{6.32\text{ acre}} = 25.3\text{ lb/ac/day}$$

14.3 TRICKLING FILTERS

Trickling filters have been used to treat wastewater since the 1890s. It was found that when settled wastewater was passed over rock surfaces, slime grew on the rocks and the water became cleaner. Today, we still use this principle, but in many installations we use plastic media instead of rocks. In most wastewater treatment systems, the trickling filter follows primary treatment and includes a secondary settling tank or clarifier, as shown in Figure 14.2. Trickling filters are widely used for the treatment of domestic and industrial wastes. The process is a fixed-film biological treatment method designed to remove BOD_5 and suspended solids.

A trickling filter consists of a rotating distribution arm that sprays and evenly distributes liquid wastewater over a circular bed of fist-sized rocks, other coarse materials, or synthetic media (see Figure 14.3). The spaces between the media allow air to circulate easily so aerobic conditions can be maintained. The spaces also allow wastewater to trickle down through, around, and over the media. A layer of biological slime that absorbs and consumes the wastes trickling through the bed covers

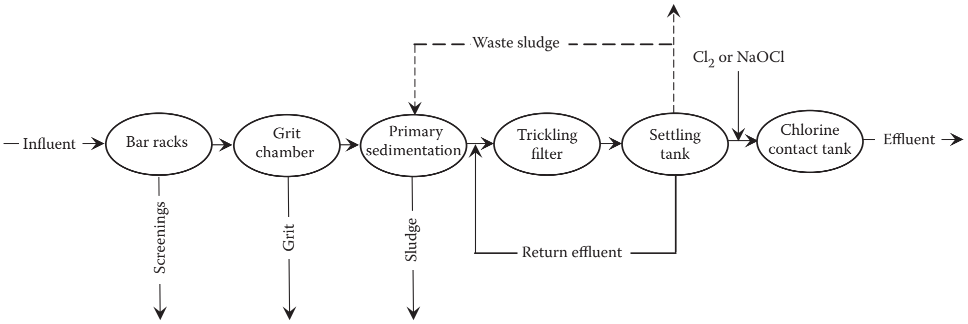

Figure 14.2 Simplified flow diagram of trickling filter used for wastewater treatment.

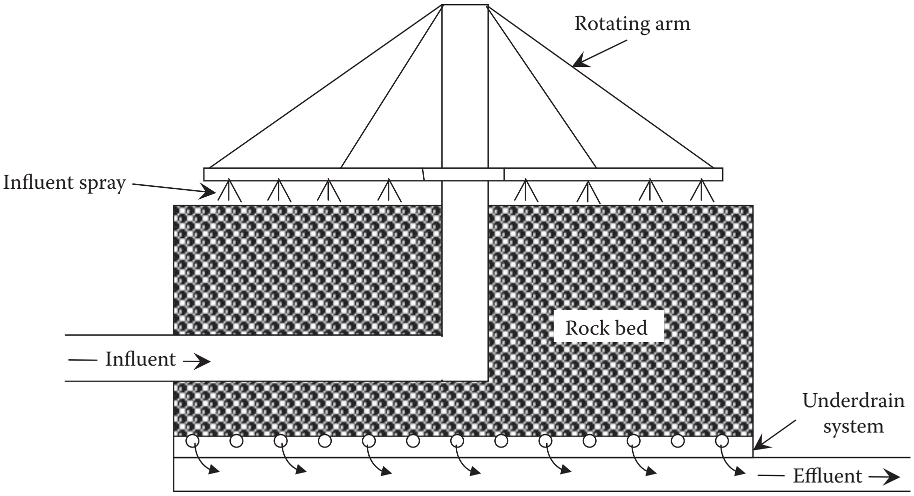

Figure 14.3 Schematic of cross-section of a trickling filter.

the media material. The organisms aerobically decompose the solids, producing more organisms and stable wastes, which either become part of the slime or are discharged back into the wastewater flowing over the media. This slime consists mainly of bacteria, but it may also include algae, protozoa, worms, snails, fungi, and insect larvae. The accumulating slime occasionally sloughs off (*sloughings*) individual media materials (see Figure 14.4) and is collected at the bottom of the filter, along with the treated wastewater, and is passed on to the secondary settling tank where it is removed. The overall performance of the trickling filter is dependent on hydraulic and organic loading, temperature, and recirculation.

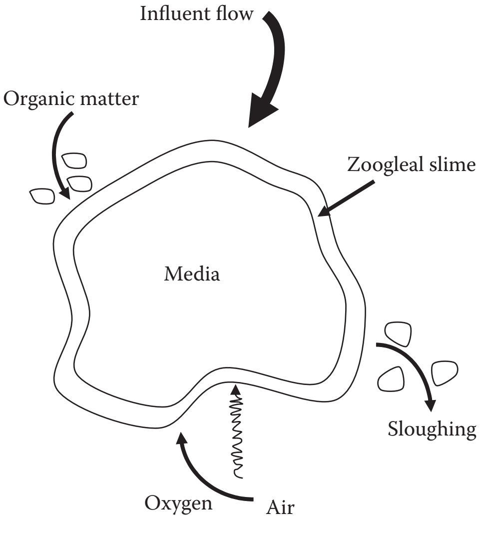

Figure 14.4 Filter media showing biological activities that take place on surface area.

14.3.1 Trickling Filter Definitions

To clearly understand the correct operation of the trickling filter, the operator must be familiar with certain terms. (Note that the following list of terms applies to the trickling filter process. We assume that other terms related to other units within the treatment system are already familiar to operators.)

Biological towers—A type of trickling filter that is very deep (10 to 20 feet). Filled with lightweight synthetic media, these towers are also know as *oxidation* or *roughing towers* or (because of their extremely high hydraulic loading) *super-high-rate trickling filters*.

Biomass—The total mass of organisms attached to the media. Similar to solids inventory in the activated sludge process, biomass is sometimes referred to as the *zoogleal slime*.

Distribution arm—The device most widely used to apply wastewater evenly over the entire surface of the media. In most cases, the force of the wastewater being sprayed through the orifices moves the arm.

Filter underdrain—The open space provided under the media to collect the liquid (wastewater and sloughings) and to allow air to enter the filter. It has a sloped floor to collect the flow to a central channel for removal.

High-rate trickling filters—A classification (see Table 14.1) in which the organic loading is in the range of 25 to 100 lb BOD_5 per 1000 ft^3 of media per day. The standard-rate filter may also produce a highly nitrified effluent.

Hydraulic loading—The amount of wastewater flow applied to the surface of the trickling filter media. It can be expressed in several ways: flow per square foot of surface per day (gpd/ft^2), flow per acre per day (MGAD), or flow per acre-foot per day (MGAFD). The hydraulic loading includes all flow entering the filter.

Media—An inert substance placed in the filter to provide a surface for the microorganism to grow on. The media can be field stone, crushed stone, slag, plastic, or redwood slats.

Organic loading—The amount of BOD_5 or chemical oxygen demand (COD) applied to a given volume of filter media. It does not include the BOD_5 or chemical oxygen demand (COD) contributed to any recirculated flow and is commonly expressed as lb BOD_5 or COD per 1000 ft^3 of media.

Recirculation—The return of filter effluent back to the head of the trickling filter. It can level flow variations and assist in solving operational problems, such as ponding, filter flies, and odors.

Roughing filters—A classification of trickling filters (see Table 14.1) in which the organic loading is in excess of 200 lb BOD_5 per 1000 ft^3 of media per day. A roughing filter is used to reduce the loading on other biological treatment processes to produce an industrial discharge that can be safely treated in a municipal treatment facility.

TABLE 14.1 TRICKLING FILTER CLASSIFICATION

Filter Class	Standard	Intermediate	High Rate	Super High Rate	Roughing
Hydraulic loading (gpd/ft^2)	25–90	90–230	230–900	350–2100	>900
Organic loading (BOD per 1000 ft^3)	5–25	15–30	25–300	Up to 300	>300
Sloughing frequency	Seasonal	Varies	Continuous	Continuous	Continuous
Distribution	Rotary	Rotary fixed	Rotary fixed	Rotary	Rotary fixed
Recirculation	No	Usually	Always	Usually	Not usually
Media depth (ft)	6–8	6–8	3–8	Up to 40	3–20
Media type	Rock Plastic Wood	Rock Plastic Wood	Rock Plastic Wood	Plastic Plastic Wood	Rock — —
Nitrification	Yes	Some	Some	Limited	None
Filter flies	Yes	Variable	Variable	Very few	Not usually
BOD removal	80–85%	50–70%	65–80%	65–85%	40–65%
TSS removal	80–85%	50–70%	65–80%	65–85%	40–65%

Sloughing—The process in which the excess growths break away from the media and wash through the filter to the underdrains with the wastewater. These sloughings must be removed from the flow by settling.

Staging—The practice of operating two or more trickling filters in series. The effluent of one filter is used as the influent of the next. This practice can produce a higher quality effluent by removing additional BOD_5 or COD.

14.3.2 Trickling Filter Equipment

The trickling filter *distribution system* is designed to spread wastewater evenly over the surface of the entire media. The most common system is the *rotary distributor*, which moves above the surface of the media and sprays the wastewater on the surface. The force of the water leaving the orifices drives the rotary system. The distributor arms usually have small plates below each orifice to spread the wastewater into a fan-shaped distribution system. The second type of distributor is the *fixed nozzle* system. In this system, the nozzles are fixed in place above the media and are designed to spray the wastewater over a fixed portion of the media. This system is used frequently with deep-bed synthetic media filters.

Note: Trickling filters that use ordinary rock are normally only about 3 meters in depth because of structural problems caused by the weight of the rocks; the weight of the rocks also requires the construction of beds that are quite wide, in many applications up to 60 feet in diameter. For synthetic media, the bed can be much deeper.

Key Point: To ensure sufficient airflow to the filter, the underdrains should never be allowed to flow more than 50% full of wastewater.

No matter which type of *media* is selected, the primary consideration is that it must be capable of providing the desired film location for the development of the biomass. Depending on the type of media used and the filter classification, the media may be 3 to 20 or more feet in depth. *Underdrains* are designed to support the media, collect the wastewater and sloughings, and carry them out of the filter and to provide ventilation to the filter.

The *effluent channel* is designed to carry the flow from the trickling filter to the secondary settling tank. The secondary settling tank provides 2 to 4 hours of detention time to separate the sloughing materials from the treated wastewater. The design, construction, and operation are similar to those of the primary settling tank. Longer detention times are provided because the sloughing materials are lighter and settle more slowly. *Recirculation pumps* and *piping* are designed to recirculate (and thus improve the performance of the trickling filter or settling tank) a portion of the effluent back to be mixed with the filter influent. When recirculation is used, pumps and metering devices must be provided.

14.3.3 Filter Classifications

Trickling filters are classified by hydraulic and organic loading. Moreover, the expected performance and the construction of the trickling filter are determined by the filter classification. Filter classifications include standard-rate, intermediate-rate, high-rate, super-high-rate (plastic media), and roughing types. Standard-rate, high-rate, and roughing are the filter types most commonly used.

The standard-rate filter has a hydraulic loading of from 25 to 90 gpd/ft^3 and a seasonal sloughing frequency. It does not employ recirculation, and it typically has an 80 to 85% BOD_5 removal rate and 80 to 85% total suspended solids (TSS) removal rate. The high-rate filter has a hydraulic loading of 230 to 900 gpd/ft^3 and a continuous sloughing frequency. It always employs recirculation and typically has a 65 to 80% BOD_5 removal rate and 65 to 80% TSS removal rate. The roughing filter has a hydraulic loading of >900 gpd/ft^3 and a continuous sloughing frequency. It does not normally include recirculation and typically has a 40 to 65% BOD_5 removal rate and 40 to 65% TSS removal rate.

14.3.4 Standard Operating Procedures

Standard operating procedures for trickling filters include sampling and testing, observation, recirculation, maintenance, and expectations of performance. The collection of influent and process effluent samples to determine the performance and monitor the condition of trickling filters is required. Dissolved oxygen, pH, and settleable solids testing should be performed daily. BOD_5 and suspended solids testing should be done as often as practical to determine the percent removal. The operation and condition of the filter should be observed daily. Items to observe include the distributor movement, uniformity of distribution, evidence of operation or mechanical problems, and the presence of objectionable odors. In addition, normal observations for a settling tank should also be performed.

Recirculation is used to reduce organic loading, improve sloughing, reduce odors, and reduce or eliminate filter fly or ponding problems. The amount of recirculation is dependent on the design of the treatment plant and the operational requirements of the process. Recirculation flow may be expressed as a specific flow rate (e.g., 2.0 MGD). In most cases, it is expressed as a ratio (e.g., 3:1, 0.5:1.0). The recirculation is always listed as the first number and the influent flow as the second number.

Note: Because the second number in the ratio is always 1.0, the ratio is sometimes written as a single number (dropping the “:1.0”).

Flows can be recirculated from various points following the filter to various points before the filter. The most common form of recirculation removes flow from the filter effluent or settling tank and returns it to the influent of the trickling filter, as shown in Figure 14.5.

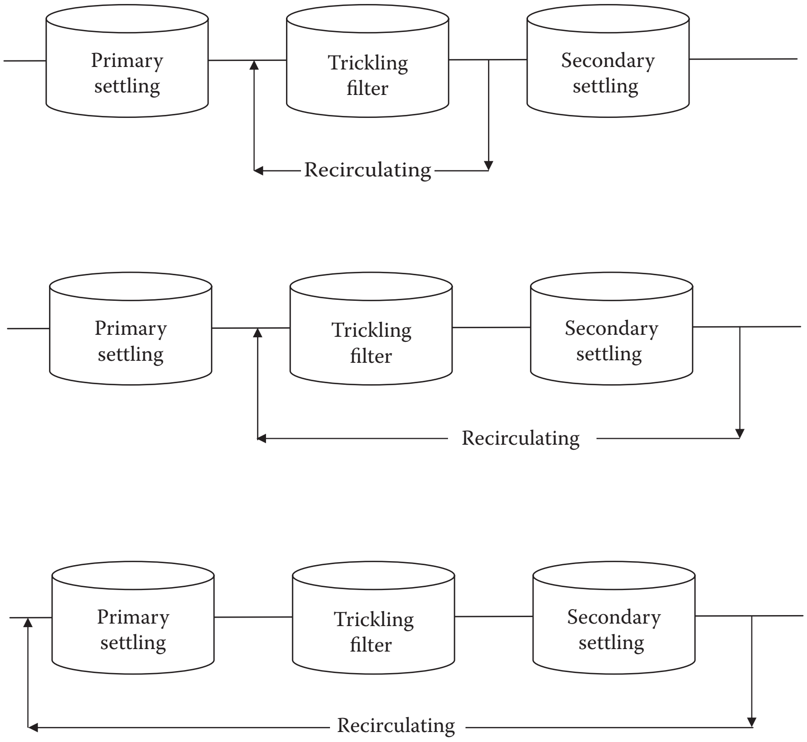

Figure 14.5 Common forms of recirculation.

Maintenance requirements include lubrication of mechanical equipment, removal of debris from the surface and orifices, and adjustment of flow patterns and maintenance associated with the settling tank. Expected performance varies for each classification of trickling filter. Moreover, the levels of BOD_5 and suspended solids removal are dependent on the type of filter.

14.3.5 Process Calculations

Several calculations are useful in the operation of a trickling filter, including total flow, hydraulic loading, and organic loading.

14.3.5.1 Total Flow

If the recirculated flow rate is given, total flow is:

$$\text{Total Flow (MGD)} = \text{Influent Flow (MGD)} + \text{Recirculation Flow (MGD)} \quad (14.9)$$

$$\text{Total Flow (gpd)} = \text{Total Flow (MGD)} \times 1{,}000{,}000\ \text{gal/MG}$$

Note: The total flow to the trickling filter includes the influent flow and the recirculated flow. This can be determined using the recirculation ratio.

$$\text{Total Flow (MGD)} = \text{Influent Flow} \times (\text{Recirculation Ratio} + 1.0)$$

■ ***Example 14.3***

Problem: The trickling filter is currently operating with a recirculation ratio of 1.5. What is the total flow applied to the filter when the influent flow rate is 3.65 MGD?

Solution:

$$\text{Total Flow} = 3.65 \text{ MGD} \times (1.5 + 1.0) = 9.13 \text{ MGD}$$

14.3.5.2 Hydraulic Loading

Calculating the hydraulic loading rate is important in accounting for both the primary effluent as well as the recirculated trickling filter effluent. Both of these are combined before being applied to the surface of the filter. The hydraulic loading rate is calculated based on the surface area of the filter.

■ ***Example 14.4***

Problem: A trickling filter 90 ft in diameter is operated with a primary effluent of 0.488 MGD and a recirculated effluent flow rate of 0.566 MGD. Calculate the hydraulic loading rate on the filter in gpd/ft^2.

Solution: The primary effluent and recirculated trickling filter effluent are applied together across the surface of the filter; therefore,

$$0.488 \text{ MGD} + 0.566 \text{ MGD} = 1.054 \text{ MGD} = 1{,}054{,}000 \text{ gpd}$$

$$\text{Circular surface area} = 0.785 \times (\text{Diameter})^2 = 0.785 \times (90 \text{ ft})^2 = 6359 \text{ ft}^2$$

$$\frac{1{,}054{,}000 \text{ gpd}}{6359 \text{ ft}^2} = 165.7 \text{ gpd/ft}^2$$

14.3.5.3 Organic Loading Rate

As mentioned earlier, trickling filters are sometimes classified by the organic loading rate applied. The organic loading rate is expressed as a certain amount of BOD applied to a certain volume of media.

■ ***Example 14.5***

Problem: A trickling filter, 50 ft in diameter, receives a primary effluent flowrate of 0.445 MGD. Calculate the organic loading rate in units of pounds of BOD applied per day per 1000 cubic feet of media volume. The primary effluent BOD concentration is 85 mg/L. The media depth is 9 ft.

Solution:

$$0.445 \text{ MGD} \times 85 \text{ mg/L} \times 8.34 \text{ lb/gal} = 315.5 \text{ lb BOD/day}$$

$$\text{Surface Area} = 0.785 \times (50)^2 = 1962.5 \text{ ft}^2$$

$$\text{Area} \times \text{Depth} = \text{Volume}$$

$$1962.5 \text{ ft}^2 \times 9 \text{ ft} = 17{,}662.5 \text{ ft}^3$$

To determine the pounds of BOD per 1000 ft^3 in a volume of thousands of cubic feet, we must set up the equation as shown below:

$$\frac{315.5 \text{ lb BOD/day}}{17{,}662.5} \times \frac{1000}{1000}$$

Regrouping the numbers and units together:

$$= \frac{315.5 \text{ lb} \times 1000}{17{,}662.5} \times \frac{\text{lb BOD/day}}{1000 \text{ ft}^3} = 17.9 \text{ lb BOD/day/1000 ft}^3$$

14.3.5.4 Settling Tanks

In the operation of settling tanks that follow trickling filters, various calculations are routinely made to determine detention time, surface settling rate, hydraulic loading, and sludge pumping.

14.4 ROTATING BIOLOGICAL CONTACTORS

The rotating biological contactor (RBC) is a biological treatment system (see Figure 14.6) that is a variation of the attached-growth idea provided by the trickling filter. Still relying on microorganisms that grow on the surface of a medium, the RBC is instead a *fixed-film* biological treatment device; the basic biological process, however, is similar to that occurring in the trickling filter. An RBC consists of a series of closely spaced (mounted side by side), circular plastic (synthetic) disks that are typically about 3.5 meters in diameter and attached to a rotating horizontal shaft (see Figure 14.6). Approximately 40% of each disk is submersed in a tank containing the wastewater to be treated. As the RBC rotates, the attached biomass film (zoogleal slime) that grows on the surface of the disk moves into and out of the wastewater. While submerged in the wastewater, the microorganisms absorb organics; when they are rotated out of the wastewater, they are supplied with the oxygen necessary for aerobic decomposition. As the zoogleal slime reenters the wastewater, excess solids and waste products are stripped off the media as sloughings. These sloughings are transported with the wastewater flow to a settling tank for removal.

Modular RBC units are placed in series (see Figure 14.7), simply because a single contactor is not sufficient to achieve the desired level of treatment; the resulting treatment achieved exceeds conventional

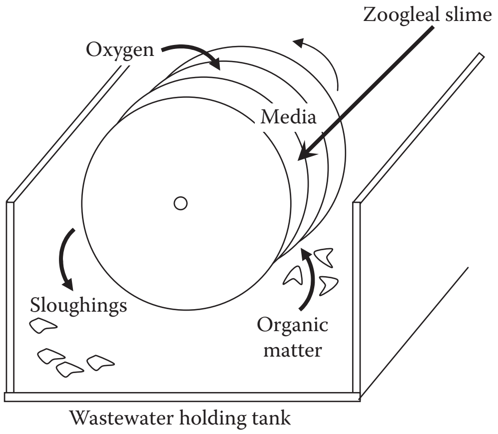

Figure 14.6 Rotating biological contactor (RBC) cross-section and treatment system.

secondary treatment. Each individual contactor is called a *stage* and the group is known as a *train*. Most RBC systems consist of two or more trains with three or more stages in each. The key advantage in using RBCs instead of trickling filters is that RBCs are easier to operate under varying load conditions, as it is easier to keep the solid media wet at all times. Moreover, the level of nitrification that can be achieved by an RBC system is significant, especially when multiple stages are employed.

14.4.1 RBC Equipment

The equipment that makes up an RBC includes the rotating biological contactor (the media, either standard or high density), a center shaft, drive system, tank, baffles, housing or cover, and a settling tank. The RBC consists of circular sheets of synthetic material (usually plastic) mounted side by side on a shaft. These sheets offer large amounts of surface area for growth of the biomass.

The *center shaft* provides support for the disks of media; they must be strong enough to support the weight of the media and the biomass; experience has shown that a major problem is the collapse of the support shaft. The *drive system* provides the motive force to rotate the disks and

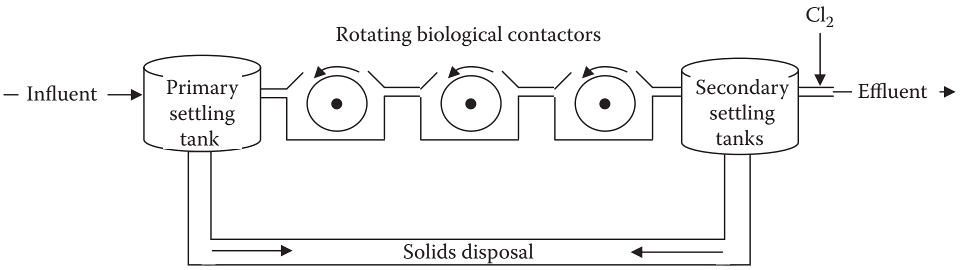

Figure 14.7 Rotating biological contactor (RBC) treatment system.

shaft. The drive system may be mechanical or air driven, or a combination of each. When the drive system does not provide uniform movement of the RBC, major operational problems can arise.

The *tank* holds the wastewater in which the RBC rotates. It should be large enough to allow variation of the liquid depth and detention time. *Baffles* are required for proper adjustment of the loading applied to each stage of the RBC process. Adjustment can be made to increase or decrease the submergence of the RBC. RBC stages are normally enclosed in some type of protective structure (*cover*) to prevent the loss of biomass due to severe weather changes (e.g., snow, rain, temperature, wind, sunlight). In many instances, this housing greatly restricts access to the RBC. The *settling tank* removes the sloughing material created by the biological activity and is similar in design to the primary settling tank. The settling tank provides 2- to 4-hour detention times to permit settling of lighter biological solids.

14.4.2 RBC Operation

During normal operation, operator vigilance is required to observe the RBC movement, slime color, and appearance; however, if the unit is covered, observations may be limited to that portion of the media that can be viewed through the access door. Slime color and appearance can indicate process condition; for example:

- Gray, shaggy slime growth indicates normal operation.
- Reddish-brown or golden shaggy growth indicates nitrification.
- A white, chalky appearance indicates high sulfur concentrations.
- No slime indicates severe temperature or pH changes.

Sampling and testing should be conducted daily for dissolved oxygen content and pH. BOD_5 and suspended solids testing should also be accomplished to aid in assessing performance.

14.4.3 RBC Expected Performance

The RBC normally produces a high-quality effluent with BOD_5 at 85 to 95% and suspended solids removal at 85 to 95%. The RBC treatment process may also significantly reduce (if designed for this purpose) the levels of organic nitrogen and ammonia nitrogen.

14.4.4 RBC Process Control Calculations

Several process control calculations may be useful in the operation of an RBC. These include soluble BOD, total media area, organic loading rate, and hydraulic loading rate. Settling tank calculations and sludge pumping calculations may be helpful for evaluation and control of the settling tank following the RBC.

14.4.4.1 RBC Soluble BOD

The soluble BOD_5 concentration of the RBC influent can be determined experimentally in the laboratory, or it can be estimated using the suspended solids concentration and the *K* factor. The *K* factor is used to approximate the BOD_5 (particulate BOD) contributed by the suspended matter. The *K* factor must be provided or determined experimentally in the laboratory. The *K* factor for domestic wastes is normally in the range in the range of 0.5 to 0.7.

$$\text{Soluble BOD}_5 = \text{Total BOD}_5 - (K \text{ Factor} \times \text{Total Suspended Solids}) \quad (14.10)$$

■ *Example 14.6*

Problem: The suspended solids concentration of a wastewater is 250 mg/L. If the normal *K* value at the plant is 0.6, what is the estimated particulate BOD concentration of the wastewater?

Note: A *K* value of 0.6 indicates that about 60% of the suspended solids are organic suspended solids (particulate BOD).

Solution:

$$(250\text{ mg/L} \times 0.6) = 150\text{ mg/L particulate BOD}$$

■ *Example 14.7*

Problem: A rotating biological contactor receives a flow of 2.2 MGD with a BOD content of 170 mg/L and suspended solids concentration of 140 mg/L. If the *K* value is 0.7, how many pounds of soluble BOD enter the RBC daily?

Solution:

$$\text{Total BOD} = \text{Particulate BOD} + \text{Soluble BOD}$$
$$170\text{ mg/L} = (140\text{ mg/L} \times 0.7) + x\text{ mg/L}$$
$$170\text{ mg/L} = 98\text{ mg/L} + x\text{ mg/L}$$
$$170\text{ mg/L} - 98\text{ mg/L} = x$$
$$x = 72\text{ mg/L soluble BOD}$$

Now, lb/day soluble BOD may be determined:

$$\begin{aligned}\text{Soluble BOD} &= \text{Soluble BOD (mg/L)} \times \text{Flow (MGD)} \times 8.34\text{ lb/gal}\\ &= 72\text{ mg/L} \times 2.2\text{ MGD} \times 8.34\text{ lb/gal} = 1321\text{ lb/day}\end{aligned}$$

14.4.4.2 RBC Total Media Area

Several process control calculations for the RBC use the total surface area of all of the stages within the train. As was the case with the soluble BOD calculation, plant design information or information supplied by the unit manufacturer must provide the individual stage areas (or the total train area), because physical determination of this would be extremely difficult.

$$\text{Total Area} = \text{1st Stage Area} + \text{2nd Stage Area} + \ldots + n\text{th Stage Area} \quad (14.11)$$

14.4.4.3 RBC Organic Loading Rate

If the soluble BOD concentration is known, the organic loading on an RBC can be determined. Organic loading on an RBC based on soluble BOD concentration can range from 3 to 4 lb/day/1000 ft^2.

■ ***Example 14.8***

Problem: An RBC has a total media surface area of 102,500 ft^2 and receives a primary effluent flowrate of 0.269 MGD. If the soluble BOD concentration of the RBC influent is 159 mg/L, what is the organic loading rate in lb/day/1000 ft^2?

Solution:

$$0.269 \text{ MGD} \times 159 \text{ mg/L} \times \frac{8.34 \text{ lb}}{1 \text{ gal}} = 356.7 \text{ lb/day}$$

$$\frac{356.7 \text{ lb/day}}{102{,}500 \text{ ft}^2} \times \frac{1000 \text{ (number)}}{1000 \text{ (unit)}} = 3.48 \text{ lb/day/1000 ft}^2$$

14.4.4.4 RBC Hydraulic Loading Rate

The manufacturer normally specifies the RBC media surface area, and the hydraulic loading rate is based on the media surface area, usually in square feet. Hydraulic loading on an RBC can range from 1 to 3 gpd/ft^2.

■ ***Example 14.9***

Problem: An RBC treats a primary effluent flow rate of 0.233 MGD. What is the hydraulic loading rate in gpd/ft^2 if the media surface area is 96,600 ft^2?

Solution:

$$\frac{233{,}000 \text{ gpd}}{96{,}600 \text{ ft}^2} = 2.41 \text{ gpd/ft}^2$$

14.5 CHAPTER REVIEW QUESTIONS

14.1 What type of waste treatment pond is most common?

14.2 Give three classifications of ponds based on their location in the treatment system.

14.3 Describe the processes occurring in a raw sewage stabilization pond (facultative).

14.4 How do changes in season affect the quality of the discharge from a stabilization pond?

14.5 A wastewater treatment pond has an average length of 690 ft with an average width of 425 ft. If the flow rate to the pond is 300,000 gpd and it is operated at a depth of 6 ft, what is the hydraulic detention time in days?

14.6 A pond 730 ft long and 410 ft wide receives an influent flow rate of 0.66 ac-ft/day. What is the hydraulic loading rate on the pond in inches per day?

14.7 Name three main parts of the trickling filter, and give the purpose or purposes of each part.

14.8 Name three categories of trickling filter based on their organic loading rate.

14.9 Which classification of trickling filter produces the highest quality effluent?

14.10 What is the purpose of recirculation?

14.11 The recirculation ratio is 0.80. The influent flow rate is 2.3 MGD. What is the total flow being applied to the filter in MGD?

14.12 Why is a settling tank required following the trickling filter?

14.13 List three things that should be checked as part of the normal operation and maintenance procedures for a trickling filter.

14.14 A trickling filter 90 ft in diameter treats a primary effluent flow rate of 0.288 MGD. If the recirculated flow to the clarifier is 0.66 MGD, what is the hydraulic loading rate on the trickling filter in gallons per day per square foot (gpd/ft^2)?

14.15 A treatment plant receives a flow rate of 3.0 MGD. If the trickling filter effluent is recirculated at a rate of 4.30 MGD, what is the recirculation ratio?

14.16 Describe the RBC.

14.17 Describe the process occurring in the RBC process.

14.18 Can an RBC be operated without primary settling?

14.19 What does a white, chalky biomass indicate?

14.20 Name two types of RBC media?

14.21 What makes the RBC similar to the trickling filter?

14.22 What makes the RBC perform at approximately the same levels of performance throughout the year?

14.23 Describe the appearance of the slime when the RBC is operating properly. What happens if the RBC is exposed to a wastewater containing high amounts of sulfur?

14.24 The slime in the first stages of the RBC is gray and shaggy. The slime in the last two stages of the train are reddish brown. What does this indicate?

14.25 An RBC unit treats a flow rate of 0.45 MGD. The two shafts used provide a total surface area of 200,000 ft^2. What is the hydraulic loading on the unit in gpd/ft^2?

CHAPTER 15

ACTIVATED SLUDGE

15.1 INTRODUCTION

The biological treatment systems discussed to this point (ponds, trickling filters, and rotating biological contactors) have been around for years. The trickling filter, for example, has been used successfully since the late 1800s. The problem with ponds, trickling filters, and rotating biological contactors is that they are temperature sensitive and remove less biochemical oxygen demand (BOD); also, trickling filters, for example, cost more to build than the activated sludge systems that were later developed.

The activated sludge process follows primary settling. The basic components of an activated sludge sewage treatment system include an aeration tank and a secondary basin, settling basin, or clarifier (see Figure 15.1). Primary effluent is mixed with settled solids recycled from the secondary clarifier and then introduced into the aeration tank. Compressed air is injected continuously into the mixture through porous diffusers located at the bottom of the tank, usually along one side. Wastewater is fed continuously into an aerated tank, where the microorganisms metabolize and biologically flocculate the organics. Microorganisms (activated sludge) are settled from the aerated mixed liquor under quiescent conditions in the final clarifier and are returned to the aeration tank. Left uncontrolled, the number of organisms would eventually become too great; therefore, some must periodically be removed (wasted). The concentrated solids at the bottom of the settling tank that must be removed from the process are known as *waste activated sludge* (WAS). Clear supernatant from the final settling tank is the plant effluent.

Key Point: Although trickling filters and other systems cost more to build than activated sludge systems, it is important to point out that activated sludge systems cost more to operate because of the need for energy to run pumps and blowers.

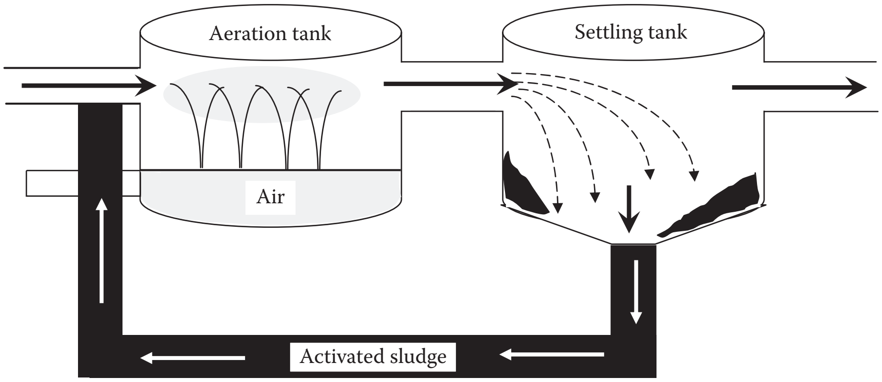

Figure 15.1 The activated sludge process.

15.1.1 Activated Sludge Terminology

To better understand the discussion of the activated sludge process presented in this chapter, you must understand the terms associated with the process. Some of these terms have been used and defined earlier in the text, but we include them here again to refresh your memory. Review these terms and remember them. They are used throughout the discussion.

Absorption—A body taking in or receiving a substance by molecular or chemical action and subsequent distribution throughout the absorber.

Activated—Refers to speeding up a reaction. When applied to sludge, it means that many aerobic bacteria and other microorganisms are in the sludge particles.

Activated sludge—A floc or solid formed by the microorganisms. It includes organisms, accumulated food materials, and waste products from the aerobic decomposition process.

Activated sludge process—A biological wastewater treatment process in which a mixture of influent and activated sludge is agitated and aerated. The activated sludge is subsequently separated from the treated mixed liquor by sedimentation and is returned to the process as needed. The treated wastewater overflows the weir of the settling tank in which separation from the sludge takes place.

Adsorption—The adherence of dissolved, colloidal, or finely divided solids to the surface of solid bodies when they are brought into contact.

Aeration—Mixing air and a liquid by one of the following methods: spraying the liquid in the air, diffusing air into the liquid, or agitating the liquid to promote surface adsorption of air.

Aerobic—Refers to a condition in which free, or dissolved, oxygen is present in the aquatic environment. Aerobic organisms must be in the presence of dissolved oxygen to be active.

Bacteria—Single-cell plants that play a vital role in stabilization of organic waste.

Biochemical oxygen demand (BOD)—A measure of the amount of food available to microorganisms in a particular waste. It is measured by determining the amount of dissolved oxygen used up during a specific time period (usually 5 days, expressed as BOD_5).

Biodegradable—From "degrade" (to wear away or break down chemically) and "bio" (by living organisms); put it all together, and you have a substance, usually organic, that can be decomposed by biological action.

Bulking—A problem in activated sludge plants that results in poor settleability of sludge particles.

Coning—A condition that may be established in a sludge hopper during sludge withdrawal, when part of the sludge moves toward the outlet while the remainder tends to stay in place; development of a cone or channel of moving liquids surrounded by relatively stationary sludge.

Decomposition—Generally, in waste treatment, refers to the changing of waste matter into simpler, more stable forms that will not harm the receiving stream.

Diffused air aeration—Occurs when an air activated sludge plant compresses air and discharges the air below the water surface to the aerator through some type of air diffusion device.

Diffuser—A porous plate or tube through which air is forced and divided into tiny bubbles for distribution in liquids; commonly made of carborundum, aluminum, or silica sand.

Dissolved oxygen—Atmospheric oxygen dissolved in water or wastewater; usually abbreviated as DO.

Note: The typical required DO for a well-operated activated sludge plant is between 2.0 and 2.5 mg/L.

Facultative—Facultative bacteria can use either molecular (dissolved) oxygen or oxygen obtained from food materials; in other words, facultative bacteria can live under aerobic or anaerobic conditions.

Filamentous bacteria—Organisms that grow in thread or filamentous form.

Food-to-microorganisms (F/M) ratio—A process control calculation used to evaluate the amount of food (BOD or COD) available per pound of mixed liquor volatile suspended solids. This may be written as:

$$\frac{\text{Food}}{\text{Microorganisms}} = \frac{\text{BOD (lb/day)}}{\text{MLVSS (lb)}} = \frac{\text{Flow (MGD)} \times \text{BOD (mg/L)} \times 8.34\ \text{lb/gal}}{\text{Volume (MG)} \times \text{MLVSS (mg/L)} \times 8.34\ \text{lb/gal}}$$

Fungi—Multicellular aerobic organisms.

Gould sludge age—A process control calculation used to evaluate the amount of influent suspended solids available per pound of mixed liquor suspended solids.

Mean cell residence time (MCRT)—The average length of time a mixed liquor suspended solids particle remains in the activated sludge process; may also be referred to as *sludge retention time* (SRT).

$$\text{MCRT (days)} = \frac{\text{Solids in Activated Sludge Process (lb)}}{\text{Solids Removed from Process (lb/day)}}$$

Mixed liquor—The contribution of return activated sludge and wastewater (either influent or primary effluent) that flows into the aeration tank.

Mixed liquor suspended solids (MLSS)—The suspended solids concentration of the mixed liquor. Many references use this concentration to represent the amount of organisms in the activated sludge process.

Mixed liquor volatile suspended solids (MLVSS)—The organic matter in the mixed liquor suspended solids. This can also be used to represent the amount of organisms in the process.

Nematodes—Microscopic worms that may appear in biological waste treatment systems.

Nutrients—Substances required to support plant organisms. Major nutrients are carbon, hydrogen, oxygen, sulfur, nitrogen, and phosphorus.

Protozoa—Single-cell animals that are easily observed under the microscope at a magnification of 100×. Bacteria and algae are prime sources of food for advanced forms of protozoa.

Return activated sludge (RAS)—The solids returned from the settling tank to the head of the aeration tank.

Rising sludge—Occurs in the secondary clarifiers or activated sludge plant when the sludge settles to the bottom of the clarifier, is compacted, and then rises to the surface in a relatively short time.

Rotifers—Multicellular animals with flexible bodies and cilia near their mouths used to attract food. Bacteria and algae are their major source of food.

Secondary treatment—A wastewater treatment process used to convert dissolved or suspended materials into a form that can be removed.

Settleability—A process control test used to evaluate the settling characteristics of the activated sludge. Readings taken at 30 to 60 minutes are used to calculate the settled sludge volume (SSV) and the sludge volume index (SVI).

Settled sludge volume—The volume (mL/L or percent) occupied by an activated sludge sample after 30 or 60 minutes of settling; normally written as SSV with a subscript to indicate the time of the reading used for calculation (SSV_{30} or SSV_{60}).

Shock load—The arrival at a plant of a sufficient quantity or strength of a waste toxic to organisms to cause operating problems, such as odor or sloughing off of the growth of slime on the trickling filter media. Organic overloads also can cause a shock load.

Sludge volume index—A process control calculation used to evaluate the settling quality of the activated sludge. Requires the SSV_{30} and mixed liquor suspended solids test results to calculate:

$$\text{Sludge Volume Index (mL/g)} = \frac{SSV_{30}\ \text{(mL/L)} \times 1000\ \text{mg/g}}{\text{MLSS (mg/L)}}$$

Solids—Material in the solid state:

Dissolved—Solids present in solution; solids that will pass through a glass fiber filter.

Fixed—Also known as the inorganic solids; the solids that are left after a sample is ignited at 550°C for 15 minutes.

Floatable—Solids that will float to the surface of still water, sewage, or other liquid; usually composed of grease particles, oils, light plastic material, etc. Also called *scum.*

Nonsettleable—Finely divided suspended solids that will not sink to the bottom in still water, sewage, or other liquid in a reasonable period, usually 2 hours. Nonsettleable solids are also known as *colloidal solids*.

Suspended—Solids that will not pass through a glass fiber filter.

Total—Solids in water, sewage, or other liquids; includes suspended solids and dissolved solids.

Volatile—Organic solids; measured as the solids that are lost on ignition of the dry solids at 550°C.

Waste activated sludge (WAS)—The solids being removed from the activated sludge process.

15.2 ACTIVATED SLUDGE PROCESS: EQUIPMENT

The equipment requirements for the activated sludge process are more complex than other processes discussed. Equipment includes an aeration tank, aeration, system settling tank, return sludge, and waste sludge. These are discussed in the following.

15.2.1 Aeration Tank

The *aeration tank* is designed to provide the required detention time (depends on the specific modification) and ensure that the activated sludge and the influent wastewater are thoroughly mixed. Tank design normally attempts to ensure that no dead spots are created.

15.2.2 Aeration

Aeration can be mechanical or diffused. *Mechanical aeration* systems use agitators or mixers to mix air and mixed liquor. Some systems use a *sparge ring* to release air directly into the mixer. *Diffused aeration* systems use pressurized air released through diffusers near the bottom of the tank. Efficiency is directly related to the size of the air bubbles produced. Fine bubble systems have a higher efficiency. The diffused air system has a blower to produce large volumes of low-pressure (5 to 10 psi) air, air lines to carry the air to the aeration tank, and headers to distribute the air to the diffusers, which release the air into the wastewater.

15.2.3 Settling Tank

Activated sludge systems are equipped with plain *settling tanks* designed to provide 2 to 4 hours of hydraulic detention time.

15.2.4 Return Sludge

The return sludge system includes pumps, a timer or variable speed drive to regulate pump delivery, and a flow measurement device to determine actual flow rates.

15.2.5 Waste Activated Sludge

In some cases, the waste activated sludge withdrawal is accomplished by adjusting valves on the return system. When a separate system is used, it includes pumps, a timer or variable-speed drive, and a flow measurement device.

15.3 OVERVIEW OF ACTIVATED SLUDGE PROCESS

The activated sludge process is a treatment technique in which wastewater and reused biological sludge full of living microorganisms are mixed and aerated. The biological solids are then separated from the treated wastewater in a clarifier and are returned to the aeration process or wasted. The microorganisms are mixed thoroughly with the incoming organic material, and they grow and reproduce by using the organic material as food. As they grow and are mixed with air, the individual organisms cling together (flocculate). Once flocculated, they more readily settle in the secondary clarifiers.

The wastewater being treated flows continuously into an aeration tank, where air is injected to mix the wastewater with the return activated sludge and to supply the oxygen needed by the microbes to live and feed on the organics. Aeration can be supplied by injection through air diffusers in the bottom of the tank or by mechanical aerators located at the surface. The mixture of activated sludge and wastewater in the aeration tank is the *mixed liquor*. The mixed liquor flows to a secondary clarifier where the activated sludge is allowed to settle.

The activated sludge is constantly growing, and more is produced than can be returned for use in the aeration basin. Some of this sludge must, therefore, be wasted to a sludge handling system for treatment and disposal. The volume of sludge returned to the aeration basins is normally 40 to 60% of the wastewater flow. The rest is wasted.

15.4 ACTIVATED SLUDGE PROCESS: FACTORS AFFECTING OPERATION

A number of factors affect the performance of an activated sludge system, including:

- Temperature
- Return rates
- Amount of oxygen available
- Amount of organic matter available
- pH
- Waste rates
- Aeration time
- Wastewater toxicity

To obtain the desired level of performance in an activated sludge system, a proper balance must be maintained among the amount of food (organic matter), organisms (activated sludge), and dissolved oxygen (DO). The majority of problems with the activated sludge process result from an imbalance among these three items.

To fully appreciate and understand the biological process taking place in a normally functioning activated sludge process, the operator must have knowledge of the key players in the process: the organisms. This makes a certain amount of sense when you consider that the heart of the activated sludge process is the mass of settleable solids formed by aerating wastewater containing biological degradable compounds in the presence of microorganisms. Activated sludge consists of organic solids plus bacteria, fungi, protozoa, rotifers, and nematodes.

15.5 GROWTH CURVE

To understand the microbiological population and its function in an activated sludge process, the operator must be familiar with the microorganism growth curve. In the presence of excess organic matter, the microorganisms multiply at a fast rate. The demand for food and oxygen is at its peak. Most of this is used for the production of new cells. This condition is known as the *log growth phase* (see Chapter 8, Figure 8.15). Over time, the amount of food available for the organisms declines. Floc begins to form, while the growth rate of bacteria and protozoa begins to decline. This is referred to as the *declining growth phase* (Figure 8.15). The *endogenous respiration phase* occurs as the food available becomes extremely limited and the organism mass begins to decline (Figure 8.15). Some of the microorganisms may die and break apart, thus releasing organic matter that can be consumed by the remaining population.

The actual operation of an activated sludge system is regulated by three factors: (1) the quantity of air supplied to the aeration tank, (2) the rate of activated sludge recirculation, and (3) the amount of excess sludge withdrawn from the system. Sludge wasting is an important operational practice because it allows the operator to establish the desired concentration of MLSS, food-to-microorganisms ratio, and sludge age.

Note: Air requirements in an activated sludge basin are governed by: (1) biochemical oxygen demand (BOD) loading and the desired removal effluent, (2) volatile suspended solids concentration in the aerator, and (3) suspended solids concentration of the primary effluent.

15.6 ACTIVATED SLUDGE FORMATION

The formation of activated sludge is achieved in three steps. The first step is the transfer of food from the wastewater to the organisms, second is the conversion of wastes to a usable form, and third is flocculation:

1. *Transfer*—Organic matter (food) is transferred from the water to the organisms. Soluble material is absorbed directly through the cell wall. Particulate and colloidal matter is adsorbed to the cell wall, where it is broken down into simpler soluble forms and then absorbed through the cell wall.
2. *Conversion*—Food matter is converted to cell matter by synthesis and oxidation into end products such as CO_2, H_2O, NH_3, stable organic waste, and new cells.
3. *Flocculation*—Flocculation is the gathering of fine particles into larger particles. This process begins in the aeration tank and is the basic mechanism for removal of suspended matter in the final clarifier. The concentrated *biofloc* that settles and forms the sludge blanket in the secondary clarifier is known as *activated sludge*.

15.7 ACTIVATED SLUDGE PERFORMANCE-CONTROLLING FACTORS

To maintain the working organisms in the activated sludge process, the operator must ensure that a suitable environment is maintained by being aware of the many factors influencing the process and by monitoring them repeatedly. *Control* is defined as maintaining the proper solids (floc mass) concentration in the aerator for the incoming water (food) flow by adjusting the return and waste sludge pumping rate and regulating the oxygen supply to maintain a satisfactory level of dissolved oxygen in the process.

15.7.1 Aeration

The activated sludge process must receive sufficient aeration to keep the activated sludge in suspension and to satisfy the organism oxygen requirements. Insufficient mixing results in dead spots, septic conditions, and the loss of activated sludge.

15.7.2 Alkalinity

The activated sludge process requires sufficient alkalinity to ensure that the pH remains in the acceptable range of 6.5 to 9.0. If organic nitrogen and ammonia are being converted to nitrate (nitrification), sufficient alkalinity must be available to support this process, as well.

15.7.3 Nutrients

The microorganisms of the activated sludge process require nutrients (nitrogen, phosphorus, iron, and other trace metals) to function. If sufficient nutrients are not available, the process will not perform as expected. The accepted minimum ratio of carbon to nitrogen, phosphorus, and iron is 100 parts carbon to 5 parts nitrogen, 1 part phosphorus, and 0.5 parts iron.

15.7.4 pH

The pH of the mixed liquor should be maintained within the acceptable range of 6.5 to 9.0 (6.5 to 8.5 is ideal). Gradual fluctuations within this range will normally not upset the process. Rapid fluctuations or fluctuations outside this range can reduce organism activity.

15.7.5 Temperature

As temperature decreases, activity of the organisms will also decrease. Cold temperatures also require longer recovery time for systems that have been upset. Warm temperatures tend to favor denitrification and filamentous growth.

Note: The activity level of bacteria within the activated sludge process increases with rise in temperature.

15.7.6 Toxicity

Elements or compounds entering a treatment plant in sufficient concentrations to kill the microorganisms (the activated sludge) are known as *toxic waste* (shock level). Common to this group are cyanides and heavy metals.

Note: A typical example of a toxic substance being added by operators is the uninhibited use of chlorine for odor control or control of filamentous organisms (prechlorination). Chlorination is for disinfection. Chlorine is a toxicant and should not be allowed to enter the activated sludge process; it is not selective with respect to the type of organisms damaged or killed. It may kill the organisms that should be retained in the process as workers; however, chlorine is very effective in disinfecting the plant effluent after treatment by the activated sludge process.

15.7.7 Hydraulic Loading

Hydraulic loading is the amount of flow entering the treatment process. When compared with the design capacity of the system, it can be used to determine if the process is hydraulically overloaded or underloaded. If more flow is entering the system than it was designed to handle, the system is hydraulically overloaded. If less flow is entering the system than it was designed for, the system is hydraulically underloaded. Generally, the system is more affected by overloading than by underloading. Overloading can be caused by stormwater, infiltration of groundwater, or excessive return rates, among many other causes. Underloading normally occurs during periods of drought or in the period following initial startup when the plant has not reached its design capacity. Excess hydraulic flow rates through the treatment plant will reduce the efficiency of the clarifier by allowing activated sludge solids to rise in the clarifier and pass over the effluent weir. This loss of solids in the effluent degrades effluent quality and reduces the amount of activated sludge in the system, in turn reducing process performance.

15.7.8 Organic Loading

Organic loading is the amount of organic matter entering the treatment plant. It is usually measured as biochemical oxygen demand (BOD). An organic overload occurs when the amount of BOD entering the system exceeds the design capacity of the system. An organic underload occurs when the amount of BOD entering the system is significantly less than the design capacity of the plant. Organic overloading may occur when the system receives more waste than it was designed to handle. It can also occur when an industry or other contributor discharges more wastes to the system than originally planned. Wastewater treatment plant processes can also lead to organic overloads returning high-strength wastes from the sludge treatment processes.

Regardless of the source, an organic overloading of the plant results in increased demand for oxygen. This demand may exceed the air supply available from the blowers. When this occurs, the activated sludge process may become septic. Excessive wasting can also result in a type of organic overload, where the food available exceeds the number of activated sludge organisms, resulting in increased oxygen demand and very rapid growth. Organic underloading may occur when a new treatment plant is initially put into service. The facility may not receive enough waste to allow the plant to operate at its design level. Underloading can also occur when excessive amounts of activated sludge are allowed to remain in the system. When this occurs, the plant will have difficulty in developing and maintaining a good activated sludge.

15.8 ACTIVATED SLUDGE MODIFICATIONS

First developed in 1913, the original activated sludge process has been modified over the years to provide better performance for specific operating conditions or different influent waste characteristics.

15.8.1 Conventional Activated Sludge

- Employing the conventional activated sludge modification requires primary treatment.
- Conventional activated sludge provides excellent treatment; however, a large aeration tank capacity is required, and construction costs are high. In operation, initial oxygen demand is high.
- The process is also very sensitive to operational problems (e.g., bulking).

15.8.2 Step Aeration

- Step aeration requires primary treatment.
- It provides excellent treatment.
- Operation characteristics are similar to conventional.
- It distributes organic loading by splitting influent flow.
- It reduces oxygen demand at the head of the system.
- It reduces solids loading on the settling tank.

15.8.3 Complete Mix

- The process may or may not include primary treatment.
- It distributes waste, return, and oxygen evenly throughout the tank.
- Aeration may be more efficient.
- It maximizes tank use.
- It permits a higher organic loading.

Note: During the complete mix, activated sludge process organisms are in a declining phase on the growth curve.

15.8.4 Pure Oxygen

- The process requires primary treatment.
- It permits higher organic loading.
- Higher solids levels are required.
- It operates at higher F/M ratios.
- It uses covered tanks.
- The use of pure oxygen poses potential safety hazards.
- Oxygen production is expensive.

15.8.5 Contact Stabilization

- Contact stabilization does not require primary treatment.
- During operation, the organisms collect organic matter (during contact).
- Solids and activated sludge are separated from flow via settling.
- Activated sludge and solids are aerated for 3 to 6 hr (stabilization).

***Note*:** Return sludge is aerated before it is mixed with influent flow.

- The activated sludge oxidizes available organic matter.
- Although the process is complicated to control, it requires less tank volume than other modifications and can be prefabricated as a *package* unit for flows of 0.05 to 1.0 million gallons per day (MGD).
- A disadvantage is that common process control calculations do not provide usable information.

15.8.6 Extended Aeration

- The process does not require primary treatment.
- It is frequently used for small flows such as schools and housing subdivisions.
- It uses 24-hour aeration.
- It produces the least amount of waste activated sludge.
- The effluent is low in BOD (the process is capable of achieving 95% or greater removal of BOD).
- The effluent is low in organic and ammonia nitrogen.

15.8.7 Oxidation Ditch

- The process does not require primary treatment.
- The oxidation ditch process is similar to the extended aeration process.

Table 15.1 lists the process parameters for each of the four most commonly used activated sludge modifications.

15.9 ACTIVATED SLUDGE PROCESS CONTROL PARAMETERS

When operating an activated sludge process, the operator must be familiar with the many important process control parameters that must be monitored frequently and adjusted occasionally to maintain optimal performance.

TABLE 15.1 ACTIVATED SLUDGE MODIFICATIONS

Parameter	Conventional	Contact Stabilization	Extended Aeration	Oxidation Ditch
Aeration time (hr)	4–8	0.5–1.5 (contact) 3–6 (reaeration)	24	24
Settling time (hr)	2–4	2–4	2–4	2–4
Return rate (% of influent flow)	25–100	25–100	25–100	25–100
MLSS (mg/L)	1500–4000	1000–3000, 3000–8000	2000–6000	2000–6000
Dissolved oxygen (mg/L)	1–3	1–3	1–3	1–3
SSV_{30} (ml/L)	400–700	400–700 (contact)	400–700	400–700
F/M ratio (lb BOD_5/lb MLVSS)	02–0.5	0.2–0.6 (contact)	0.05–0.15	0.05–0.15
MCRT (whole system, days)	5–15	—	20–30	20–30
% Removal BOD_5	85–95%	85–95%	85–95%	85–95%
% Removal TSS	85–95%	85–95%	85–95%	85–95%
Primary treatment	Yes	No	No	No

15.9.1 Alkalinity

Monitoring alkalinity in the aeration tank is essential to control of the process. Insufficient alkalinity will reduce organism activity and may result in low effluent pH and, in some cases, extremely high chlorine demand in the disinfection process.

15.9.2 Dissolved Oxygen

The activated sludge process is an aerobic process that requires some dissolved oxygen (DO) to be present at all times. The amount of oxygen required is dependent on the influent food (BOD), the activity of the activated sludge, and the degree of treatment desired.

15.9.3 pH

Activated sludge microorganisms can be injured or destroyed by wide variations in pH. The pH of the aeration basin will normally be in the range of 6.5 to 9.0. Gradual variations within this range will not cause any major problems; however, rapid changes of one or more pH units can have a significant impact on performance. Industrial waste discharges, septic wastes, or significant amounts of stormwater flows may produce wide variations in pH. pH should be monitored as part of the routine process-control testing schedule. Sudden changes in or abnormal pH values may indicate an industrial discharge of strongly acidic or alkaline wastes. Because these wastes can upset the environmental balance of the activated sludge, the presence of wide pH variations can result in poor performance. Processes undergoing nitrification may show a significant decrease in effluent pH.

15.9.4 Mixed Liquor Suspended Solids, Mixed Liquor Volatile Suspended Solids, and Mixed Liquor Total Suspended Solids

Mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) can be used to represent the activated sludge or microorganisms present in the process. Process control indicators, such as sludge age and sludge volume index, cannot be calculated unless the MLSS is determined. Adjust the MLSS and MLVSS by increasing or decreasing the waste sludge rates. The level of mixed liquor total suspended solids (MLTSS) is an important activated sludge control parameter. To increase the MLTSS, for example, the operator must decrease the waste rate and/or increase the MCRT. The MCRT must be decreased to prevent the MLTSS from changing when the number of aeration tanks in service is reduced.

Note: When performing the Gould sludge age test, assume that the source of the MLTSS in the aeration tank is influent solids.

15.9.5 Return Activated Sludge Rate and Concentration

The sludge rate is a critical control variable. The operator must maintain a continuous return of activated sludge to the aeration tank or the process will show a drastic decrease in performance. If the rate is too low, solids remain in the settling tank, resulting in solids loss and a septic return. If the rate is too high, the aeration tank can become hydraulically overloaded, causing reduced aeration time and poor performance. The return concentration is also important because it may be used to determine the return rate required to maintain the desired MLSS.

15.9.6 Waste Activated Sludge Flow Rate

Because the activated sludge contains living organisms that grow, reproduce, and produce waste matter, the amount of activated sludge is continuously increasing. If the activated sludge is allowed to remain in the system too long, the performance of the process will decrease. If too much activated sludge is removed from the system, the solids become very light and will not settle quickly enough to be removed in the secondary clarifier.

15.9.7 Temperature

Because temperature directly affects the activity of the microorganisms, accurate monitoring of temperature can be helpful in identifying the causes of significant changes in organization populations or process performance.

15.9.8 Sludge Blanket Depth

The separation of solids and liquid in the secondary clarifier results in a blanket of solids. If solids are not removed from the clarifier at the same rate they enter, the blanket will increase in depth. If this occurs, the solids may carry over into the process effluent. The sludge blanket depth may be affected by other conditions, such as temperature variation, toxic wastes, or sludge bulking. The best sludge blanket depth is dependent upon such factors as hydraulic load, clarifier design, sludge characteristics, and many more. The best blanket depth must be determined on an individual basis by experimentation.

Note: When measuring sludge blanket depth, it is general practice to use a clear plastic pipe that is 15 to 20 feet long, marked at 6-inch intervals and equipped with a ball valve at the bottom.

15.9.9 Activated Sludge Operational Control Levels[*]

The operator has two methods available to operate an activated sludge system. The operator can wait until the process performance deteriorates and make drastic changes, or the operator can establish *normal* operational levels and make minor adjustments to keep the process within the established operational levels.

Note: Control levels can be defined as the upper and lower values for a process control variable that can be expected to produce the desired effluent quality.

Although the first method will guarantee that plant performance will always be maintained within effluent limitations, the second method has a much higher probability of achieving this objective. This section discusses methods used to establish *normal* control levels for the activated sludge process. Several major factors should be considered when establishing control levels for the activated sludge system, including:

- Influent characteristics
- Industrial contributions
- Process sidestreams
- Seasonal variations
- Required effluent quality

15.9.9.1 Influent Characteristics

Influent characteristics were discussed earlier; however, major factors to consider when evaluating influent characteristics are the nature and volume of industrial contributions to the system. Waste characteristics (BOD, solids, pH, metals, toxicity, and temperature), volume, and

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[*] Much of the information in this section is based on *Activated Sludge Process Control*, Part II, 2nd ed., Virginia Water Control Board, Richmond, VA, 1990.

discharge pattern (e.g., continuous, slug, daily, weekly) should be evaluated when determining if a waste will require pretreatment by the industry or adjustments to operational control levels.

15.9.9.2 Industrial Contributions

One or more industrial contributors produce a significant portion of the plant loading (in many systems). Identifying and characterizing all industrial contributors are important. Remember that the volume of waste generated may not be as important as the characteristics of the waste. Extremely high-strength wastes can result in organic overloading and poor performance because of insufficient nutrient availability. A second consideration is the presence of materials that even in small quantities are toxic to the process microorganisms or create a toxic condition in the plant effluent or plant sludge. Industrial contributions to a biological treatment system should be thoroughly characterized prior to acceptance, monitored frequently, and controlled by either local ordinance or by implementation of a pretreatment program.

15.9.9.3 Process Sidestreams

Process sidestreams are flows produced in other treatment processes that must be returned to the wastewater system for treatment prior to disposal. Examples of process sidestreams include the following:

- Thickener supernatant
- Aerobic and anaerobic digester supernatant
- Liquids removed by sludge dewatering processes (filtrate, centrate, and subnate)
- Supernatant from heat treatment and chlorine oxidation sludge treatment processes

Testing these flows periodically to determine both their quantity and strength is important. In many treatment systems, a significant portion of the organic and hydraulic loading for the plant is generated by sidestream flows. The contribution of the plant sidestream flows can significantly change the operational control levels of the activated sludge system.

15.9.9.4 Seasonal Variations

Seasonal variations in temperature, oxygen solubility, organism activity, and waste characteristics may require several *normal* control levels for the activated sludge process. During cold months of the year, for example, aeration tank solids levels may have to be maintained at significantly higher levels than are required during warm weather. Likewise, the aeration rate may be controlled by the mixing requirements of the system during the colder months and by the oxygen demand of the system during the warm months.

15.9.9.5 Control Levels at Startup

Control levels for an activated sludge system during startup are usually based on design engineer recommendations or information available from recognized reference sources. Although these levels provide a starting point, you should recognize that both the process control parameter sensitivity and control levels should be established on a plant-by-plant basis. During the first 12 months of operation, you should evaluate all potential process control options to determine the following:

- Sensitivity to effluent quality changes
- Seasonal variability
- Potential problems

15.10 VISUAL INDICATORS FOR INFLUENT OR AERATION TANKS

Wastewater operators are required to monitor or to make certain observations of treatment unit processes to ensure optimum performance and to make adjustments when required. When monitoring the operation of an aeration tank, the operator should look for the three physical parameters—turbulence, surface foam and scum, and sludge color and odor—that aid in determining how the process is operating and indicate if any operational adjustments should be made. This information should be recorded each time operational tests are performed. The following sections summarize aeration tank and secondary settling tank observations. Remember that many of these observations are very subjective and must be based upon experience. Plant personnel must be properly trained on the importance of ensuring that recorded information is consistent throughout the operating period.

15.10.1 Turbulence

Normal operation of an aeration basin includes a certain amount of turbulence. This turbulent action is, of course, required to ensure a consistent mixing pattern; however, whenever excessive, deficient, or nonuniform mixing occurs, adjustments may be necessary to the airflow or diffusers may require cleaning or replacement.

15.10.2 Surface Foam and Scum

The type, color, and amount of foam or scum present may indicate the required wasting strategy to be employed. Types of foam include the following:

- *Fresh, crisp, white foam*—Moderate amounts of crisp white foam are usually associated with activated sludge processes producing an excellent final effluent (normal operation; no adjustment necessary).

- *Thick, greasy, dark tan foam*—A thick, greasy dark tan or brown foam or scum normally indicates an old sludge that is overoxidized, a high mixed liquor concentration, and too high of a waste rate (old sludge; more wasting required).
- *White billowing foam*—Large amounts of a white, soap-suds-like foam indicate a very young, underoxidized sludge (young sludge; less wasting required).

15.10.3 Sludge Color and Odor

Though not as reliable an indicator of process operations as foam, sludge colors and odor are also useful indicators. Colors and odors that are important include the following:

- *Chocolate brown/earthy odor* indicates normal operation (no adjustment necessary).
- *Light tan or brown/no odor* indicates sand and clay from infiltration/inflow (extremely young sludge; decrease wasting).
- *Dark brown/earthy odor* indicates old sludge with high solids (increase wasting).
- *Black color/rotten-egg odor* indicates septic conditions, low dissolved oxygen concentration, and too low of an airflow rate (increase aeration).

15.10.4 Mixed Liquor Color

A light chocolate brown mixed liquor color indicates a well-operated activated sludge process.

15.11 FINAL SETTLING TANK (CLARIFIER) OBSERVATIONS

Settling tank observations include flow pattern (normally uniform distribution), settling, amount, and type of solids leaving with the process effluent (normally very low) and the clarity or turbidity of the process effluent (normally very clear). Observations should include the following conditions:

- *Sludge bulking*—Solids are evenly distributed throughout the tank and are leaving over the weir in large quantities.
- *Sludge solids washout*—Sludge blanket is down but solids are flowing over the effluent weir in large quantities; control tests indicate good-quality sludge.
- *Clumping*—Large “clumps” or masses of sludge (several inches or more) rise to the top of the settling tank.
- *Ashing*—Fine particles of gray to white material are flowing over the effluent weir in large quantities.

- *Straggler floc*—Small, almost transparent, very fluffy, buoyant solids particles (1/8 to 1/4 inch in diameter) are rising to the surface; usually accompanied by a very clean effluent. New growth is most noticeable in the early morning hours. Sludge age is slightly below optimum.
- *Pin floc*—Very fine solids particles (usually less than 1/32 inch in diameter) are suspended throughout lightly turbid liquid; usually the result of an overoxidized sludge.

15.12 PROCESS CONTROL TESTING AND SAMPLING

The activated sludge process generally requires more sampling and testing to maintain adequate process control than any of the other unit processes in the wastewater treatment system. During periods of operational problems, both the parameters tested and the frequency of testing may increase substantially. Process control testing may include settleability testing to determine: (1) the settled sludge volume; (2) influent and mixed liquor suspended solids; (3) return activated sludge solids and waste activated sludge concentrations; (4) volatile content of the mixed liquor suspended solids; (5) dissolved oxygen and pH of the aeration tank; and (6) BOD_5 and chemical oxygen demand (COD) of the aeration tank influent and process effluent. Microscopic evaluation of the activated sludge is used to determine the predominant organism. The following sections describe most of the common process control tests.

15.12.1 Aeration Influent and Effluent Sampling

15.12.1.1 pH

pH is tested daily with a sample taken from the aeration tank influent and process effluent. pH is normally close to 7.0 (normal), with the best pH ranging from 6.5 to 8.5 (although a pH range of 6.5 to 9.0 is satisfactory). A pH greater than 9.0 may indicate toxicity from an industrial waste contributor. A pH less than 6.5 may indicate loss of flocculating organisms, potential toxicity, industrial waste contributor, or acid storm flow. Keep in mind that the effluent pH may be lower because of nitrification.

15.12.1.2 Temperature

Temperature is important because it forecasts the following:

When the temperature increases …

- Organism activity increases.
- Aeration efficiency decreases.
- Oxygen solubility decreases.

When the temperature decreases …

- Organism activity decreases.
- Aeration efficiency increases.
- Oxygen solubility increases.

15.12.1.3 Dissolved Oxygen

The content of dissolved oxygen (DO) in the aeration process is critical to performance. DO should be tested at least daily (peak demand). Optimum is determined for individual plants, but normal is from 1 to 3 mg/L. If the system contains too little DO, the process will become septic. If it contains too much DO, energy and money are wasted.

15.12.1.4 Settled Sludge Volume (Settleability)

Settled sludge volume (SSV) is determined at specified times during sample testing. Both 30- and 60-minute observations are used for control. Subscripts (e.g., SSV_{30}, SSV_{60}) indicate the settling time. The test is performed on aeration tank effluent samples.

$$\text{SSV} = \frac{\text{Milliliters of Settled Sludge} \times 1000 \text{ mL/L}}{\text{Milliliters of Sample}} \tag{15.1}$$

$$\%\text{SSV} = \frac{\text{Milliliters of Settled Sludge} \times 100}{\text{Milliliters of Sample}} \tag{15.2}$$

Under normal conditions, sludge settles as a mass, producing clear supernatant with SSV_{60} values in the range of 400 to 700 ml/L. Higher values may indicate excessive solids (old sludge) or bulking conditions. Solids in well-oxidized sludge may rise after 2 or more hours; however, solids rising in less than 1 hour indicates a problem.

Key Point: Running the settleability test with a diluted sample can assist in determining if the activated sludge is old (too many solids) or bulking (not settling). Old sludge will settle to a more compact level when diluted.

15.12.1.5 Centrifuge Testing

The centrifuge test provides a quick, relatively easy control test for the solids level in the aerator, but does not usually correlate with MLSS results. Results are directly affected by variations in sludge quality.

15.12.1.6 Alkalinity

Alkalinity is essential to biological activity. Nitrification requires 7.3-mg/L alkalinity per mg/L total Kjeldahl nitrogen.

15.12.1.7 BOD$_5$

Testing showing an increase in BOD$_5$ indicates increased organic loading; a decrease in BOD$_5$ indicates decreased organic loading.

15.12.1.8 Total Suspended Solids

An increase in total suspended solids (TSS) indicates an increase in organic loading; a decrease in TSS indicates a decrease in organic loading.

15.12.1.9 Total Kjeldahl Nitrogen

Total Kjeldahl nitrogen (TKN) determination is required to monitor the status of the nitrification process and to determine alkalinity requirements.

15.12.1.10 Ammonia Nitrogen

Determination of ammonia nitrogen is required to monitor the status of the nitrification process.

15.12.1.11 Metals

Metal contents are measured to determine toxicity levels.

15.12.2 Aeration Tank

15.12.2.1 pH

Normal pH range in the aeration tank is 6.5 to 9.0; pH decreases indicate process sidestreams or insufficient alkalinity is available.

15.12.2.2 Dissolved Oxygen

Normal DO range in an aeration tank is 1 to 3 mg/L. Dissolved oxygen level decreases may indicate increased activity, increased temperature, increased organic loading, or decreased MLSS/MLVSS. An increase in dissolved oxygen could be indicative of decreased activity, decreased temperature, decreased organic loading, increased MLSS/MLVSS, or influent toxicity.

15.12.2.3 Dissolved Oxygen Profile

All dissolved oxygen profile readings should be >0.5 mg/L. Readings of <0.5 mg/L indicate inadequate aeration or poor mixing.

TABLE 15.2 PROCESS CONDITION VS. ORGANISM POPULATIONS

Process Condition	Organism Population
Poor BOD_5 and TSS removal	Predominance of amoebas and flagellates
No floc formation	Mainly dispersed bacteria
Very cloudy effluent	A few ciliates present
Poor-quality effluent	Predominance of amoeba and flagellates
Dispersed bacteria	Some free-swimming ciliates
Some free-swimming ciliates	
Some floc formation	
Cloudy effluent	
Satisfactory effluent	Predominance of free-swimming ciliates
Good floc formation	Few amoebas and flagellates
Good settleability	
Good clarity	
High-quality effluent	Predominance of stalked ciliates
Excellent floc formation	Some free-swimming ciliates
Excellent settleability	A few rotifers
High effluent clarity	A few flagellates
Effluent high TSS and low BOD_5	Predominance of rotifers
High settled sludge volume	Large numbers of stalked ciliates
Cloudy effluent	A few free-swimming ciliates
	No flagellates

15.12.2.4 Mixed Liquor Suspended Solids

The range of mixed liquor volatile suspended solids is determined by the process modification used. When MLSS levels increase, more solids and organisms and an older, more oxidized sludge are typical.

15.12.2.5 Microscopic Examination

The activated sludge process cannot operate as designed without the presence of microorganisms; thus, microscopic examination of an aeration basin sample to determine the presence and type of microorganisms is important. Different species prefer different conditions; therefore, the presence of different species can indicate process conditions. Table 15.2 lists process conditions indicated by the presence and population of various microorganisms.

Key Point: It is important to point out that, during microscopic examination, identifying all of the organisms present is not required, but identifying the predominant species is.

15.12.3 Interpretation

Routine process control identification can be limited to the general category of organisms present. For troubleshooting more difficult problems, a more detailed study of organism distribution may be required (the knowledge required to perform this type of detailed study is beyond the scope of this text). The major categories of organisms found in the activated sludge are:

- Protozoa
- Rotifers
- Filamentous organisms

Key Point: The presence of free-swimming and stalked ciliates, some flagellates, and rotifers in mixed liquor indicates a balanced, properly settling environment.

Bacteria are the most important microorganisms in the activated sludge. They perform most of the stabilization or oxidation of the organic matter and are normally present in extremely large numbers. They are not, however, normally visible with a conventional microscope operating at the recommended magnification and are not included in the Table 15.2 list of indicator organisms.

15.12.3.1 Protozoa

Protozoa are secondary feeders in the activated sludge process (secondary as feeders, but nonetheless definitely important to the activated sludge process). Their principal function is to remove (eat or crop) dispersed bacteria and help to produce a clear process effluent. To help gain an appreciation for the role of protozoa in the activated sludge process, consider the following explanation.

The activated sludge process is typified by the successive development of protozoa and mature floc particles. This succession can be indicated by the type of dominant protozoa present. At the start of the activated process (or recovery from an upset condition), the amoebae dominate.

Note: Amoebae have very flexible cell walls and move by shifting fluids within the cell wall. Amoebae predominate during process startup or during recovery from severe plant upsets.

As the process continues uninterrupted or without upset, small populations of bacteria begin to grow in logarithmic fashion which, as the population increases, develop into mixed liquor. When this occurs, the flagellates dominate.

Note: Flagellated protozoa typically have single hair-like flagella, or “tails,” that they use for movement. The flagellate predominates when the MLSS and bacterial populations are low and organic load is high. As the activated sludge gets older and denser, the flagellates decrease until they are seldom used.

When the sludge attains an age of about 3 days, lightly dispersed floc particles begin to form (flocculation converts fine solids into larger, more settleable solids), and bacteria increase. At this point, free-swimming ciliates dominate.

Note: The free-swimming ciliated protozoa have hair-like projections (cilia) that cover all or part of the cell. The cilia are used for motion and create currents that carry food to the organism. The free-swimming ciliates are sometimes divided into two subcategories: free swimmers and crawlers. The free swimmers are usually seen moving through the fluid portion of the activated sludge, while the crawlers appear to be walking or grazing on the activated sludge solids. The free-swimming ciliated protozoa usually predominate when a large number of dispersed bacteria are present that can be used as food. Their predominance indicates a process nearing optimum conditions and effluent quality.

The process continues with floc particles beginning to stabilize, taking on irregular shapes, and beginning to show filamentous growth. At this stage, the crawling ciliates dominate. Eventually, mature floc particles develop and increase in size, and large numbers of crawling and stalked ciliates are present. When this occurs, the succession process has reached its terminal point. The succession of protozoan and mature floc particle development just described details the occurrence of phases of development in a step-by-step progression. Protozoan succession is also based on other factors, including dissolved oxygen and food availability.

Probably the best way to understand protozoan succession based on dissolved oxygen and food availability is to view the aeration basin of the wastewater treatment plant as a “stream within a container.” By using the *saprobity system* to classify the various phases of the activated sludge process in relation to the self-purification process that takes place in a stream, we are able to identify a clear relationship between the two processes based on available dissolved oxygen and food supply. Any change in the relative numbers of bacteria in the activated sludge process has a corresponding change in the population of microorganisms. A decrease in bacteria increases competition among the protozoa and results in only the dominant groups of protozoa thriving.

The success or failure of protozoa to capture bacteria depends on several factors. Those with more advanced locomotion capability are able to capture more bacteria. Individual protozoan feeding mechanisms are also important in the competition for bacteria. At the beginning of the activated sludge process, amoebae and flagellates are the first protozoan groups to appear in large numbers. They can survive on smaller quantities of bacteria because their energy requirements are lower than other protozoan types. Because few bacteria are present, competition for dissolved substrates is low; however, as the bacteria population increases, these protozoa are not able to compete for the available food. This is when the next group of protozoa, the free-swimming protozoa, enter the scene.

The free-swimming protozoa take advantage of the large populations of bacteria because they are better equipped with food-gathering mechanisms than the amoebae and flagellates. The free swimmers are important for their insatiable appetites for bacteria and also in floc formation. They secrete polysaccharides and mucoproteins that are absorbed by bacteria, which makes the bacteria “sticky” through biological agglutination (biological gluing together); this allows them to stick together and, more importantly, to stick to floc. Thus, large quantities of floc are prepared for removal from secondary effluent and being returned to aeration basins or wasted. The crawlers and stalked ciliates succeed the free swimmers.

Note: Stalked ciliated protozoa are attached directly to the activated sludge solids by a stalk. In some cases, the stalk is rigid and fixed in place, while in others the organism can move (contract or expand the stalk) to change its position. The stalked ciliated protozoa normally have several cilia that are used to create currents that carry bacteria and organic matter to them. The stalked ciliated protozoa predominate when the dispersed bacteria population decreases and does not provide sufficient food for the free swimmers. Their predominance indicates a stable process, operating at optimum conditions.

The free swimmers are replaced in part because the increasing level of mature floc retards their movement. Additionally, the type of environment that is provided by the presence of mature floc is more suited to the needs of the crawlers and stalked ciliates. The crawlers and stalked ciliates also aid in floc formation by adding weight to floc particles, thus enabling removal.

15.12.3.2 Rotifers

Rotifers are a higher life form normally associated with clean, unpolluted waters. Significantly larger than most of the other organisms observed in activated sludge, rotifers can use other organisms, as well as organic matter, as their food source. Rotifers are usually the predominant organism; the effluent will usually be cloudy (pin or ash floc) and will have very low BOD_5.

15.12.3.3 Filamentous Organisms

Filamentous organisms (bacteria, fungi, etc.) occur whenever the environment of the activated sludge favors their predominance. They are normally present in small amounts and provide the basic framework for floc formation. When the environmental conditions (e.g., pH, nutrient levels, DO) favor their development, they become the predominant organisms. When this occurs, they restrict settling, and the condition known as bulking occurs.

Key Point: Microscopic examination of activated sludge that reveals a predominance of amoebas indicates that the activated sludge is very young.

Note: Microscopic examination of activated sludge is a useful control tool. When attempting to identify the microscopic contents of a sample, the operator should try to identify the predominant groups of organisms.

15.12.4 Settling Tank Influent

15.12.4.1 Dissolved Oxygen

The dissolved oxygen level of the activated sludge settling tank should be 1 to 3 mg/L; lower levels may result in rising sludge.

15.12.4.2 pH

Normal pH range in an activated sludge settling tank should be maintained between 6.5 and 9.0. Decreases in pH may indicate alkalinity deficiency.

15.12.4.3 Alkalinity

A lack of alkalinity in an activated sludge settling tank will prevent nitrification.

15.12.4.4 Total Suspended Solids

Mixed liquor suspended solids sampling and testing are required for determining solids loading, mass balance, and return rates.

15.12.4.5 Settled Sludge Volume (Settleability)

Settled sludge volume (SSV) is determined at specified times during sample testing (e.g., 30- and 60-minute observations).

- *Normal operation*—When the process is operating properly, the solids will settle as a "blanket" (a mass), with a crisp or sharp edge between the solids and the liquor above. The liquid over the solids will be clear, with little or no visible solids remaining in suspension. Settled sludge volume at the end of 30 to 60 minutes will be in the range of 400 to 700 mL.
- *Old or overoxidized activated sludge*—When the activated sludge is overoxidized, the solids will settle as discrete particles. The edge between the solids and liquid will be fuzzy, with a large number of visible solids (e.g., pin floc, ash floc) in the liquid. The settled sludge volume at the end of 30 or 60 minutes will be greater than 700 mL.
- *Young or underoxidized activated sludge*—When the activated sludge is underoxidized, the solids settle as discrete particles, and the boundary between the solids and the liquid is poorly defined. Large amounts of small visible solids are suspended in the liquid. The settled sludge volume after 30 to 60 minutes will usually be less than 400 mL.
- *Bulking activated sludge*—When the activated sludge is experiencing a bulking condition, very little or no settling is observed.

$$\text{SSV} = \frac{\text{Milliliters of Settled Sludge} \times 1000\ \text{mL/L}}{\text{Milliliters of Sample}} \tag{15.3}$$

$$\%\text{SSV} = \frac{\text{Milliliters of Settled Sludge} \times 100}{\text{Milliliters of Sample}} \tag{15.4}$$

Note: Running the settleability test with a diluted sample can assist in determining if the activated sludge is old (too many solids) or bulking (not settling). Old sludge will settle to a more compact level when diluted.

15.12.4.6 Flow

Monitoring flow in settling tank influent is important for determination of mass balance.

15.12.4.7 Jar Tests

Jar tests are performed as required on settling tank influent and are beneficial in determining the best flocculant aid and appropriate doses to improve solids capture during periods of poor settling.

15.12.5 Settling Tank

15.12.5.1 Sludge Blanket Depth

Sludge blanket depth refers to the distance from the surface of the liquid to the solids–liquid interface or the thickness of the sludge blanket as measured from the bottom of the tank to the solids–liquid interface. Part of the operator’s sampling routine, this measurement is taken directly in the final clarifier. Sludge blanket depth is dependent on hydraulic load, return rate, clarifier design, waste rate, sludge characteristics, and temperature. If all other factors remain constant, the blanket depth will vary with amount of solids in the system and the return rate; thus, it will vary throughout the day.

Note: The depth of the sludge blanket provides an indication of sludge quality; it is used as a trend indicator. Many factors affect the test result.

15.12.5.2 Suspended Solids and Volatile Suspended Solids

Suspended solids and volatile suspended solids concentrations of the mixed liquor suspended solids, return activated sludge, and waste activated sludge are routinely sampled and tested because they are critical to process control.

15.12.6 Settling Tank Effluent

15.12.6.1 BOD_5 and Total Suspended Solids

Testing for BOD_5 and total suspended solids is conducted variably (daily, weekly, and monthly). Increases indicate that treatment performance is decreasing; decreases indicate that treatment performance is increasing.

15.12.6.2 Total Kjeldahl Nitrogen

Total Kjeldahl nitrogen (TKN) sampling and testing are variable. An increase in TKN indicates that nitrification is decreasing; a decrease in TKN indicates that nitrification is increasing.

15.12.6.3 Nitrate Nitrogen

Nitrate nitrogen sampling and testing are variable. Increases in nitrate nitrogen indicate nitrification is increasing or an industrial contribution of nitrates; a decrease indicates reduced nitrification.

15.12.6.4 Flow

Settling tank effluent flow is sampled and tested daily. Results are required for several process control calculations.

15.12.7 Return Activated Sludge/Waste Activated Sludge

15.12.7.1 Total Suspended Solids and Volatile Suspended Solids

Total suspended solids and total volatile suspended solids concentrations of the mixed liquor suspended solids, return activated sludge, and waste activated sludge are routinely sampled (using either grab or composite samples) and tested, because they are critical to process control. The results of the suspended and volatile suspended tests can be used directly or to calculate such process control figures as mean cell residence time (MCRT) or food-to-microorganisms (F/M) ratio. In most situations, increasing the MLSS produces an older, denser sludge, and decreasing MLSS produces a younger, less dense sludge.

Key Point: The activated sludge aeration tank should be observed daily to evaluate the type and amount of foam, mixing uniformity, and color.

Note: Control of the sludge wasting rate by maintaining a constant MLVSS concentration requires maintaining a certain concentration of volatile suspended solids in the aeration tank.

15.12.7.2 Flow

Test the flow of return activated sludge daily. Test results are required to determine the mass balance and to control the sludge blanket, MLSS, and MLVSS. For waste activated sludge, flow is sampled and tested whenever sludge is wasted. Results are required to determine mass balance and to control solids level in process.

15.12.8 Process Control Calculations

As with other wastewater treatment unit processes, the process control calculations reviewed below are important tools for optimizing and controlling process operations.

15.12.8.1 Settled Sludge Volume

Settled sludge volume (SSV) is the volume that a settled activated sludge occupies after a specified time. The settling time may be shown as a subscript; for example, SSV_{60} indicates that the reported value was determined at 60 minutes. The settled sludge volume can be determined for any time interval; however, the most common values are the 30-minute reading (SSV_{30}) and 60-minute reading (SSV_{60}). The settled sludge volume can be reported as milliliters of sludge per liter of sample (mL/L) or as percent settled sludge volume:

$$\text{Settled Sludge Volume (mL/L)} = \frac{\text{Settled Sludge Volume (mL)}}{\text{Sample Volume (L)}} \tag{15.5}$$

Note: 1000 milliliters = 1 liter.

$$\text{Sample Volume (L)} = \frac{\text{Sample Volume (mL)}}{\text{1000 mL/L}} \tag{15.6}$$

$$\text{\% Settled Sludge Volume} = \frac{\text{Settled Sludge Volume (mL)} \times 100}{\text{Sample Volume (mL)}} \tag{15.7}$$

■ *Example 15.1*

Problem: Using the information provided below, calculate the SSV_{30} and $\%SSV_{60}$.

Time	Milliliters
Start	2500
15 minutes	2250
30 minutes	1800
45 minutes	1700
60 minutes	1600

Solution:

$$\text{Settled Sludge Volume } (SSV_{30}) = \frac{1800 \text{ mL}}{2.5 \text{ L}} = 720 \text{ mL/L}$$

$$\text{\% Settled Sludge Volume } (SSV_{60}) = \frac{1600 \text{ mL} \times 100}{2500 \text{ mL}} = 64\%$$

15.12.8.2 Estimated Return Rate

Many different methods are available for estimating the proper return sludge rate. A simple method described in the *Operation of Wastewater Treatment Plants: A Field Study Training Program* (Kerri et al., 2007) uses the 60-minute percent settled sludge volume ($\%SSV_{60}$), which can provide an approximation of the appropriate return activated sludge rate. The results of this calculation can then be adjusted based on sampling and visual observations to develop the optimum return sludge rate.

Note: The %SSV_{60} must be converted to a decimal percent and total flow rate, and wastewater flow and current return rate in million gallons per day (MGD) must be used.

$$\text{Est. Return Rate (MGD)} = \begin{pmatrix} \text{Influent Flow (MGD)} \\ + \text{Current Return Flow (MGD)} \end{pmatrix} \times \%SSV_{60}$$

where we assume that %SSV_{60} is representative and the return rate, in percent, equals %SSV_{60}. The actual return rate is normally set slightly higher to ensure that organisms are returned to the aeration tank as quickly as possible. The rate of return must be adequately controlled to prevent the following:

- Aeration and settling hydraulic overloads
- Low MLSS levels in the aerator
- Organic overloading of aeration
- Solids loss due to excessive sludge blanket depth

■ *Example 15.2*

Problem: The influent flow rate is 4.2 MGD and the current return activated sludge flow rate is 1.5 MGD. The SSV_{60} is 38%. Based on this information, what should be the return sludge rate in million gallons per day?

Solution:

$$\text{Return Sludge Rate} = (4.2\text{ MGD} + 1.5\text{ MGD}) \times 0.38 = 2.2\text{ MGD}$$

15.12.8.3 Sludge Volume Index

The sludge volume index (SVI) is a measure of the settling quality (a quality indicator) of the activated sludge. As the SVI increases, the sludge settles more slowly, does not compact as well, and is likely to result in an increase in effluent suspended solids. As the SVI decreases, the sludge becomes denser, settling is more rapid, and the sludge is becoming older. SVI is the volume in milliliters occupied by 1 gram of activated sludge. The SSV (mL/L) and the MLSS (mg/L) are required for this calculation:

$$\text{Sludge Volume Index (SVI)} = \frac{\text{SSV (mL/L)} \times 1000}{\text{MLSS (mg/L)}} \tag{15.8}$$

TABLE 15.3 SETTLING VOLUME INDEX TRENDS

SVI Value	Result	Adjustment
Increasing	Sludge is becoming less dense.	Decrease waste rate.
	Sludge is either younger or bulking.	Increase return rate.
	Sludge will settle more slowly.	
	Sludge will compact less.	
Decreasing	Sludge is becoming denser.	Increase waste rate.
	Sludge is becoming older.	
	Sludge will settle more rapidly.	Decrease return rate.
	Sludge will compact more with no other process changes.	
Holding constant	Sludge should continue to have its current characteristics.	No changes are indicated.

■ ***Example 15.3***

Problem: The SSV_{30} is 365 mL/L and the MLSS is 2365 mg/L. What is the SVI?

Solution:

$$\text{Sludge Volume Index} = \frac{365\text{ mL/L} \times 1000}{2365\text{ mg/L}} = 154.3$$

The SVI equals 154.3. What does this mean? It means that the system is operating normally with good settling and low effluent turbidity. How do we know this? Another good question. We know this because we compare the 154.3 result with the parameters listed below to obtain the expected condition (the result).

SVI Value	Indicates
Less than 100	Old sludge
	Possible pin floc
	Effluent turbidity increasing
100 to 200	Normal operation
	Good settling
	Low effluent turbidity
Greater than 250	Bulking sludge
	Poor settling
	High effluent turbidity

The SVI is best used as a trend indicator to evaluate what is occurring compared to previous SVI values. Based on this evaluation, the operator may determine if the SVI trend is increasing or decreasing (see Table 15.3).

15.12.8.4 *Waste Activated Sludge*

The quantity of solids removed from the process as waste activated sludge is an important process control parameter that operators need to be familiar with and, more importantly, know how to calculate:

$$\begin{aligned}\text{Waste (lb/day)} = {} & \text{WAS Concentration (mg/L)} \\ & \times \text{WAS Flow (MGD)} \times 8.34 \text{ lb/MG/mg/L}\end{aligned} \tag{15.9}$$

■ *Example 15.4*

Problem: The operator wastes 0.44 MGD of activated sludge. The waste activated sludge has a solids concentration of 5540 mg/L. How many pounds of waste activated sludge are removed from the process?

Solution:

$$\text{Waste} = 5540 \text{ mg/L} \times 0.44 \text{ MGD} \times 8.34 \text{ lb/MG/mg/L} = 20{,}329.6 \text{ lb/day}$$

15.12.8.5 *Food-to-Microorganisms Ratio*

The food-to-microorganisms (F/M) ratio is a process control calculation used in many activated sludge facilities to control the balance between available food materials (BOD or COD) and available organisms (mixed liquor volatile suspended solids). The chemical oxygen demand test is sometimes used, because the results are available in a relatively short period of time. To calculate the F/M ratio, the following information is required:

- Aeration tank influent flow rate (MGD)
- Aeration tank influent BOD or COD (mg/L)
- Aeration tank MLVSS (mg/L)
- Aeration tank volume (MG)

$$\begin{matrix}\text{F/M} \\ \text{Ratio}\end{matrix} = \frac{\text{Effluent BOD/COD (mg/L)} \times \text{Flow (MGD)} \times 8.34 \text{ lb/MG/mg/L}}{\text{MLVSS (mg/L)} \times \text{Aerator Volume (MG)} \times 8.34 \text{ lb/MG/mg/L}} \tag{15.10}$$

Table 15.4 shows typical F/M ratios for activated sludge processes.

■ *Example 15.5*

Problem: Given the following data, what is the F/M ratio?

Primary effluent flow = 2.5 MGD
Primary effluent BOD = 145 mg/L
Primary effluent TSS = 165 mg/L
Aeration volume = 0.65 MG
Settling volume = 0.30 MG
MLSS = 3650 mg/L

TABLE 15.4 TYPICAL F/M RATIOS FOR ACTIVATED SLUDGE PROCESSES

Process	lb BOD_5/lb MLVSS	lb COD/lb MLVSS
Conventional	0.2–0.4	0.5–1.0
Contact stabilization	0.2–0.6	0.5–1.0
Extended aeration	0.05–0.15	0.2–0.5
Oxidation ditch	0.05–0.15	0.2–0.5
Pure oxygen	0.25–1.0	0.5–2.0

Effluent flow = 2.2 MGD

Effluent BOD = 22 mg/L

Effluent TSS = 16 mg/L

MLVSS = 2550 mg/L

% Waste, volatile = 71%

Desired F/M = 0.3

Solution:

$$\text{F/M Ratio} = \frac{145 \text{ mg/L} \times 2.2 \text{ MGD} \times 8.34 \text{ lb/MG/mg/L}}{2550 \text{ mg/L} \times 0.65 \text{ MG} \times 8.34 \text{ lb/MG/mg/L}} = 0.19 \text{ lb BOD/lb MLVSS}$$

Note: If the MLVSS concentration is not available, it can be calculated if percent volatile matter (%VM) of the mixed liquor suspended solids is known (see Equation 15.11).

$$\text{MLVSS} = \text{MLSS} \times \%\text{VM (decimal)} \tag{15.11}$$

Note: The "F" value in the F/M ratio for computing loading to an activated sludge process can be either BOD or COD. Remember that the reason for sludge production in the activated sludge process is to convert BOD to bacteria. One advantage of using COD over BOD for analysis of organic load is that COD is more accurate.

■ *Example 15.6*

Problem: The aeration tank contains 2985 mg/L of MLSS. Laboratory tests indicate the MLSS is 66% volatile matter. What is the MLVSS concentration in the aeration tank?

Solution:

$$\text{MLVSS} = 2985 \text{ mg/L} \times 0.66 = 1970 \text{ mg/L}$$

15.12.8.5.1 F/M Ratio Control

Maintaining the F/M ratio within a specified range can be an excellent control method. Although the F/M ratio is affected by adjustment of the return rates, the most practical method for adjusting the ratio is through waste rate adjustments:

Increasing the waste rate will …

- Decrease the MLVSS.
- Increase the F/M ratio.

Decreasing the waste rate will …

- Increase the MLVSS.
- Decrease the F/M ratio.

The desired F/M ratio must be established on a plant-by-plant basis. Comparison of F/M ratios with plant effluent quality is the primary means to identify the most effective range for individual plants where the range of F/M values that produce the desired effluent quality has been established.

15.12.8.5.2 Required MLVSS Quantity

The pounds of MLVSS required in the aeration tank to achieve an optimum F/M ratio can be determined from the average influent food (BOD or COD) and the desired F/M ratio:

$$\text{MLVSS (lb)} = \frac{\left(\begin{array}{l}\text{Primary Effluent BOD or COD}\\ \times\ \text{Flow (MGD)} \times 8.34\ \text{lb/MG/mg/L}\end{array}\right)}{\text{Desired F/M Ratio}} \tag{15.12}$$

The required pounds of MLVSS determined by this calculation can then be converted to a concentration value by:

$$\text{MLVSS (mg/L)} = \frac{\text{Desired MLVSS (lb)}}{\text{Aeration Volume (MG)} \times 8.34\ \text{lb/gal}} \tag{15.13}$$

■ *Example 15.7*

Problem: The aeration tank influent flow is 4.0 MGD, and the influent COD is 145 mg/L. The aeration tank volume is 0.65 MG. The desired F/M ratio is 0.3 lb COD/lb MLVSS. (1) How many pounds of MLVSS must be maintained in the aeration tank to achieve the desired F/M ratio? (2) What is the required concentration of MLVSS in the aeration tank?

Solution:

$$\text{MLVSS (lb)} = \frac{145\ \text{mg/L} \times 4.0\ \text{MGD} \times 8.34\ \text{lb/gal}}{0.3\ \text{lb COD/lb MLVSS}} = 16{,}124\ \text{lb}$$

$$\text{MLVSS (mg/L)} = \frac{16{,}124\ \text{MLVSS}}{0.65\ \text{MG} \times 8.34} = 2974\ \text{mg/L}$$

15.12.8.5.3 Calculating Waste Rates Using F/M Ratio

Maintaining the desired F/M ratio is achieved by controlling the MLVSS level in the aeration tank. This may be accomplished by adjustment of return rates; however, the most practical method is by proper control of the waste rate:

$$\begin{aligned}\text{Waste Volume Solids (lb/day)} = {} & \text{Actual MLVSS (lb)} \\ & - \text{Desired MLVSS (lb)}\end{aligned} \tag{15.14}$$

If the desired MLVSS is greater than the actual MLVSS, wasting is stopped until the desired level is achieved. Practical considerations require that the required waste quantity be converted to a required volume to waste per day. This is accomplished by converting the waste pounds to flow rate in million gallons per day (MGD) or gallons per minute (gpm):

$$\text{Waste (MGD)} = \frac{\text{Waste volatile content (lb/day)}}{\text{Waste volatile concentration (mg/L)} \times 8.34} \tag{15.15}$$

Note: When the F/M ratio is used for process control, the volatile content of the waste activated sludge should be determined.

■ *Example 15.8*

Problem: Given the following information, determine the required waste rate in gallons per minute to maintain an F/M ratio of 0.17 lb COD/lb MLVSS.

Primary effluent COD = 140 mg/L

Primary effluent flow = 2.2 MGD

MLVSS = 3549 mg/L

Aeration tank volume = 0.75 MG

Waste volatile solids concentration = 4440 mg/L

Solution:

$$\text{Actual MLVSS} = 3.549\ \text{mg/L} \times 0.75\ \text{MG} \times 8.34 = 22{,}199\ \text{lb}$$

$$\text{Required MLVSS} = \frac{140\ \text{mg/L} \times 2.2\ \text{MGD} \times 8.34}{0.17\ \text{lb COD/lb MLVSS}} = 15{,}110\ \text{lb}$$

$$\text{Waste (lb)} = 22{,}199\ \text{lb} - 15{,}110\ \text{lb} = 7089\ \text{lb}$$

$$\text{Waste (MGD)} = \frac{7089\ \text{lb/day}}{4440\ \text{mg/L} \times 8.34} = 0.19\ \text{MGD}$$

$$\text{Waste (gpm)} = \frac{0.19\ \text{MGD} \times 1{,}000{,}000\ \text{gpd/MGD}}{1440\ \text{min/day}} = 132\ \text{gpm}$$

15.12.8.6 Mean Cell Residence Time

Mean cell residence time (MCRT), sometimes called *sludge retention time*, is a process control calculation used for activated sludge systems. The MCRT calculation illustrated in Example 15.9 uses the entire volume of the activated sludge system (aeration and settling).

$$\begin{matrix}\text{MCRT}\\\text{(days)}\end{matrix} = \frac{\text{MLSS (mg/L)} \times \begin{bmatrix}\text{Aeration Volume (MG)}\\ +\text{Clarifier Volume (MG)}\end{bmatrix} \times 8.34 \text{ lb/MG/mg/L}}{\begin{matrix}\left[\text{WAS (mg/L)} \times \text{WAS Flow (MGD)} \times 8.34 \text{ lb/MG/mg/L}\right]\\ +\left[\text{TSS out (mg/L)} \times \text{Flow (MGD)} \times 8.34 \text{ lb/MG/mg/L}\right]\end{matrix}} \tag{15.16}$$

Note: MCRT can be calculated using only the aeration tank solids inventory. When comparing plant operational levels to reference materials, it is important to determine which calculation the reference manual uses to obtain its example values. Other methods are available to determine the clarifier solids concentration; however, the simplest method assumes that the average suspended solids concentration is equal to the solids concentration of the aeration tank.

■ *Example 15.9*

Problem: Given the following data, what is the MCRT?

Influent flow = 4.2 MGD	Aeration volume = 1.20 MG
Influent BOD = 135 mg/L	Settling volume = 0.60 MG
Influent TSS = 150 mg/L	MLSS = 3350 mg/L
Effluent flow = 4.2 MGD	Waste rate = 0.080 MGD
Effluent BOD = 22 mg/L	Waste concentration = 6100 mg/L
Effluent TSS = 10 mg/L	Desired MCRT = 8.5 days

Solution:

$$\text{MCRT} = \frac{3350 \text{ mg/L} \times (1.2 \text{ MG} + 0.6 \text{ MG}) \times 8.34}{(6100 \text{ mg/L} \times 0.08 \text{ MGD} \times 8.34) + (10 \text{ mg/L} \times 4.2 \text{ MGD} \times 8.34)}$$

$$= 11.4 \text{ days}$$

15.12.8.6.1 Mean Cell Residence Time Control

Because it provides an accurate evaluation of the process condition and takes all aspects of the solids inventory into account, the MCRT is an excellent process control tool. Increases in the waste rate will decrease the MCRT, as will large losses of solids over the effluent weir. Reductions in waste rate will result in increased MCRT values.

Note: You should remember these important process control parameters.

15.12.8.6.2 Process Parameters and Impact on MCRT/MCRT

- To increase F/M, decrease MCRT.
- To increase MCRT, decrease waste rate.
- When MCRT increases, so do the MLTSS and the 30-minute setting.
- Return sludge rate has no impact on MCRT.
- MCRT has no impact on the F/M ratio when the number of aeration tanks in service is reduced.

15.12.8.6.3 Typical MCRT Values

The following lists the various aeration process modifications and associated MCRT values.

Process	**MCRT (days)**
Conventional	5–15
Step aeration	5–15
Contact stabilization (contact)	5–15
Extended aeration	20–30
Oxidation ditch	20–30
Pure oxygen	8–20

15.12.8.6.4 Control Values for MCRT

Control values for the MCRT are normally established based on effluent quality. Once the MCRT range required to produce the desired effluent quality is established, it can be used to determine the waste rate required to maintain it.

15.12.8.6.5 Waste Quantities/Requirements

The MCRT for process control requires determining the optimum range for MCRT values. This is accomplished by comparison of the effluent quality with MCRT values. When the optimum MCRT is established, the quantity of solids to be removed (wasted) is determined by:

$$\text{Waste (lb/day)} = \left[\frac{\text{MLSS} \times \left(\text{Aeration (MG)} + \text{Clarifier (MG)}\right) \times 8.34}{\text{Desired MCRT}}\right] - (\text{TSS}_{\text{out}} \times \text{Flow} \times 8.34) \tag{15.17}$$

■ *Example 15.10*

$$\text{Waste} = \frac{3400\text{ mg/L} \times (1.4\text{ MG} + 0.50\text{ MG}) \times 8.34}{8.6\text{ days}} - (10\text{ mg/L} \times 5.0\text{ MGD} \times 8.34)$$

$$= 5848\text{ lb/day}$$

15.12.8.6.6 Waste Rate in Million Gallons per Day

When the quantity of solids to be removed from the system is known, the desired waste rate in million gallons per day can be determined. The unit used to express the rate (MGD, gpd, or gpm) is a function of the volume of waste to be removed and the design of the equipment.

$$\text{Waste (MGD)} = \frac{\text{Waste (lb/day)}}{\text{WAS Concentrations (mg/L)} \times 8.34} \tag{15.18}$$

$$\text{Waste (gpm)} = \frac{\text{Waste (MGD)} \times 1{,}000{,}000 \text{ gpd/MGD}}{1440 \text{ min/day}} \tag{15.19}$$

■ ***Example 15.11***

Problem: Given the following data, determine the required waste rate to maintain a MCRT of 8.8 days.

MLSS = 2500 mg/L

Aeration volume = 1.20 MG

Clarifier volume = 0.20 MG

Effluent TSS = 11 mg/L

Effluent flow = 5.0 MGD

Waste concentrations = 6000 mg/L

Solution:

$$\text{Waste (lb/day)} = \frac{2500 \text{ mg/L} \times (1.20 + 0.20) \times 8.34}{8.8 \text{ days}} - (11 \text{ mg/L} \times 5.0 \text{ MGD} \times 8.34)$$

$$= 3317 \text{ lb/day} - 459 \text{ lb/day} = 2858 \text{ lb/day}$$

$$\text{Waste (MGD)} = \frac{2858 \text{ lb/day}}{6000 \text{ mg/L} \times 8.34} = 0.057 \text{ MGD}$$

$$\text{Waste (gpm)} = \frac{0.057 \text{ MGD} \times 1{,}000{,}000 \text{ gpd/MGD}}{1440 \text{ min/day}} = 40 \text{ gpm}$$

15.12.8.7 Mass Balance

Mass balance is based on the fact that solids and BOD are not lost in the treatment system. In simple terms, the mass balance concept states that, "What comes in must equal waste that goes out." The concept can be used to verify operational control levels and to determine if potential problems exist within the plant's process control monitoring program.

Note: Influent values and effluent values that do not correlate within 10 to 15% usually indicate either a sampling or testing error or a process control discrepancy.

Mass balance procedures for evaluating the operation of a settling tank and a biological process are described in this section. Operators should recognize that, although the procedures are discussed in reference to the activated sludge process, the concepts can be applied to any settling or biological process.

15.12.8.7.1 Mass Balance: Settling Tank Suspended Solids

The settling tank mass balance calculation assumes that no suspended solids are produced in the settling tank. Any settling tank operation can be evaluated by comparing the solids entering the unit with the solids leaving the tank as effluent suspended solids or as sludge solids. If sampling and testing are accurate and representative, and process control and operation are appropriate, the quantity of suspended solids entering the settling tank should equal (±10%) the quantity of suspended solids leaving the settling tanks as sludge, scum, and effluent total suspended solids.

Note: In most instances, the amount of suspended solids leaving the process as scum is so small that it is ignored in the calculation.

15.12.8.7.2 Mass Balance Calculation

$$\text{Total suspended solids in (lb)} = \text{TSS}_{\text{in}} \times \text{Flow (MGD)} \times 8.34 \tag{15.20}$$

$$\text{Total suspended solids out (lb)} = \text{TSS}_{\text{out}} \times \text{Flow (MGD)} \times 8.34 \tag{15.21}$$

$$\text{Sludge solids} = \text{Sludge pumped (gal)} \times \text{\% Solids} \times 8.34 \tag{15.22}$$

$$\begin{matrix}\text{\% Mass}\\ \text{Balance}\end{matrix} = \frac{\left[\text{TSS}_{\text{in}}\ \text{(lb)} - \left(\text{TSS}_{\text{out}}\ \text{(lb)} + \text{Sludge Solids (lb)}\right)\right] \times 100}{\text{TSS}_{\text{in}}\ \text{(lb)}} \tag{15.23}$$

15.12.8.7.3 Explanation of Results

- Mass balance is ±15%—The process is considered to be in balance. Sludge removal should be adequate, with the sludge blanket depth remaining stable. Sampling is considered to be producing representative samples that are being tested accurately.
- Mass balance is greater than ±15%—More solids are entering the settling tank than are being removed. The sludge blanket depth should be increasing, effluent solids may also be increasing, and effluent quality is decreasing. If the changes described are not occurring, the mass balance may indicate that the sample type, location, times, and procedures or testing procedures are not producing representative results.

- Mass balance is less than ±15%—Indicates that fewer solids are entering the settling tank than are being removed. The sludge blanket depth should be decreasing, and the sludge solids concentration may also be decreasing. This could adversely impact sludge treatment processes. If the changes described are not occurring, the mass balance may indicate that sample type, location, times, and procedure or testing procedures are not producing representative results.

■ *Example 15.12*

Problem: Given the following data, determine the solids mass balance for the settling tank.

Influent flow = 2.6 MGD
Influent TSS = 2445 mg/L
Effluent flow = 2.6 MGD
Effluent TSS = 17 mg/L
Return flow = 0.5 MGD
Return TSS = 8470 mg/L

Solution:

$$\text{Solids In} = 2445\text{ mg/L} \times 2.6\text{ MGD} \times 8.34 = 53{,}017\text{ lb/day}$$

$$\text{Solids Out} = 17\text{ mg/L} \times 2.6\text{ MGD} \times 8.34 = 369\text{ lb/day}$$

$$\text{Sludge Solids Out} = 8470\text{ mg/L} \times 0.5\text{ MGD} \times 8.34 = 35{,}320\text{ lb/day}$$

$$\text{Mass Balance} = \frac{\left[53{,}017\text{ lb/day} - (369\text{ lb/day} + 35{,}320\text{ lb/day})\right] \times 100}{53{,}017\text{ lb/day}} = 32.7\%$$

This value indicates either of the following:

- The sampling point, sample collection procedure, or laboratory procedure is producing inaccurate data upon which to make process control decisions.
- More solids are entering the settling tank each day than are being removed. This should result in either a solids buildup in the settling tank or a loss of solids over the effluent weir.

Investigate further to determine the specific cause of the imbalance.

15.12.8.7.4 Mass Balance for Biological Processes

Solids are produced whenever biological processes are used to remove organic matter from wastewater. Mass balance for an aerobic biological process must take into account both the solids removed by

TABLE 15.5 CONVERSION FACTORS (*K*)

Process	lb Solids/lb BOD_5 Removed
Primary	1.7
Activated sludge with primary	0.7
Activated sludge without primary	
Conventional	0.85
Step aeration	0.85
Extended aeration	0.65
Oxidation ditch	0.65
Contact stabilization	1.00
Trickling filter	1.00
Rotating biological contactor	1.00

physical settling processes and the solids produced by biological conversion of soluble organic matter to insoluble suspended matter or organisms. Research has shown that the amount of solids produced per pound of BOD_5 removed can be predicted based on the type of process being used. Although the exact amount of solids produced can vary from plant to plant, research has developed a series of *K* factors that can be used to estimate the solids production for plants using a particular treatment process. These average factors provide a simple method to evaluate the effectiveness of a facility's process control program. The mass balance also provides an excellent mechanism to evaluate the validity of process control and effluent monitoring data generated. Table 15.5 lists average *K* factors in pounds of solids produced per pound of BOD removed for selected processes.

15.12.8.7.5 Conversion Factor

Conversion factors depend on the activated sludge modification involved. Factors generally range from 0.5 to 1.0 lb of solids per pound of BOD removed (see Table 15.5).

15.12.8.7.6 Mass Balance Calculation

$$\text{BOD}_5\ \text{In (lb)} = \text{BOD (mg/L)} \times \text{Flow (MGD)} \times 8.34$$

$$\text{BOD}_5\ \text{Out (lb)} = \text{BOD (mg/L)} \times \text{Flow (MGD)} \times 8.34$$

$$\text{Solids Produced (lb/day)} = [\text{BOD}_{\text{in}}\ \text{(lb)} - \text{BOD}_{\text{out}}\ \text{(lb)}] \times K$$

$$\text{TSS}_{\text{out}}\ \text{(lb/day)} = \text{TSS}_{\text{out}}\ \text{(mg/L)} \times \text{Flow (MGD)} \times 8.34$$

$$\text{Waste (lb/day)} = \text{Waste (mg/L)} \times \text{Flow (MGD)} \times 8.34$$

$$\text{Solids Removed (lb/day)} = \text{TSS}_{\text{out}}\ \text{(lb/day)} + \text{Waste (lb/day)}$$

$$\%\ \text{Mass Balance} = \frac{(\text{Solids Produced} - \text{Solids Removed}) \times 100}{\text{Solids Produced}} \tag{15.24}$$

15.12.8.7.7 Explanation of Results

If the mass balance is ±15%, the process sampling and testing and process control are within acceptable levels. If the balance is greater than ±15%, investigate further to determine if the discrepancy represents a process control problem or is the result of nonrepresentative sampling and inaccurate testing.

15.12.8.7.8 Sludge Waste Based on Mass Balance

The mass balance calculation predicts the amount or sludge that will be produced by a treatment process. This information can then be used to determine what, under current operating conditions, that waste rate must be to maintain the current solids level:

$$\text{Waste Rate (MGD)} = \frac{\text{Solids Produced (lb/day)}}{\text{Waste Concentration} \times 8.34} \tag{15.25}$$

■ ***Example 15.13***

Problem: Given the following data, determine the mass balance of the biological process and the appropriate waste rate to maintain current operating conditions.

Process = extended aeration (no primary)
Influent flow = 1.1 MGD
Influent BOD_5 = 220 mg/L
Influent TSS = 240 mg/L
Effluent flow = 1.5 MGD
Effluent flow BOD_5 = 18 mg/L
Effluent flow TSS = 22 mg/L
Waste flow = 24,000 gpd
Waste TSS = 8710 mg/L

Solution:

BOD_5 In = 220 mg/L × 1.1 MGD × 8.34 = 2018 lb/day
BOD_5 Out = 18 mg/L × 1.1 MGD × 8.34 = 165 lb/day
BOD_5 Removed = 2018 lb/day – 165 lb/day = 1853 lb/day
Solids Produced = 1853 lb/day × 0.65 lb/lb BOD_5 = 1204 lb/day

Solids Out = 22 mg/L × 1.1 MGD × 8.34 = 202 lb/day
Sludge Out = 8710 mg/L × 0.024 MGD × 8.34 = 1743 lb/day
Solids Removed = (292 lb/day + 1743 lb/day) = 1945 lb/day

$$\text{\% Mass Balance} = \frac{(1204\text{ lb/day} - 1945\text{ lb/day}) \times 100}{1204\text{ lb/day}} = 62\%$$

The mass balance indicates either of the following:

- The sampling points, collection methods, or laboratory testing procedures are producing nonrepresentative results.
- The process is removing significantly more solids than is required. Additional testing should be performed to isolate the specific cause of the imbalance.

To assist in the evaluation, the waste rate based on the mass balance information can be calculated:

$$\text{Waste (gpd)} = \frac{\text{Solids Produced (lb/day)}}{\text{Waste TSS (mg/L)} \times 8.34} \tag{15.26}$$

$$\text{Waste} = \frac{1204 \text{ lb/day} \times 1{,}000{,}000}{8710 \text{ mg/L} \times 8.34} = 16{,}575 \text{ gpd}$$

15.12.9 Solids Concentration: Secondary Clarifier

The solids concentration in the secondary clarifier can be assumed to be equal to the solids concentration in the aeration tank effluent. It may also be determined in the laboratory using a core sample taken from the secondary clarifier. The secondary clarifier solids concentration can be calculated as an average of the secondary effluent suspended solids and the return activated sludge suspended solids concentration.

15.12.10 Activated Sludge Process Recordkeeping Requirements

Wastewater operators soon learn that recordkeeping is a major requirement and responsibility of their jobs. Records are important (essential) for process control, for providing information on the cause of problems, for providing information to make seasonal changes, and for compliance with regulatory agencies. Records should include sampling and testing data, process control calculations, meter readings, process adjustments, operational problems and corrective action taken, and process observations.

15.13 CHAPTER REVIEW QUESTIONS

15.1 What two purposes does the air supplied to the aeration basin serve?

15.2 What do we call the liquid mixture of microorganisms and solids removed from the bottom of the settling tank?

15.3 What do we call the mixture of primary effluent and return sludge?

15.4 What are the three things that must be balanced to make the activated sludge process perform properly?

15.5 What is the major purpose of an activated sludge process?

15.6 Name two types of aeration device used in the activated sludge process.

15.7 List three observations the operator should make as part of the daily operation of the activated sludge process.

15.8 A 2200-mL sample of activated sludge is allowed to settle for 60 minutes. At the end of the 60 minutes, the sludge has settled 1300 mL. What is the SSV_{60} of the sample?

15.9 An activated sludge sample has an MLSS concentration of 2245 mg/L. The SSV_{60} of the sample is 420 mL/L. What is the sludge volume index of the sample?

15.10 The operator wastes 0.069 MGD of activated sludge. The waste activated sludge concentration is 8185 mg/L. How many pounds of activated sludge solid have been removed from the process?

15.11 Which activated sludge process aerates the return sludge before mixing it with the influent flow?

15.12 Name three treatment processes used to reduce sludge volume.

REFERENCE AND RECOMMENDED READING

Kerri, K. et al., Eds. (2007). *Operation of Wastewater Treatment Plants: A Field Study Training Program*, 7th ed. Sacramento: California State University.

CHAPTER 16

CHLORINATION

16.1 INTRODUCTION

Like drinking water, liquid wastewater effluent is disinfected. Unlike drinking water, wastewater effluent is disinfected not to directly (direct end-of-pipe connection) protect a drinking water supply but to protect public health in general. This is particularly important when the secondary effluent is discharged into a body of water used for swimming or for a downstream water supply. This chapter discusses basic chlorination and dechlorination.

16.2 CHLORINE DISINFECTION

Chlorination for disinfection follows all other steps in conventional wastewater treatment. The purpose of chlorination is to reduce the population of organisms in the wastewater to levels low enough to ensure that pathogenic organisms will not be present in sufficient quantities to cause disease when discharged.

Key Point: The safest action to take in the event of a major chlorine container leak is to call the fire department.

Note: Chlorine gas (vapor density of 2.5) is heavier than air; therefore, exhaust from a chlorinator room should be taken from floor level.

Note: You might wonder why it is that chlorination of critical waters such as natural trout streams is not normal practice. This practice is strictly prohibited because chlorine and its byproducts (e.g., chloramines) are extremely toxic to aquatic organisms.

16.2.1 Chlorination Terminology

Remember that several terms are used when discussing disinfection by chlorination. Because it is important for the operator to be familiar with them, we repeat the key terms here:

Chlorine—A strong oxidizing agent with strong disinfecting capability. It is a yellow–green gas that is extremely corrosive and is toxic to humans even at extremely low concentrations in the air.

Contact time—The length of time the disinfecting agent and the wastewater remain in contact.

Demand—The chemical reactions that must be satisfied before a residual or excess chemical will appear.

Disinfection—The selective destruction of disease-causing organisms. All of the organisms are not destroyed during the process, which differentiates disinfection from sterilization, which is the destruction of all organisms.

Dose—The amount of chemical being added in milligrams/liter.

Feed rate—The amount of chemical being added in pounds per day.

Residual—The amount of disinfecting chemical remaining after the demand has been satisfied.

Sterilization—The removal of all living organisms.

16.2.2 Wastewater Chlorination Facts

16.2.2.1 Chlorine Facts

- Elemental chlorine (Cl_2) is a yellow–green gas that is 2.5 times heavier than air.
- The most common use of chlorine in wastewater treatment is for disinfection. Other uses include odor control and activated sludge bulking control. Chlorination takes place prior to discharge of the final effluent to the receiving waters (see Figure 19.1).
- Chlorine may also be used for nitrogen removal through a process called *breakpoint chlorination.* For nitrogen removal, enough chlorine is added to the wastewater to convert all of the ammonium nitrogen gas. Approximately 10 mg/L of chlorine must be added for every 1 mg/L of ammonium nitrogen in the wastewater.
- For disinfection, chlorine is fed manually or automatically into a chlorine contact tank or basin, where it contacts flowing wastewater for at least 30 minutes to destroy disease-causing microorganisms (pathogens) found in treated wastewater.
- Chorine may be applied as a gas or solid or in liquid hypochlorite form.
- Chorine is a very reactive substance. It has the potential to react with many different chemicals (including ammonia), as well as with organic matter. When chlorine is added to wastewater, several reactions occur:

1. Chlorine will react with any reducing agent (i.e., sulfide, nitrite, iron, and thiosulfate) present in wastewater. These reactions are known as *chlorine demand*. The chlorine used for these reactions is not available for disinfection.
2. Chlorine also reacts with organic compounds and ammonia compounds to form chlororganics and chloramines. Chloramines are part of the group of chlorine compounds that have disinfecting properties and show up as part of the chlorine residual test.
3. After all of the chlorine demands are met, the addition of more chlorine will produce free chlorine residual. Producing free chlorine residual in wastewater requires very large additions of chlorine.

16.2.2.2 Hypochlorite Facts

Hypochlorite (HTH) is relatively safe to work with, although some minor hazards are associated with its use (skin and nose irritation and burning eyes). It is normally available in dry form as a white powder, pellet, or tablet or in liquid form. It can be added directly using a dry chemical feeder or dissolved and fed as a solution.

Note: In most wastewater treatment systems, disinfection is accomplished by means of combined residual.

16.2.3 Process Description

Chlorine is a very reactive substance. Chlorine is added to wastewater to satisfy all chemical demands—that is, to react with certain chemicals (e.g., sulfide, sulfite, ferrous iron). When these initial chemical demands have been satisfied, chlorine will react with substances such as ammonia to produce chloramines and other substances that, although not as effective as chlorine, have disinfecting capability. The resulting combined residual can be measured using residual chlorine test methods. If additional chlorine is added, free chlorine residual can be produced. Due to the chemicals normally found in wastewater, chlorine residuals are normally combined rather than free residuals. Control of the disinfection process is usually based on maintaining total chlorine residual of at least 1.0 mg/L for a contact time of at least 30 minutes at design flow.

Key Point: Residual level, contact time, and effluent quality affect disinfection. Failure to maintain the desired residual levels for the required contact time will result in lower efficiency and increased probability that disease organisms will be discharged.

Based on water quality standards, total residual limitations on chlorine are:

- Freshwater—Less than 11 ppb total residual chlorine
- Estuaries—Less that 7.5 ppb for halogen-produced oxidants
- Endangered species—Use of chlorine prohibited

16.2.4 Chlorination Equipment

16.2.4.1 Hypochlorite Systems

Depending on the form of hypochlorite selected for use, special equipment that will control the addition of hypochlorite to the wastewater is required. Liquid forms require the use of metering pumps, which deliver varying flows of hypochlorite solution. Dry chemicals require the use of a feed system designed to provide variable doses of the form used. The tablet form of hypochlorite requires the use of a tablet chlorinator designed specifically to provide the desired dose of chlorine. Hypochlorite is dispensed as hypochlorite solution or via a dry feed system and is then mixed with the flow. The treated wastewater enters the contact tank for the required contact time.

16.2.4.2 Chlorine Systems

Because of the potential hazards associated with the use of chlorine, the equipment requirements are significantly greater than those associated with hypochlorite use. The system most widely used is a solution feed system. In this system, chlorine is removed from the container at a flow rate controlled by a variable orifice. Water moving through the chlorine injector creates a vacuum, which draws the chlorine gas to the injector and mixes it with the water. The chlorine gas reacts with the water to form hypochlorous and hydrochloric acid. The solution is then piped to the chlorine contact tank and dispersed into the wastewater through a diffuser. Larger facilities may withdraw the liquid form of chlorine and use evaporators (heaters) to convert it to the gas form. Small facilities will normally draw the gas form of chlorine from the cylinder. As gas is withdrawn, liquid will be converted to the gas form. This requires heat energy and may result in chlorine line freeze-up if the withdrawal rate exceeds the available energy levels.

16.2.5 Chlorination System Operation

In either type of system, normal operation requires adjustment of feed rates to ensure that the required residual levels are maintained. This normally requires chlorine residual testing and adjustment based on the results of the test. Other activities include removal of accumulated solids from the contact tank, collection of bacteriological samples to evaluate process performance, and maintenance of safety equipment (e.g., respirator air pack, safety lines). Hypochlorite operation may also require adding powder or pellets to the dry chemical feeder or tablets to the tablet chlorinator as a make-up solution (solution feed systems). Chlorine operations include adjustment of chlorinator feed rates, inspection of mechanical equipment, testing for leaks using ammonia swabs (white smoke means leaks), changing containers (requires more than one person for safety), and adjusting the injector water feed rate when required. Chlorination requires routine testing of plant effluent for total residual chlorine and may also require collection and analysis of samples to determine the fecal coliform concentration in the effluent.

16.2.6 Dechlorination

The purpose of dechlorination is to remove chlorine and reaction products (chloramines) before the treated wastestream is discharged into its receiving waters. Dechlorination follows chlorination, usually at the end of the contact tank to the final effluent. Sulfur dioxide gas, sodium sulfate, sodium metabisulfate, and sodium bisulfates are the chemicals used to dechlorinate. No matter which chemical is used to dechlorinate, its reaction with chlorine is instantaneous.

16.2.7 Chlorination Environmental Hazards and Safety

Chlorine is an extremely toxic substance that can cause severe damage when released to the environment. For this reason, most state regulatory agencies have established chlorine water quality standards; for example, in Virginia, the standard is 0.011 mg/L in freshwaters for total residual chlorine and 0.0075 mg/L for chlorine-produced oxidants in saline waters. Studies have indicated that above these levels chlorine can reduce shellfish growth and destroy sensitive aquatic organisms. Such standards have made it necessary for many treatment facilities to add an additional process to remove chlorine prior to discharge. As mentioned, the process known as dechlorination uses chemicals that react quickly with chlorine to convert it to a less harmful form. Elemental chlorine is a chemical associated with potentially fatal hazards. For this reason, many different state and federal agencies regulate the transport, storage, and use of chlorine. All operators required to work with chlorine should be trained in proper handling techniques. They should also be trained to ensure that all procedures for storage transport, handling, and use of chlorine are in compliance with appropriate state and federal regulations.

16.2.7.1 Safe Work Practice for Chlorine

Because of the inherent dangers involved with handling chlorine, each facility using chlorine (for any reason) should ensure that written safe work practices are in place and followed by plant operators. Sample safe work practices for handling chlorine are provided below:

1. Plant personnel *must* be trained and instructed on the use and handling of chlorine, chlorine equipment, chlorine emergency repair kits, and other chlorine emergency procedures.
2. Use extreme care and caution when handling chlorine.
3. Lift chlorine cylinders only with an approved and load-tested device.
4. Secure chlorine cylinders into position immediately. *Never* leave a cylinder suspended.
5. Avoid dropping chlorine cylinders.
6. Avoid banging chlorine cylinders into other objects.

7. Store chlorine 1-ton cylinders in a cool, dry place away from direct sunlight or heating units. Railroad tank cars are direct-sunlight compensated.
8. Store chlorine 1-ton cylinders on their sides only (horizontally).
9. Do not stack unused or used chlorine cylinders.
10. Provide positive ventilation to the chlorine storage area and chlorinator room.
11. *Always* keep chlorine cylinders at ambient temperature. *Never* apply direct flame to a chlorine cylinder.
12. Use the oldest chlorine cylinder in stock first.
13. Always keep valve protection hoods in place until the chlorine cylinders are ready for connection.
14. Except to repair a leak, do not tamper with the fusible plugs on chlorine cylinders.
15. Wear a self-contained breathing apparatus (SCBA) whenever changing a chlorine cylinder and have at least one other person with a standby SCBA unit outside the immediate area.
16. Inspect all threads and surfaces of the chlorine cylinder, and have at least one other person with a standby SCBA unit outside the immediate area.
17. Use new lead gaskets each time a chlorine cylinder connection is made.
18. Use only the specified wrench to operate chlorine cylinder valves.
19. Open chlorine cylinder valves slowly—no more than one full turn.
20. Do not hammer, bang, or force chlorine cylinder valves under any circumstances.
21. Check for chlorine leaks as soon as the chlorine cylinder connection is made. Gently expel ammonia mist from a plastic squeeze bottle filled with approximately 2 ounces of liquid ammonia solution. Do not put liquid ammonia on valves or equipment.
22. Correct all minor chlorine leaks at the chlorine cylinder connection immediately.
23. Except for automatic systems, draw chlorine from only one manifolded chlorine cylinder at a time. *Never* simultaneously open two or more chlorine cylinders connected to a common manifold pulling liquid chlorine; however, it is acceptable to have two or more cylinders connected to a common manifold pulling gaseous chlorine.
24. Contact trained plant personnel to repair chlorine leaks.
25. Provide positive ventilation to a contaminated chlorine atmosphere before entering whenever possible.
26. Have at least two personnel present before entering a chlorine atmosphere: one person to enter the chlorine atmosphere, the other to observe in the event of an emergency. *Never* enter a chlorine

atmosphere unattended. Remember that OSHA mandates that only fully qualified Level III HAZMAT responders are authorized to aggressively attack a hazardous materials leak such as chlorine.

27. Wear SCBA and chemical protective clothing covering face, arms, and hands before entering an enclosed chlorine area to investigate a chlorine odor or chlorine leak (two-person rule required).
28. Use only supplied-air breathing equipment when entering a chlorine atmosphere. *Never* use canister-type gas masks when entering a chlorine atmosphere.
29. Ensure that the supplied-air breathing equipment has been properly maintained in accordance with the plant's SCBA inspection guidelines, as specified in the plant's respiratory protection program.
30. Stay upwind from all chlorine leak danger areas unless involved with making repairs. Look to plant windsocks for wind direction.
31. Roll uncontrollable leaking chlorine cylinders so the chlorine escapes as a gas, not as a liquid.
32. Stop leaking chlorine cylinders or leaking chlorine equipment (by closing off valves, if possible) prior to attempting repair.
33. Connect uncontrollable leaking chlorine cylinders to the chlorination equipment and feed the maximum chlorine feed rate possible.
34. Keep leaking chlorine cylinders at the plant site. Chlorine cylinders received at the plant site must be inspected for leaks prior to taking delivery from the shipper. *Never* ship a leaking chlorine cylinder back to the supplier after it has been accepted (bill of lading has been signed by plant personnel) from the shipper; instead, repair or stop the leak first.
35. Keep moisture away from a chlorine leak. *Never* put water onto a chlorine leak.
36. Call the fire department or rescue squad if a person is incapacitated by chlorine.
37. Administer CPR (use barrier mask if possible) immediately to a person who has been incapacitated by chlorine.
38. Take shallow rather than deep breaths if exposed to chlorine without the appropriate respiratory protection.
39. Place a person who does not have difficulty breathing and is heavily contaminated with chlorine into a deluge shower. Remove the person's clothing under the water and flush all body parts that were exposed to chlorine.
40. Flush eyes contaminated with chlorine with copious quantities of lukewarm running water for at least 15 minutes.
41. Drink milk if throat is irritated by chlorine.
42. *Never* store other materials in chlorine cylinder storage areas; substances such as acetylene and propane are not compatible with chlorine.

16.2.8 Chlorination Process Calculations

Several calculations are useful in operating a chlorination system. Many of these calculations are discussed and illustrated in this section.

16.2.8.1 Chlorine Demand

Chlorine demand is the amount of chlorine in milligrams per liter that must be added to the wastewater to complete all of the chemical reactions that must occur prior to producing a residual.

$$\text{Chlorine Demand} = \text{Chlorine Dose (mg/L)} - \text{Chlorine Residual (mg/L)} \tag{16.1}$$

■ ***Example 16.1***

Problem: The plant effluent currently requires a chlorine dose of 7.1 mg/L to produce the required 1.0 mg/L chlorine residual in the chlorine contact tank. What is the chlorine demand in milligrams per liter?

Solution:

$$\text{Chlorine Demand} = 7.1\text{ mg/L} - 1.0\text{ mg/L} = 6.1\text{ mg/L}$$

16.2.8.2 Chlorine Feed Rate

Chlorine feed rate is the amount of chlorine added to the wastewater in pounds per day:

$$\text{Chlorine Feed Rate} = \text{Dose (mg/L)} \times \text{Flow (MGD)} \times 8.34\text{ lb/MG/mg/L} \tag{16.2}$$

■ ***Example 16.2***

Problem: The current chlorine dose is 5.55 mg/L. What is the feed rate in pounds per day if the flow is 22.89 MGD?

Solution:

$$\text{Feed} = 5.55\text{ mg/L} \times 22.89\text{ MGD} \times 8.34\text{ lb/mg/L/MG} = 1060\text{ lb/day}$$

16.2.8.3 Chlorine Dose

Chlorine dose is the concentration of chlorine being added to the wastewater. It is expressed in milligrams per liter:

$$\text{Dose (mg/L)} = \frac{\text{Chlorine Feed Rate (lb/day)}}{\text{Flow (MGD)} \times 8.34\text{ lb/MG/mg/L}} \tag{16.3}$$

■ ***Example 16.3***

Problem: 320 lb of chlorine are added per day to a wastewater flow of 5.60 MGD. What is the chlorine does in milligrams per liter?

$$\text{Dose} = \frac{320 \text{ lb/day}}{5.60 \text{ MGD} \times 8.34 \text{ lb/MG/mg/L}} = 6.9 \text{ mg/L}$$

16.2.8.4 Available Chlorine

When hypochlorite forms of chlorine are used, the available chlorine is listed on the label. In these cases, the amount of chemical added must be converted to the actual amount of chlorine using the following calculation.

$$\text{Available Chlorine} = \text{Amount of Hypochlorite} \times \% \text{ Available Chlorine} \quad (16.4)$$

■ ***Example 16.4***

Problem: The calcium hypochlorite used for chlorination contains 62.5% available chlorine. How many pounds of chlorine are added to the plant effluent if the current feed rate is 30 lb of calcium hypochlorite per day?

Solution:

$$\text{Quantity of chlorine} = 30 \text{ lb} \times 0.625 = 18.75 \text{ lb}$$

16.2.8.5 Required Quantity of Dry Hypochlorite

This calculation is used to determine the amount of hypochlorite needed to achieve the desired dose of chlorine:

$$\text{Hypochlorite (lb/day)} = \frac{\begin{pmatrix} \text{Required Chlorine Dose (mg/L)} \\ \times \text{Flow (MGD)} \times 8.34 \text{ lb/MG/mg/L} \end{pmatrix}}{\% \text{ Available Chlorine}} \quad (16.5)$$

■ ***Example 16.5***

Problem: The laboratory reports that the chlorine dose required to maintain the desired residual level is 8.5 mg/L. Today's flow rate is 3.25 MGD. The hypochlorite powder used for disinfection is 70% available chlorine. How many pounds of hypochlorite must be used?

Solution:

$$\text{Hypochlorite} = \frac{8.5 \text{ mg/L} \times 3.25 \text{ MGD} \times 8.34 \text{ lb/MG/mg/L}}{0.70} = 329 \text{ lb/day}$$

16.2.8.6 Required Quantity of Liquid Hypochlorite

$$\text{Hypochlorite (gpd)} = \frac{\begin{pmatrix}\text{Required Chlorine Dose (mg/L)}\\ \times\text{Flow (MGD)}\times 8.34\text{ lb/MG/mg/L}\end{pmatrix}}{\begin{pmatrix}\text{\% Available Chlorine}\times 8.34\\ \times\text{Hypochlorite Solution Specific Gravity}\end{pmatrix}} \tag{16.6}$$

■ ***Example 16.6***

Problem: The chlorine dose is 8.8 mg/L and the flow rate is 3.28 MGD. The hypochlorite solution is 71% available chlorine and has a specific gravity of 1.25. How many pounds of hypochlorite must be used?

Solution:

$$\text{Hypochlorite} = \frac{8.8\text{ mg/L}\times 3.28\text{ MGD}\times 8.34\text{ lb/MG/mg/L}}{0.71\times 8.34\text{ lb/gal}\times 1.25} = 32.5\text{ gpd}$$

16.2.8.7 Ordering Chlorine

Because disinfection must be continuous, the supply of chlorine must never be allowed to run out. The following calculation provides a simple method for determining when additional supplies must be ordered. The process consists of three steps:

1. Adjust the flow and use variations if projected changes are provided.
2. If an increase in flow or required dosage is projected, the current flow rate or dose must be adjusted to reflect the projected change.
3. Calculate projected flow and projected dose:

$$\text{Projected Flow} = \text{Current Flow (MGD)}\times(1.0 + \text{\% change}) \tag{16.7}$$

$$\text{Projected Dose} = \text{Current Dose (mg/L)}\times(1.0 + \text{\% change}) \tag{16.8}$$

■ ***Example 16.7***

Problem: Based on the available information for the past 12 months, the operator projects that the effluent flow rate will increase by 7.5% during the next year. If the average daily flow has been 4.5 MGD, what will be the projected flow for the next 12 months?

Solution:

$$\text{Projected flow} = 4.5\text{ MGD}\times(1.0 + 0.075) = 4.84\text{ MGD}$$

■ ***Example 16.8***

Problem: The plant currently uses 90 lb of chlorine per day. The town wishes to order enough chlorine to supply the plant for 4 months (assume 31 days per month). How many pounds of chlorine should be ordered to provide the needed supply?

Solution:

$$\text{Chlorine Required (lb)} = \text{Feed Rate (lb/day)} \times \text{No. of Days Required}$$

$$\text{Chlorine Required} = 90\ \text{lb/day} \times 124\ \text{days} = 11{,}160\ \text{lb}$$

Note: In some instances, projections for flow or dose changes are not available, but the plant operator wishes to include an extra amount of chlorine as a safety factor. This safety factor can be stated as a specific quantity or as a percentage of the projected usage. The safety factor as a specific quantity can be expressed as total required Cl_2 = chlorine required (lb) + safety factor.

Note: Because chlorine is only shipped in full containers, unless asked specifically for the amount of chlorine actually required or used during a specified period, all decimal parts of a cylinder are rounded up to the next highest number of full cylinders.

16.3 CHAPTER REVIEW QUESTIONS

16.1 Explain the difference between disinfection and sterilization.

16.2 To be effective enough, chlorine must be added to satisfy the ____________ and produce a ____________ mg/L ____________ for at least ____________ minutes at design flow rates.

16.3 Elemental chorine is ____________ in color and is ____________ times heavier than air.

16.4 Why is it necessary to take safety precautions when working with chlorine?

16.5 You are currently adding 400 lb of chlorine per day to a wastewater flow of 5.55 MGD. What is the chlorine dose in mg/L?

16.6 The chlorine dose is 8.22 mg/L. If the residual is 1.10 mg/L, the chlorine demand is ____________.

16.7 Why is dechlorination required to be installed (in any facilities) following chlorination for disinfection?

16.8 A plant adds 350 lb per day of dry hypochlorite powder to the plant effluent. The hypochlorite powder is 42% available chlorine. What is the chlorine feed rate in pounds per day?

16.9 A plant uses liquid HTH, which is 69% available chlorine and has a specific gravity of 1.18. The required feed rate to comply with the plant's discharge permit total residual chlorine limit is 290 lb/day. What is the required flow rate for the HTH solution in gallons per day?

16.10 A plant currently uses 45.7 lb of chlorine per day. Assuming the chlorine usage will increase by 10% during the next year, how many 2000-lb cylinders of chlorine will be needed for the year (365 days)?

16.11 Why are chlorine additions to critical waters, such as natural trout streams, prohibited?

CHAPTER 17

SOLIDS HANDLING

17.1 INTRODUCTION

Key Point: *Sludge* is the commonly accepted name for wastewater solids; however, if wastewater sludge is used for beneficial reuse (e.g., as a soil amendment or fertilizer), it is commonly referred to as *biosolids*.

The wastewater treatment unit processes described to this point remove solids and biochemical oxygen demand (BOD) from the wastestream before the liquid effluent is discharged to its receiving waters. What remains to be disposed of is a mixture of solids and wastes, called *process residuals*, more commonly referred to as *sludge* or *biosolids*. The most costly and complex aspect of wastewater treatment can be the collection, processing, and disposal of sludge, as the quantity of sludge produced may be as high as 2% of the original volume of wastewater, depending somewhat on the treatment process being used. Because sludge can have a water content as high as 99% and because the cost of disposal will be related to the volume of sludge being processed, one of the primary goals of sludge treatment is to separate as much of the water from the solids as possible (along with stabilizing it so it is no longer objectionable or environmentally damaging). Sludge treatment methods may be designed to accomplish both of these purposes.

Note: Sludge treatment methods are generally divided into three major categories: thickening, stabilization, and dewatering. Many of these processes include complex sludge treatment methods, such as heat treatment, rotary vacuum filtration, and incineration.

17.1.1 Sludge: Background Information

When we speak of *sludge* or *biosolids*, we are speaking of the same material; each is defined as the suspended solids removed from wastewater during sedimentation and then concentrated for further treatment and disposal or reuse. The difference between *sludge* and *biosolids* lies is in the way they are managed. Sludge is typically considered to be wastewater solids that are disposed of, whereas biosolids is the same substance managed for beneficial reuse (e.g., for land application as a soil amendment, such as biosolids compost). As wastewater treatment standards have become more stringent because of increasing environmental regulations, the volume of wastewater sludge has increased. Note also that, before sludge can be disposed of or reused, it requires some form of treatment to reduce its volume, to stabilize it, and to inactivate pathogenic organisms.

Note: The task of disposing, treating, or reusing wastewater solids is called *sludge* or *biosolids management.*

Sludge forms initially as a 3 to 7% suspension of solids; with each person typically generating about 4 gallons of sludge per week, the total quantity generated each day, week, month, and year is significant. Because of the volume and nature of the material, sludge management is a major factor in the design and operation of all water pollution control plants.

Note: Wastewater solids account for more than half of the total costs in a typical secondary treatment plant.

17.2 SOURCES OF SLUDGE

Wastewater sludge is generated in primary, secondary, and chemical treatment processes. In primary treatment, the solids that float or settle are removed. The floatable material makes up a portion of the solid waste known as *scum*. Scum is not normally considered sludge; however, it should be disposed of in an environmentally sound way. The settleable material that collects on the bottom of the clarifier is known as *primary sludge*. Primary sludge can also be referred to as *raw sludge* because it has not undergone decomposition. Raw primary sludge from a typical domestic facility is quite objectionable and has a high percentage of water, two characteristics that make handling difficult.

Those solids not removed in the primary clarifier are carried out of the primary unit. These solids are known as *colloidal suspended solids*. The secondary treatment system (e.g., trickling filter, activated sludge) is designed to change those colloidal solids into settleable solids that can be removed. Once in the settleable form, these solids are removed in the secondary clarifier. The sludge at the bottom of the secondary clarifier is called *secondary sludge.* Secondary sludges are light and fluffy and more difficult to process than primary sludges—in short, secondary sludges do not dewater well.

The addition of chemicals and various organic and inorganic substances prior to sedimentation and clarification may increase the solids capture and reduce the amount of solids lost in the effluent. This *chemical addition* results in the formation of heavier solids, which trap

TABLE 17.1 TYPICAL WATER CONTENT OF SLUDGES

Water Treatment Process	% Moisture of Sludge	lb Water/lb Sludge Solids Generated
Primary sedimentation	95	19
Trickling filter		
Humus, low rate	93	13.3
Humus, high rate	97	32.3
Activated sludge	99	99

Source: USEPA, *Operational Manual: Sludge Handling and Conditioning*, EPA-430/9-78-002, U.S. Environmental Protection Agency, Washington, D.C., 1978.

the colloidal solids or convert dissolved solids to settleable solids. The resultant solids are known as *chemical sludges*. As chemical usage increases, so does the quantity of sludge that must be handled and disposed of. Chemical sludges can be very difficult to process; they do not dewater well and contain lower percentages of solids.

17.3 SLUDGE CHARACTERISTICS

The composition and characteristics of sewage sludge vary widely and can change considerably with time. Notwithstanding these facts, the basic components of wastewater sludge remain the same. The only variations occur in the quantity of the various components as the type of sludge and the process from which it originated change. The main component of all sludges is *water*. Prior to treatment, most sludge contains 92 to over 99% water (see Table 17.1). This high water content makes sludge handling and processing extremely costly in terms of both money and time. Sludge handling may represent up to 40% of the capital costs and 50% of the operation costs of a treatment plant. As a result, the importance of optimum design for handling and disposal of sludge cannot be overemphasized. The water content of the sludge is present in a number of different forms. Some forms can be removed by several different sludge treatment processes, thus allowing some flexibility in choosing the optimum sludge treatment and disposal methods.

The forms of water and their approximate percentages for a typical activated sludge are shown in Table 17.2. The forms of water associated with sludges include:

- *Free water*—Water that is not attached to sludge solids in any way. This can be removed by simple gravitational settling.
- *Floc water*—Water that is trapped within the floc and travels with it. Its removal is possible by mechanical dewatering.
- *Capillary water*—Water that adheres to the individual particles and can be squeezed out of shape and compacted.
- *Particle water*—Water that is chemically bound to the individual particles and cannot be removed without inclination.

TABLE 17.2 DISTRIBUTION OF WATER IN TYPICAL ACTIVATED SLUDGE

Water Type	% Volume
Free water	75
Floc water	20
Capillary water	2
Particle water	2.5
Solids	0.5
Total	100

Source: USEPA, *Operational Manual: Sludge Handling and Conditioning*, EPA-430/9-78-002, U.S. Environmental Protection Agency, Washington, D.C., 1978.

From a public health standpoint, the second and probably more important component of sludge is the *solids matter.* Although representing a small portion of the total mixture, these solids are extremely unstable. Wastewater solids can be classified into two categories based on their origin—organic and inorganic. *Organic solids* in wastewater, simply put, are materials that were at one time alive and will burn or volatilize at 550°C after 15 minutes in a muffle furnace. The percent organic material within sludge will determine how unstable it is.

The inorganic material within sludge will determine how stable it is. The *inorganic solids* are those solids that were never alive and will not burn or volatilize at 550°C after 15 minutes in a muffle furnace. Inorganic solids are generally not subject to breakdown by biological action and are considered stable. Certain inorganic solids, however, can create problems when related to the environment—for example, heavy metals such as copper, lead, zinc, mercury, and others. These can be extremely harmful if discharged. Organic solids may be subject to biological decomposition in either an aerobic or anaerobic environment. Decomposition of organic matter (with its production of objectionable byproducts) and the possibility of toxic organic solids within the sludge compound the problems of sludge disposal.

Before moving on to a discussion of the fundamentals of sludge treatment methods, it is important to cover sludge pumping calculations. It is difficult (if not impossible) to treat the sludge unless it is pumped to the specific sludge treatment process.

17.4 SLUDGE PUMPING CALCULATIONS

While on shift, wastewater operators are often called upon to make various process control calculations. An important calculation involves sludge pumping. The sludge pumping calculations the operator may be required to make during plant operations (and should be known for licensure examinations) are covered in this section.

17.4.1 Estimating Daily Sludge Production

The calculation to estimate the required sludge pumping rate establishes an initial pumping rate or allows evaluation of the adequacy of the current withdrawal rate:

$$\text{Estimated Pump Rate (gpm)} = \frac{\left[\begin{array}{c}\text{(Influent TSS Conc.} - \text{Effluent TSS Conc.)} \\ \times \text{Flow (MGD)} \times 8.34\ \text{lb/gal}\end{array}\right]}{\%\ \text{Solids in Sludge} \times 8.34\ \text{lb/gal} \times 1440\ \text{min/day}} \tag{17.1}$$

■ ***Example 17.1***

Problem: Sludge withdrawn from a primary settling tank contains 1.4% solids. The unit influent contains 285 mg/L total suspended solids (TSS) and the effluent contains 140 mg/L TSS. If the influent flow rate is 5.55 MGD, what is the estimated sludge withdrawal rate in gallons per minute (assuming the pump operates continuously)?

Solution:

$$\text{Sludge Withdrawal Rate} = \frac{(285\ \text{mg/L} - 140\ \text{mg/L}) \times 5.55\ \text{MGD} \times 8.34\ \text{lb/gal}}{0.014 \times 8.34\ \text{lb/gal} \times 1440\ \text{min/day}}$$

$$= 40\ \text{gpm}$$

17.4.2 Sludge Pumping Time

The sludge pumping time is the total time the pump operates (in minutes) over a 24-hr period.

$$\text{Pump Operating Time} = \text{Time/Cycle (min)} \times \text{Frequency (cycles/day)} \tag{17.2}$$

Note: Use the following information for Example 17.2 through Example 17.7:

Operating time = 15 min/cycle
Frequency = 24 cycles/day
Pump rate = 120 gpm
Solids = 3.70%
Volatile matter (VM) = 66%

■ ***Example 17.2***

Problem: What is the pump operating time?

Solution:

$$\text{Pump Operating Time} = 15\ \text{min/hr} \times 24\ \text{cycles/day} = 360\ \text{min/day}$$

17.4.3 Sludge Pumped per Day in Gallons

$$\text{Sludge (gpd)} = \text{Operating Time (min/day)} \times \text{Pump Rate (gpm)} \qquad (17.3)$$

■ ***Example 17.3***

Problem: What is the sludge pumped per day in gallons?

Solution:

$$\text{Sludge} = 360 \text{ min/day} \times 120 \text{ gpm} = 43{,}200 \text{ gpd}$$

17.4.4 Sludge Pumped per Day in Pounds

$$\text{Sludge (lb/day)} = \text{Sludge Pumped (gal)} \times 8.34 \text{ lb/gal} \qquad (17.4)$$

■ ***Example 17.4***

Problem: What is the sludge pumped in pounds per day?

Solution:

$$\text{Sludge} = 43{,}200 \text{ gpd} \times 8.34 \text{ lb/gal} = 360{,}300 \text{ lb/day}$$

17.4.5 Solids Pumped per Day in Pounds

$$\text{Solids Pumped (lb/day)} = \text{Sludge Pumped (gpd)} \times \text{\% Solids} \qquad (17.5)$$

■ ***Example 17.5***

Problem: What are the solids pumped per day?

Solution:

$$\text{Solids Pumped} = 360{,}300 \text{ lb/day} \times 0.0370 = 13{,}331 \text{ lb/day}$$

17.4.6 Volatile Matter Pumped per Day in Pounds

$$\text{Volatile Matter (lb/day)} = \text{Solids Pumped (lb/day)} \times \text{\%VM} \qquad (17.6)$$

■ ***Example 17.6***

Problem: What is the volatile matter in pounds per day?

Solution:

$$\text{Volatile Matter} = 13{,}331 \text{ lb/day} \times 0.66 = 8798 \text{ lb/day}$$

Note: If you wish to calculate the pounds of solids or the pounds of volatile solids removed per day, the individual equations demonstrated above can be combined into a single calculation:

$$\begin{aligned}\text{Solids (lb/day)} &= \text{Pump Time (min/cycle)}\\ &\quad\times\text{Frequency (cycles/day)}\times\text{Rate (gpm)}\\ &\quad\times 8.34\ \text{lb/gal}\times\%\ \text{Solids}\\ \text{Volatile Matter (lb/day)} &= \text{Pump Time (min/cycle)}\\ &\quad\times\text{Frequency (cycles/day)}\times\text{Rate (gpm)}\\ &\quad\times 8.34\ \text{lb/gal}\times\%\ \text{solids}\times\%\text{VM}\end{aligned}\tag{17.7}$$

■ ***Example 17.7***

$$\begin{aligned}\text{Solids} &= 15\ \text{min/cycle}\times 24\ \text{cycles/day}\times 120\ \text{gpm}\times 8.34\ \text{lb/gal}\times 0.0370\\ &= 13{,}331\ \text{lb/day}\end{aligned}$$

$$\begin{aligned}\text{VM} &= 15\ \text{min/cycle}\times 24\ \text{cycles/day}\times 120\ \text{gpm}\times 8.34\ \text{lb/gal}\times 0.0370\times .66\\ &= 8798\ \text{lb/day}\end{aligned}$$

17.4.7 Sludge Production in Pounds per Million Gallons

A common method of expressing sludge production is in pounds of sludge per million gallons of wastewater treated:

$$\text{Sludge (lb/MG)} = \frac{\text{Total Sludge Production (lb)}}{\text{Total Wastewater Flow (MG)}}\tag{17.8}$$

■ ***Example 17.8***

Problem: Records show that the plant has produced 85,000 gal of sludge during the past 30 days. The average daily flow for this period was 1.2 MGD. What was the sludge production in pounds per million gallons?

Solution:

$$\text{Sludge} = \frac{85{,}000\ \text{gal}\times 8.34\ \text{lb/gal}}{1.2\ \text{MGD}\times 30\ \text{days}} = 19{,}692\ \text{lb/MG}$$

17.4.8 Sludge Production in Wet Tons per Year

Sludge production can also be expressed in terms of the amount of sludge (water and solids) produced per year. This is normally expressed in wet tons per year:

$$\text{Sludge (wet tons/yr)} = \frac{\begin{bmatrix}\text{Sludge Produced (lb/MG)}\\ \times\text{Avg. Daily Flow (MGD)}\times 365\ \text{days/yr}\end{bmatrix}}{2000\ \text{lb/ton}}\tag{17.9}$$

■ ***Example 17.9***

Problem: A plant is currently producing sludge at the rate of 16,500 lb/MG. The current average daily wastewater flow rate is 1.5 MGD. What will be the total amount of sludge produced per year in wet tons per year?

Solution:

$$\text{Sludge (wet tons/yr)} = \frac{16{,}500\ \text{lb/MG} \times 1.5\ \text{MGD} \times 365\ \text{days/yr}}{2000\ \text{lb/ton}}$$

The release of wastewater solids without proper treatment could result in severe damage to the environment. Obviously, we must have a system to treat the volume of material removed as sludge throughout the system. Release without treatment would defeat the purpose of environmental protection. A design engineer can choose from many processes when developing sludge treatment systems. No matter what the system or combination of systems chosen, the ultimate purpose will be the same: the conversion of wastewater sludges into a form that can be handled economically and disposed of without damage to the environment or creating nuisance conditions. Leaving either condition unmet will require further treatment. The degree of treatment will generally depend on the proposed method of disposal. Sludge treatment processes can be classified into a number of major categories. In this handbook, we discuss the processes of thickening, digestion (or stabilization), dewatering, incineration, and land application. Each of these categories has then been further subdivided according to the specific processes that are used to accomplish sludge treatment. As mentioned, the importance of adequate, efficient sludge treatment cannot be overlooked when designing wastewater treatment facilities. The inadequacies of a sludge treatment system can severely affect the overall performance capabilities of a plant. The inability to remove and process solids as fast as they accumulate in the process can lead to the discharge of large quantities of solids to receiving waters. Even with proper design and capabilities in place, no system can be effective unless it is properly operated. Proper operation requires proper operator performance. Proper operator performance begins and ends with proper training.

17.5 SLUDGE THICKENING

The solids content of primary, activated, trickling filter, or even mixed sludge (i.e., primary plus activated sludge) varies considerably, depending on the characteristics of the sludge. Note that the sludge removal and pumping facilities and the method of operation also affect the solids content. *Sludge thickening* (or *concentration*) is a unit process used to increase the solids content of the sludge by removing a portion of the liquid fraction. By increasing the solids content, more economical treatment of the sludge can be effected. Sludge thickening processes include:

- Gravity thickeners
- Flotation thickeners
- Solids concentrators

17.5.1 Gravity Thickening

Gravity thickening is most effective on primary sludge. In operation, solids are withdrawn from primary treatment (and sometimes secondary treatment) and are pumped to the thickener. The solids buildup in the thickener forms a solids blanket on the bottom. The weight of the blanket compresses the solids on the bottom and squeezes the water out. By adjusting the blanket thickness, the percent solids in the underflow (solids withdrawn from the bottom of the thickener) can be increased or decreased. The supernatant (clear water) that rises to the surface is returned to the wastewater flow for treatment. Daily operations of the thickening process include pumping, observation, sampling and testing, process control calculations, maintenance, and housekeeping.

Note: The equipment employed in thickening depends on the specific thickening processes used.

Equipment used for gravity thickening consists of a thickening tank, which is similar in design to the settling tank used in primary treatment. Generally the tank is circular and provides equipment for continuous solids collection. The collector mechanism uses heavier construction than that in a settling tank because the solids being moved are more concentrated. The gravity thickener pumping facilities (i.e., pump and flow measurement) are used for withdrawal of thickened solids.

The solids concentrations achieved by gravity thickeners are typically 8 to 10% solids from primary underflow, 2 to 4% solids from waste activated sludge, 7 to 9% solids from trickling filter residuals, and 4 to 9% from combined primary and secondary residuals. The performance of gravity thickening processes depends on various factors, including:

- Type of sludge
- Condition of influent sludge
- Temperature
- Blanket depth
- Solids loading
- Hydraulic loading
- Solids retention time
- Hydraulic detention time

17.5.2 Flotation Thickening

Flotation thickening is used most efficiently for waste sludges from suspended-growth biological treatment processes, such as the activated sludge process. Recycled water from the flotation thickener is aerated under pressure. During this time, the water absorbs more air than it would under normal pressure. Chemical additives (if used) are mixed with the recycled water flow. When the mixture enters the flotation thickener, the excess air is released in the form of fine bubbles. These bubbles become attached to the solids and lift them toward the surface.

The accumulation of solids on the surface is the *float cake*. As more solids are added to the bottom of the float cake, it becomes thicker and water drains from the upper levels of the cake. The solids are then moved up an inclined plane by a scraper and discharged. The supernatant leaves the tank below the surface of the float solids and is recycled or returned to the wastestream for treatment. Typically, flotation thickener performance is 3 to 5% solids for waste activated sludge with polymer addition and 2 to 4% solids without polymer addition.

The flotation thickening process requires pressurized air, a vessel for mixing the air with all or part of the process residual flow, a tank where the flotation process occurs, and solids collector mechanisms to remove the float cake (solids) from the top of the tank and accumulated heavy solids from the bottom of the tank. The process normally requires chemicals to be added to improve separation, so chemical mixing equipment, storage tanks, and metering equipment to dispense the chemicals at the desired dose are required.

The performance of dissolved air thickening process depends on:

- Bubble size
- Solids loading
- Sludge characteristics
- Chemical selection
- Chemical dose

17.5.3 Solids Concentrators

Solids concentrators (belt thickeners) usually consist of a mixing tank, chemical storage and metering equipment, and a moving porous belt. In operation, the process residual flow is chemically treated and then spread evenly over the surface of the moving porous belt. As the flow is carried down the belt (similar to a conveyor belt) the solids are mechanically turned or agitated and water drains through the belt. This process is primarily used in facilities where space is limited.

17.5.4 Process Calculations (Gravity/Dissolved Air Flotation)

Sludge thickening calculations are based on the concept that the solids in the primary or secondary sludge are equal to the solids in the thickened sludge. Assuming that a negligible amount of solids is lost in the thickener overflow, the solids are the same. Note that the water is removed to thicken the sludge, resulting in higher percent solids.

17.5.4.1 Estimating Daily Sludge Production

The calculation that follows provides a method to establish an initial pumping rate or to evaluate the adequacy of the current pump rate:

$$\begin{array}{l}\text{Est. Pump}\\ \text{Rate (gpm)}\end{array} = \frac{\left[\begin{array}{c}\text{(Influent TSS Conc.} - \text{Effluent TSS Conc.)}\\ \times \text{Flow (MGD)} \times 8.34\text{ lb/gal}\end{array}\right]}{\%\text{ Solids in Sludge} \times 8.34\text{ lb/gal} \times 1440\text{ min/day}} \qquad (17.10)$$

■ ***Example 17.10***

Problem: The sludge withdrawn from the primary settling tank contains 1.5% solids. The unit influent contains 280 mg/L TSS, and the effluent contains 141 mg/L. If the influent flow rate is 5.55 MGD, what is the estimated sludge withdrawal rate in gallons per minute (assuming the pump operates continuously)?

Solution:

$$\text{Sludge Withdrawal Rate} = \frac{(280\text{ mg/L} - 141\text{ mg/L}) \times 5.55\text{ MGD} \times 8.34\text{ lb/gal}}{0.015 \times 8.34\text{ lb/gal} \times 1440\text{ min/day}}$$

$$= 36\text{ gpm}$$

17.5.4.2 Surface Loading Rate (gpd/ft^2)

Surface loading rate (surface settling rate) is hydraulic loading—the amount of sludge applied per square foot of gravity thickener.

$$\text{Surface Loading (gpd/ft}^2\text{)} = \frac{\text{Sludge Applied to the Thickener (gpd)}}{\text{Thickener Area (ft}^2\text{)}} \qquad (17.11)$$

■ ***Example 17.11***

Problem: A 70-ft-diameter gravity thickener receives 32,000 gpd of sludge. What is the surface loading in gallons per day per square foot?

Solution:

$$\text{Surface Loading} = \frac{32{,}000\text{ gpd}}{0.785 \times 70\text{ ft} \times 70\text{ ft}} = 8.32\text{ gpd/ft}^2$$

17.5.4.3 Solids Loading Rate (lb/day/ft^2)

The solids loading rate is the pounds of solids per day being applied to 1 square foot of tank surface area. The calculation uses the surface area of the bottom of the tank. It assumes that the floor of the tank is flat and has the same dimensions as the surface:

$$\text{Solids Loading Rate (lb/day/ft}^2\text{)} = \frac{\left[\begin{array}{c}\text{\% Sludge Solids} \times \text{Sludge Flow (gpd)} \\ \times 8.34 \text{ lb/gal}\end{array}\right]}{\text{Thickener Area (ft}^2\text{)}} \tag{17.12}$$

■ ***Example 17.12***

Problem: The thickener influent contains 1.6% solids. The influent flow rate is 39,000 gpd. The thickener is 50 ft in diameter and 10 ft deep. What is the solids loading in pounds per day per square foot?

Solution:

$$\text{Solids Loading Rate} = \frac{0.016 \times 39{,}000 \text{ gpd} \times 8.34 \text{ lb/gal}}{0.785 \times 50 \text{ ft} \times 50 \text{ ft}} = 2.7 \text{ lb/day/ft}^2$$

17.5.4.4 Concentration Factor

The concentration factor (CF) represents the increase in concentration resulting from the thickener:

$$\text{Concentration Factor} = \frac{\text{Thickened Sludge Concentration (\%)}}{\text{Influent Sludge Concentration (\%)}} \tag{17.13}$$

■ ***Example 17.13***

Problem: The influent sludge contains 3.5% solids. The thickened sludge solids concentration is 7.7%. What is the concentration factor?

Solution:

$$\text{Concentration Factor} = \frac{7.7\%}{3.5\%} = 2.2$$

17.5.4.5 Air-to-Solids Ratio

The air-to-solids ratio is the ratio between the pounds of air being applied and the pounds of solids entering the thickener.

$$\text{Air/Solids Ratio} = \frac{\text{Air Flow (ft}^3\text{/min)} \times 0.075 \text{ lb/ft}^3}{\text{Sludge Flow (gpm)} \times \text{\% Solids} \times 8.34 \text{ lb/gal}} \tag{17.14}$$

■ ***Example 17.14***

Problem: The sludge pumped to the thickener is 0.85% solids. The airflow is 13 cfm. What is the air-to-solids ratio if the current sludge flow rate entering the unit is 50 gpm?

Solution:

$$\text{Air-to-Solids Ratio} = \frac{13 \text{ cfm} \times 0.075 \text{ lb/ft}}{50 \text{ gpm} \times 0.0085 \times 8.34 \text{ lb/gal}} = 0.28$$

17.5.4.6 Recycle Flow in Percent

The amount of recycle flow can be expressed as a percent:

$$\text{Recycle Flow (\%)} = \frac{\text{Recycle Flow Rate (gpm)} \times 100}{\text{Sludge Flow (gpm)}} \tag{17.15}$$

■ ***Example 17.15***

Problem: The sludge flow to the thickener is 80 gpm. The recycle flow rate is 140 gpm. What is the percent recycle flow?

Solution:

$$\text{Recycle Flow} = \frac{140 \text{ gpm} \times 100}{80 \text{ gpm}} = 175\%$$

17.6 SLUDGE STABILIZATION

The purpose of *sludge stabilization* is to reduce volume, stabilize the organic matter, and eliminate pathogenic organisms to permit reuse or disposal. The equipment required for stabilization depends on the specific process used. Sludge stabilization processes include:

- Aerobic digestion
- Anaerobic digestion
- Composting
- Lime stabilization
- Wet air oxidation (heat treatment)
- Chemical oxidation (chlorine oxidation)
- Incineration

17.6.1 Aerobic Digestion

Equipment used for *aerobic digestion* consists of an aeration tank (digester), which is similar in design to the aeration tank used for the activated sludge process. Either diffused or mechanical aeration equipment is necessary to maintain the aerobic conditions in the tank. Solids and supernatant removal equipment is also required.

TABLE 17.3 AEROBIC DIGESTER NORMAL OPERATING LEVELS

Parameter	Normal Levels
Detention time (days)	10–20
Volatile solids loading (lb/ft^3/day)	0.1–0.3
Dissolved oxygen (mg/L)	1.0
pH	5.9–7.7
Volatile solids reduction (%)	40–50

Process residuals (sludge) are added to the digester and aerated to maintain a dissolved oxygen (DO) concentration of 1.0 mg/L. Aeration also ensures that the tank contents are well mixed. Generally, aeration continues for approximately 20 days' retention time. Periodically, aeration is stopped and the solids are allowed to settle. Sludge and the clear liquid supernatant are withdrawn as needed to provide more room in the digester. When no additional volume is available, mixing is stopped for 12 to 24 hours before solids are withdrawn for disposal. Process control testing should include alkalinity, pH, percent solids, percent volatile solids for influent sludge, supernatant, digested sludge, and digester contents. Normal operating levels for an aerobic digester are listed in Table 17.3. A typical operational problem associated with an aerobic digester is pH control. When pH drops, for example, this may indicate normal biological activity or low influent alkalinity. This problem is corrected by adding alkalinity (e.g., lime, bicarbonate).

17.6.2 Process Control Calculations for an Aerobic Digester

Wastewater operators who operate aerobic digesters must make certain process control calculations. Moreover, licensing examinations typically include aerobic digester problems for determining volatile solids loading, digestion time, digester efficiency, and pH adjustment. These process control calculations are explained in the following sections.

17.6.2.1 Volatile Solids Loading

Volatile solids loading for the aerobic digester is expressed in pounds of volatile solids entering the digester per day per cubic foot of digester capacity:

$$\text{Volatile Solids Loading} = \frac{\text{Volatile Solids Added (lb/day)}}{\text{Digester Volume (ft}^3\text{)}} \tag{17.16}$$

■ ***Example 17.16***

Problem: The aerobic digester is 25 ft in diameter and has an operating depth of 24 ft. The sludge added to the digester daily contains 1350 lb of volatile solids. What is the volatile solids loading in pounds per day per cubic foot?

Solution:

$$\text{Volatile Solids Loading} = \frac{1350 \text{ lb/day}}{.785 \times 25 \text{ ft} \times 25 \text{ ft} \times 24 \text{ ft}} = 0.11 \text{ lb/day/ft}^3$$

17.6.2.2 Digestion Time (Days)

Digestion time is the theoretical time the sludge remains in the aerobic digester:

$$\text{Digestion Time (days)} = \frac{\text{Digester Volume (gal)}}{\text{Sludge Added (gpd)}} \tag{17.17}$$

■ *Example 17.17*

Problem: Digester volume is 240,000 gal. Sludge is being added to the digester at the rate of 13,500 gpd. What is the digestion time in days?

Solution:

$$\text{Digestion Time} = \frac{240{,}000 \text{ gal}}{13{,}500 \text{ gpd}} = 17.8 \text{ days}$$

17.6.2.3 Digester Efficiency (Percent Reduction)

To determine digester efficiency or the percent reduction, a two-step procedure is required. First the percent volatile matter reduction must be calculated and then the percent moisture reduction:

1. *Volatile matter*—Because of the changes occurring during sludge digestion, the calculation used to determine percent volatile matter reduction is more complicated:

$$\%\text{VM Reduction} = \frac{(\%\text{VM}_{\text{in}} - \%\text{VM}_{\text{out}}) \times 100}{\%\text{VM}_{\text{in}} - (\%\text{VM}_{\text{in}} \times \%\text{VM}_{\text{out}})} \tag{17.18}$$

■ *Example 17.18*

Problem: Using the digester data provided below, determine the percent volatile matter reduction for the digester.

Raw sludge volatile matter = 71%

Digested sludge volatile matter = 53%

Solution:

$$\%\text{VM Reduction} = \frac{(0.71 - 0.53) \times 100}{0.71 - (0.71 \times 0.53)} = 53.9, \text{ or } 54\%$$

2. *Moisture reduction*:

$$\text{\% Moisture Reduction} = \frac{(\text{\% Moisture}_{\text{in}} - \text{\% Moisture}_{\text{out}}) \times 100}{\text{\% Moisture}_{\text{in}} - (\text{\% Moisture}_{\text{in}} \times \text{\% Moisture}_{\text{out}})} \quad (17.19)$$

■ *Example 17.19*

Problem: Using the digester data provided below, determine the percent moisture reduction for the digester.

Note: % Moisture = 100% – Percent Solids

Solution:

Raw sludge
  Percent solids = 6%
  Percent moisture = 100% – 6% = 94%
Digested sludge
  Percent solids = 15%
  Percent moisture = 100% – 15% = 85%

$$\text{\% Moisture Reduction} = \frac{(0.94 - 0.85) \times 100}{0.94 - (0.94 \times 0.85)} = 64\%$$

17.6.2.4 pH Adjustment

Occasionally, the pH of the aerobic digester will fall below the levels required for good biological activity. When this occurs, the operator must perform a laboratory test to determine the amount of alkalinity required to raise the pH to the desired level. The results of the lab test results must then be converted to the actual quantity of chemical (usually lime) required by the digester:

$$\begin{array}{c}\text{Chemical}\\ \text{Required (lb)}\end{array} = \frac{\text{Chemical Used (mg)} \times \text{Digester Vol. (MG)} \times 3.785\text{ L/gal}}{\text{Sample Vol. (L)} \times 454\text{ g/lb} \times 1000\text{ mg/g}} \quad (17.20)$$

■ *Example 17.20*

Problem: The lab reports that it took 225 mg of lime to increase the pH of a 1-L sample of the aerobic digester contents to pH 7.2. The digester volume is 240,000 gal. How many pounds of lime will be required to increase the digester pH to 7.2?

Solution:

$$\text{Chemical Required} = \frac{225\text{ mg} \times 240{,}000\text{ gal} \times 3.785\text{ L/gal}}{1\text{ L} \times 454\text{ g/lb} \times 1000\text{ mg/g}} = 450\text{ lb}$$

17.6.3 Anaerobic Digestion

Key Point: In an anaerobic digester, the entrance of air should be prevented because air mixing with the gas produced in the digester could create an explosive mixture.

Anaerobic digestion is the traditional method of sludge stabilization. It involves using bacteria that thrive in the absence of oxygen. It is slower than aerobic digestion but has the advantage that only a small percentage of the wastes are converted into new bacterial cells. Instead, most of the organics are converted into carbon dioxide and methane gas. Equipment used in anaerobic digestion includes a sealed digestion tank with either a fixed or a floating cover, heating and mixing equipment, gas storage tanks, solids and supernatant withdrawal equipment, and safety equipment (e.g., vacuum relief, pressure relief, flame traps, explosion-proof electrical equipment).

Process residual (thickened or unthickened sludge) is pumped into the sealed digester. The organic matter digests anaerobically by a two-stage process. Sugars, starches, and carbohydrates are converted to volatile acids, carbon dioxide, and hydrogen sulfide. The volatile acids are then converted to methane gas. This operation can occur in a single tank (single stage) or in two tanks (two stages).

In a single-stage system, supernatant and digested solids must be removed whenever flow is added. In a two-stage operation, solids and liquids from the first stage flow into the second stage each time fresh solids are added. Supernatant is withdrawn from the second stage to provide additional treatment space. Periodically, solids are withdrawn for dewatering or disposal. The methane gas produced in the process may be used for many plant activities.

Note: The primary purpose of a secondary digester is to allow for solids separation.

Various performance factors affect the operation of the anaerobic digester; for example, percent volatile matter (%VM) in raw sludge, digester temperature, mixing, volatile acids-to-alkalinity ratio, feed rate, percent solids in raw sludge, and pH are all important operational parameters that the operator must monitor. Along with being able to recognize normal/abnormal anaerobic digester performance parameters, wastewater operators must also know and understand normal operating procedures. Normal operating procedures include sludge additions, supernatant withdrawal, sludge withdrawal, pH control, temperature control, mixing, and safety requirements. Important performance parameters are listed in Table 17.4.

17.6.3.1 Sludge Additions

Sludge must be pumped (in small amounts) several times each day to achieve the desired organic loading and optimum performance. Keep in mind that, in fixed-cover operations, additions must be balanced by withdrawals; if not, structural damage occurs.

TABLE 17.4 SLUDGE PARAMETERS FOR AN ANAEROBIC DIGESTER

Raw Sludge Solids	Impact
<4% solids	Loss of alkalinity Decreased sludge retention time Increased heating requirements Decreased volatile acids-to-alkalinity ratio
4 to 8% solids	Normal operation
>8% solids	Poor mixing Organic overloading Decreased volatile acids-to-alkalinity ratio

17.6.3.2 Supernatant Withdrawal

Supernatant withdrawal must be controlled for maximum sludge retention time. When sampling, sample all drawoff points and select the level with the best quality.

17.6.3.3 Sludge Withdrawal

Digested sludge is withdrawn only when necessary; always leave at least 25% seed.

17.6.3.4 pH Control

pH should be adjusted to maintain 6.8 to 7.2 pH by adjusting feed rate, sludge withdrawal, or alkalinity additions. The buffer capacity of an anaerobic digester is indicated by the volatile acids-to-alkalinity ratio. Decreases in alkalinity cause a corresponding increase in the ratio.

17.6.3.5 Temperature Control

If the digester is heated, the temperature must be controlled to a normal temperature range of 90 to 95°F. Never adjust the temperature by more than 1°F per day.

17.6.3.6 Mixing

If the digester is equipped with mixers, mixing should be accomplished to ensure that organisms are exposed to food materials.

17.6.3.7 Safety

Anaerobic digesters are inherently dangerous; several catastrophic failures have been recorded. To prevent such failures, safety equipment such as pressure relief and vacuum relief valves, flame traps, condensate traps, and gas collection safety devices are installed. It is important that these critical safety devices be checked and maintained for proper operation.

Note: Because of the inherent danger involved with working inside anaerobic digesters, they are automatically classified as permit-required confined spaces; therefore, all operations involving internal entry must be made in accordance with the Occupational Safety and Health Administration (OSHA) confined space entry standard.

17.6.4 Process Control Calculations for an Anaerobic Digester

Process control calculations involved with anaerobic digester operation include determining the required seed volume, volatile acids-to-alkalinity ratio, sludge retention time, estimated gas production, volatile matter reduction, and percent moisture reduction in digester sludge. Examples on how to make these calculations are provided in the following sections.

17.6.4.1 Required Seed Volume in Gallons

$$\text{Seed Volume (gal)} = \text{Digester Volume} \times \%\ \text{Seed} \tag{17.21}$$

■ ***Example 17.21***

Problem: The new digester requires a 25% seed to achieve normal operation within the allotted time. If the digester volume is 266,000 gal, how many gallons of seed material will be required?

Solution:

$$\text{Seed Volume} = 266{,}000\ \text{gal} \times 0.25 = 66{,}500\ \text{gal}$$

17.6.4.2 Volatile Acids-to-Alkalinity Ratio

The volatile acids-to-alkalinity ratio can be used to control operation of an anaerobic digester:

$$\text{Ratio} = \frac{\text{Volatile Acids Concentration}}{\text{Alkalinity Concentration}} \tag{17.22}$$

■ ***Example 17.22***

Problem: The digester contains 240 mg/L volatile acids and 1860-mg/L alkalinity. What is the volatile acids-to-alkalinity ratio?

Solution:

$$\text{Volatile Acids-to-Alkalinity Ratio} = \frac{240\ \text{mg/L}}{1860\ \text{mg/L}} = 0.13$$

TABLE 17.5 OPERATING CONDITIONS AND VOLATILE ACIDS-TO-ALKALINITY RATIO

Operating Condition	Volatile Acids-to-Alkalinity Ratio
Optimum	0.1
Acceptable range	0.1–0.3
Percent carbon dioxide in gas increases	0.5
pH decreases	0.8

Note: Increases in the ratio normally indicate a potential change in the operation conditions of the digester, as shown in Table 17.5.

17.6.4.3 Sludge Retention Time

Sludge retention time is the length of time the sludge remains in the digester:

$$\text{Sludge Retention Time (days)} = \frac{\text{Digester Volume (gal)}}{\text{Sludge Volume (gpd)}} \tag{17.23}$$

■ ***Example 17.23***

Problem: Sludge is added to a 525,000-gal digester at the rate of 12,250 gpd. What is the sludge retention time?

Solution:

$$\text{Sludge Retention Time} = \frac{525{,}000\text{ gal}}{12{,}250\text{ gpd}} = 42.9\text{ days}$$

17.6.4.4 Estimated Gas Production in Cubic Feet per Day

The rate of gas production is normally expressed as the volume of gas (ft^3) produced per pound of volatile matter destroyed. The total cubic feet of gas a digester will produce per day can be calculated by:

$$\begin{aligned}\text{Gas Production (ft}^3) &= \text{Volatile Matter in (lb/day)} \times \text{\%VM Reduction}\\ &\times \text{Production Rate (ft}^3\text{/lb)}\end{aligned} \tag{17.24}$$

■ ***Example 17.24***

Problem: The digester receives 11,450 lb of volatile matter per day. Currently, the volatile matter reduction achieved by the digester is 52%. The rate of gas production is 11.2 ft^3 of gas per pound of volatile matter destroyed. What is the estimated gas production in cubic feet per day?

Solution:

$$\text{Est. Gas Production} = 11{,}450 \text{ lb/day} \times 0.52 \times 11.2 \text{ ft}^3/\text{lb} = 66{,}685 \text{ ft}^3/\text{day}$$

17.6.4.5 Percent Volatile Matter Reduction

Because of the changes occurring during sludge digestion, determining the percent volatile matter (%VM) reduction is more complicated:

$$\%\text{VM Reduction} = \frac{(\%\text{VM}_{\text{in}} - \%\text{VM}_{\text{out}}) \times 100}{\%\text{VM}_{\text{in}} - (\%\text{VM}_{\text{in}} \times \%\text{VM}_{\text{out}})} \qquad (17.25)$$

■ *Example 17.25*

Problem: Using the data provided below, determine the percent volatile matter reduction for the digester:

Raw sludge volatile matter = 74%

Digested sludge volatile matter = 55%

Solution:

$$\%\text{VM Reduction} = \frac{(0.74 - 0.55) \times 100}{0.74 - (0.74 \times 0.55)} = 57\%$$

17.6.4.6 Percent Moisture Reduction in Digested Sludge

$$\%\text{ Moisture Reduction} = \frac{(\%\text{ Moisture}_{\text{in}} - \%\text{ Moisture}_{\text{out}}) \times 100}{\%\text{ Moisture}_{\text{in}} - (\%\text{ Moisture}_{\text{in}} \times \%\text{ Moisture}_{\text{out}})} \qquad (17.26)$$

■ *Example 17.26*

Problem: Using the data provide below, determine the percent moisture reduction and percent volatile matter reduction for the digester.

Raw sludge percent solids = 6%

Digested sludge percent solids = 14%

Note: % Moisture = 100% – percent solids.

Solution:

$$\%\text{ Moisture Reduction} = \frac{(0.94 - 0.86) \times 100}{0.94 - (0.94 \times 0.86)} = 61\%$$

17.6.5 Other Sludge Stabilization Processes

Along with aerobic and anaerobic digestion, other sludge stabilization processes include composting, lime stabilization, wet air oxidation, and chemical (chlorine) oxidation. These other stabilization processes are briefly described in this section.

17.6.5.1 Composting

Composting sludge stabilizes the organic matter, reduces volume, and eliminates pathogenic organisms. In a composting operation, dewatered solids are usually mixed with a bulking agent (i.e., hardwood chips) and stored until biological stabilization occurs. The composting mixture is ventilated during storage to provide sufficient oxygen for oxidation and to prevent odors. After the solids are stabilized, they are separated from the bulking agent. The composted solids are then stored for curing and applied to farmlands or other beneficial uses. Expected performance of the composting operation for both percent volatile matter reduction and percent moisture reduction ranges from 40 to over 60%.

17.6.5.2 Lime Stabilization

In lime stabilization, process residuals are mixed with lime to achieve a pH of 12.0. This pH is maintained for at least 2 hr. The treated solids can then be dewatered for disposal or directly land applied.

17.6.5.3 Thermal Treatment

Thermal treatment (or wet air oxidation) subjects sludge to high temperatures and pressure in a closed reactor vessel. The high temperatures and pressure rupture the cell walls of any microorganisms present in the solids and causes chemical oxidation of the organic matter. This process substantially improves dewatering and reduces the volume of material for disposal. It also produces a very high-strength waste, which must be returned to the wastewater treatment system for further treatment.

17.6.5.4 Chlorine Oxidation

Chlorine oxidation also occurs in a closed vessel. In this process chlorine (100 to 1000 mg/L) is mixed with a recycled solids flow. The recycled flow and process residual flow are mixed in the reactor. The solids and water are separated after leaving the reactor vessel. The water is returned to the wastewater treatment system, and the treated solids are dewatered for disposal. The main advantage of chlorine oxidation is that it can be operated intermittently. The main disadvantage is production of extremely low pH and high chlorine content in the supernatant.

17.6.6 Stabilization Operation

Depending on the stabilization process employed, the operational components vary. In general, operations include pumping, observations, sampling and testing, process control calculations, maintenance, and housekeeping. Performance of the stabilization process will also vary with the type of process used. Generally, stabilization processes can produce a 40 to 60% reduction of both volatile matter (organic content) and moisture.

17.6.6.1 Sludge Dewatering

Digested sludge removed from the digester is still mostly liquid. *Sludge dewatering* is used to reduce volume by removing the water to permit easy handling and economical reuse or disposal. Dewatering processes include sand drying beds, vacuum filters, centrifuges, filter presses (belt and plate), and incineration.

17.6.6.2 Sand Drying Beds

Drying beds have been used successfully for years to dewater sludge. Composed of a sand bed (consisting of a gravel base, underdrains, and 8 to 12 inches of filter-grade sand), a drying bed includes an inlet pipe, splash pad containment walls, and a system to return filtrate (water) for treatment. In some cases, the sand beds are covered to protect drying solids from the elements. In operation, solids are pumped to the sand bed and allowed to dry by draining off excess water through the sand and then by evaporation. This is the simplest and least expensive method for dewatering sludge. Moreover, no special training or expertise is required. There are some disadvantages, though, in that drying beds require a great deal of manpower to clean them, they can create odor and insect problems, and they can cause sludge buildup during inclement weather.

17.6.7 Rotary Vacuum Filtration

Rotary vacuum filters have also been used for many years to dewater sludge. The vacuum filter includes filter media (belt, cloth, or metal coils), media support (drum), vacuum system, chemical feed equipment, and conveyor belts to transport the dewatered solids. Chemically treated solids are pumped to a vat or tank in which a rotating drum is submerged. As the drum rotates, a vacuum is applied to the drum. Solids collect on the media and are held there by the vacuum as the drum rotates out of the tank. The vacuum removes additional water from the captured solids. When solids reach the discharge zone, the vacuum is released and the dewatered solids are discharged onto a conveyor belt for disposal. The media are then washed prior to returning to the start of the cycle.

17.6.7.1 Types of Rotary Vacuum Filters

The three principal types of rotary vacuum filters are rotary drum, coil, and belt. The rotary drum filter consists of a cylindrical drum rotating partially submerged in a vat or pan of conditioned sludge. The drum is divided lengthwise into a number of sections that are connected through internal piping to ports in the valve body (plant) at the hub. This plate rotates in contact with a fixed valve plate with similar parts, which are connected to a vacuum supply, a compressed air supply, and an atmosphere vent. As the drum rotates, each section is thus connected to the appropriate service. The coil type of vacuum filter uses two layers of stainless steel coils arranged in corduroy fashion around the drum. After a dewatering cycle, the two layers of springs leave the drum bed and are separated from each other so the cake is lifted off the lower layer and discharged from the upper layer. The coils are then washed and reapplied to the drum. The coil filter has been used successfully for all types of sludges; however, sludges with extremely fine particles or ones that are resistant to flocculation dewater poorly with this system. The media on a belt filter leave the drum surface at the end of the drying zone and pass over a small-diameter discharge roll to aid cake discharge. Washing of the media occurs next. The media are then returned to the drum and to the vat for another cycle. This type of filter normally has a small-diameter curved bar between the point where the belt leaves the drum and the discharge roll. This bar primarily aids in maintaining belt dimensional stability.

17.6.7.1.1 Filter Media

Drum and belt vacuum filters use natural or synthetic fiber materials. On the drum filter, the cloth is stretched and secured to the surface of the drum. In the belt filter, the cloth is stretched over the drum and through the pulley system. The installation of a blanket requires several days. The cloth will (with proper care) last several hundred to several thousand hours, depending on the cloth selected, the conditioning chemical, backwash frequency, and cleaning (i.e., acid bath) frequency.

17.6.7.1.2 Filter Drum

The filter drum is a maze of pipe work running from a metal screen and wooden skeleton and connecting to a rotating valve port at each end of the drum. The drum is equipped with a variable-speed drive to turn the drum from 1/8 to 1 rpm. Normally, solids pickup is indirectly related to the drum speed. The drum is partially submerged in a vat containing the conditioned sludge. Submergence is usually limited to 1/5 or less of the filter surface at a time.

17.6.7.1.3 Chemical Conditioning

Sludge dewatered using vacuum filtration is normally chemically conditioned just prior to filtration. Sludge conditioning increases the percentage of solids captured by the filter and improves the dewatering characteristics of the sludge; however, conditioned sludge must be filtered as quickly as possible after chemical addition to obtain these desirable results.

17.6.7.2 Calculating Vacuum Filter Yield (lb/hr/ft²)

Probably the most frequent calculation that vacuum filter operators have to make is determining filter yield. Example 17.27 illustrates how this calculation is made.

■ ***Example 17.27***

Problem: Thickened, thermally conditioned sludge is pumped to a vacuum filter at a rate of 50 gpm. The vacuum area of the filter is 12 ft wide with a drum diameter of 9.8 ft. If the sludge concentration is 12%, what is the filter yield in lb/hr/ft^2? Assume the sludge weighs 8.34 lb/gal.

Solution: First calculate the filter surface area:

$$\begin{aligned}\text{Area of a cylinder side} &= 3.14 \times \text{Diameter} \times \text{Length}\\ &= 3.14 \times 9.8 \text{ ft} \times 12 \text{ ft}\\ &= 369.3 \text{ ft}^2\end{aligned}$$

Next, calculate the pounds of solids per hour:

$$\frac{50 \text{ gpm}}{1 \text{ min}} \times \frac{60 \text{ min}}{1 \text{ hr}} \times \frac{8.34 \text{ lb}}{1 \text{ gal}} \times \frac{12\%}{100\%} = 3002.4 \text{ lb/hr}$$

Dividing the two:

$$\frac{3002.4 \text{ lb/hr}}{369.3 \text{ ft}^2} = 8.13 \text{ lb/hr/ft}^2$$

17.6.8 Pressure Filtration

Pressure filtration differs from vacuum filtration in that the liquid is forced through the filter media by a positive pressure instead of a vacuum. Several types of filter presses are available, but the most commonly used types are belt presses and plate-and-frame presses. The *belt filter* includes two or more porous belts, rollers, and related handling systems for chemical makeup and feed, as well as supernatant and solids collection and transport. The *plate-and-frame filter* consists of a support frame, filter plates covered with porous material, a hydraulic or mechanical mechanism for pressing plates together, and related handling systems for chemical makeup and feed, as well as supernatant and solids collection and transport.

The belt filter uses a coagulant (polymer) mixed with the influent solids. The chemically treated solids are discharged between two moving belts. First, water drains from the solids by gravity. Then, as the two belts move between a series of rollers, pressure squeezes additional water out of the solids. The solids are then discharged onto a conveyor belt for transport to storage or disposal. Performance factors for the belt press include sludge feed rate, belt speed, belt tension, belt permeability, chemical dosage, and chemical selection.

In the plate-and-frame filter, solids are pumped (sandwiched) between plates. Pressure (200 to 250 psi) is applied to the plates and water is squeezed from the solids. At the end of the cycle, the pressure is released and as the plates separate the solids drop out onto a conveyor belt for transport to storage or disposal. Performance factors for plate-and-frame presses include feed sludge characteristics, type and amount of chemical conditioning, operating pressures, and the type and amount of precoat.

Filter presses have lower operation and maintenance costs than vacuum filters or centrifuges. They typically produce a good-quality cake and can be batch operated; however, construction and installation costs are high. Moreover, chemical addition is required, and the presses must be operated by skilled personnel.

17.6.8.1 Process Control Calculations for Filter Presses

As part of the operating routine for filter presses, operators are called upon to make certain process control calculations. The one most commonly used when operating the belt filter press determines the hydraulic loading rate on the unit, and the most commonly used process control calculation for plate and filter presses determines the pounds of solids pressed per hour. Both of these calculations are demonstrated below.

17.5.8.1.1 Belt Filter Press Hydraulic Loading Rate

■ ***Example 17.28***

Problem: A belt filter press receives a daily sludge flow of 0.30 gal. If the belt is 60 in. wide, what is the hydraulic loading rate on the unit in gallons per minute for each foot of belt width (gpm/ft)?

Solution:

$$\frac{0.30\text{ MG}}{1\text{ day}} \times \frac{1{,}000{,}000\text{ gal}}{1\text{ MG}} \times \frac{1\text{ day}}{1440\text{ min}} = \frac{208.3\text{ gal}}{1\text{ min}} = 208.3\text{ gpm}$$

$$60\text{ in.} \times \frac{1\text{ ft}}{12\text{ in.}} = 5\text{ ft}$$

$$\frac{208.3\text{ gpm}}{5\text{ ft}} = 41.7\text{ gpm/ft}$$

17.6.8.1.2 Pounds of Solids Pressed Per Hour in a Plate-and-Frame Press

■ ***Example 17.29***

Problem: A plate-and-frame filter press can process 850 gal of sludge during its 120-min operating cycle. If the sludge concentration is 3.7% and if the plate surface area is 140 ft^2, how many pounds of solids are pressed per hour for each square foot of plate surface area?

Solution:

$$850\text{ gal}\times\frac{3.7\%}{100\%}\times\frac{8.34\text{ lb}}{1\text{ gal}}=262.3\text{ lb}$$

$$\frac{262.3\text{ lb}}{120\text{ min}}\times\frac{60\text{ min}}{1\text{ hr}}=131.2\text{ lb/hr}$$

$$\frac{131.2\text{ lb/hr}}{140\text{ ft}^2}=0.94\text{ lb/hr/ft}^2$$

17.6.9 Centrifugation

Centrifuges of various types have been used in dewatering operations for at lease 30 years and appear to be gaining in popularity. Depending on the type of centrifuge used, in addition to centrifuge pumping equipment for solids feed and centrate removal, chemical makeup and feed equipment and support systems for removal of dewatered solids are required.

17.6.10 Sludge Incineration

Not surprisingly, sludge incinerators produce the maximum solids and moisture reductions. The equipment required depends on whether the unit is a multiple hearth or fluid-bed incinerator. Generally, the system will require a source of heat to reach the ignition temperature, a solids feed system, and ash handling equipment. It is important to note that the system must also include all of the required equipment (e.g., scrubbers) to achieve compliance with air-pollution control requirements. In operation, solids are pumped to the incinerator. The solids are dried and then ignited (burned). As they burn, the organic matter is converted to carbon dioxide and water vapor, and the inorganic matter is left behind as ash or fixed solids. The ash is then collected for reuse or disposal.

17.6.10.1 Process Description

The incineration process first dries then burns the sludge. The process involves the following steps:

1. The temperature of the sludge feed is raised to 212°F.
2. Water evaporates from the sludge.
3. The temperature of the water vapor and air mixture increases.
4. The temperature of the dried sludge volatile solids rises to the ignition point.

Note: Incineration will achieve maximum reductions if sufficient fuel, air, time, temperature, and turbulence are provided.

17.6.10.2 Incineration Processes

17.6.10.2.1 Multiple Hearth Furnace

The multiple hearth furnace consists of a circular steel shell surrounding a number of hearths. Scrapers (rabble arms) are connected to a central rotating shaft. Units range from 4.5 to 21.5 feet in diameter and have from 4 to 11 hearths. In operation, dewatered sludge solids are placed on the outer edge of the top hearth. The rotating rabble arms move them slowly to the center of the hearth. At the center of the hearth, the solids fall through ports to the second level. The process is repeated in the opposite direction. Hot gases generated by burning on lower hearths dry the solids. The dry solids pass to the lower hearths. The high temperature on the lower hearths ignites the solids. Burning continues to completion. Ash materials discharge to lower cooling hearths where they are discharged for disposal. Air flowing inside the center column and rabble arms continuously cools internal equipment.

17.6.10.2.2 Fluidized Bed Furnace

The fluidized bed incinerator consists of a vertical circular steel shell (reactor) with a grid to support a sand bed and an air system to provide warm air to the bottom of the sand bed. The evaporation and incineration process takes place within the superheated sand bed layer. Air is pumped to the bottom of the unit. The airflow expands (fluidizes) the sand bed inside. The fluidized bed is heated to its operating temperature (1200 to 1500°F). Auxiliary fuel is added when needed to maintain operating temperature. The sludge solids are injected into the heated sand bed. Moisture immediately evaporates. Organic matter ignites and reduces to ash. Residues are ground to fine ash by the sand movement. Fine ash particles flow up and out of the unit with exhaust gases. Ash particles are removed using common air-pollution control processes. Oxygen analyzers in the exhaust gas stack control the airflow rate.

Note: Because these systems retain a high amount of heat in the sand, the system can be operated as little as 4 hours per day with little or no reheating.

17.6.11 Land Application of Biosolids

The purpose of land application of biosolids is to dispose of the treated biosolids in an environmentally sound manner by recycling nutrients and soil conditioners. To be land applied, wastewater biosolids must comply with state and federal biosolids management and disposal regulations. Biosolids must not contain materials that are dangerous to human health (e.g., toxicity, pathogenic organisms) or dangerous to the environment (e.g., toxicity, pesticides, heavy metals). Treated biosolids are land applied by either direct injection or application and plowing in (incorporation).

17.6.11.1 Sampling and Testing Process Control

Land application of biosolids requires precise control to avoid problems. The quantity and the quality of biosolids applied must be accurately determined. For this reason, the operator's process control activities include biosolids sampling and testing functions. Biosolids sampling and testing include determining percent solids, heavy metals, organic pesticides and herbicides, alkalinity, total organic carbon (TOC), organic nitrogen, and ammonia nitrogen.

17.6.11.2 Process Control Calculations for Land Application of Biosolids

Process control calculations include determining disposal cost, plant available nitrogen (PAN), application rate (dry tons and wet tons per acre), metals loading rates, maximum allowable applications based on metals loading, and site life based on metals loading.

17.6.11.2.1 Disposal Cost

The cost of disposal of biosolids can be determined by:

$$\text{Cost} = \text{Biosolids (wet tons/year)} \times \text{\% Solids} \times \text{Cost per dry ton} \quad (17.27)$$

■ ***Example 17.30***

Problem: A treatment system produces 1925 wet tons of biosolids for disposal each year. The biosolids are 18% solids. A contractor disposes of the biosolids for $28.00 per dry ton. What is the annual cost for sludge disposal?

Solution:

$$\text{Cost} = 1925 \text{ wet tons/year} \times 0.18 \times \$28.00\text{/dry ton} = \$9702$$

17.6.11.2.2 Plant Available Nitrogen (PAN)

One factor considered when land applying biosolids is the amount of nitrogen in the biosolids available to the plants grown on the site. This includes ammonia nitrogen and organic nitrogen. The organic nitrogen must be mineralized for plant consumption. Only a portion of the organic nitrogen is mineralized per year. The mineralization factor (f_1) is assumed to be 0.20. The amount of ammonia nitrogen available is directly related to the time elapsed between applying the biosolids and incorporating (plowing) the sludge into the soil:

$$\text{PAN (lb/dry ton)} = \begin{bmatrix} \left(\text{Organic Nitrogen (mg/kg)} \times f_1\right) \\ + \left(\text{Ammonia Nitrogen (mg/kg)} \times V_1\right) \end{bmatrix} \times 0.002 \text{ lb/dry ton} \tag{17.28}$$

where:

f_1 = Mineralization rate for organic nitrogen (assume 0.20).

V_1 = Volatilization rate for ammonia nitrogen.

V_1 = 1.00 if biosolids are injected.

V_1 = 0.85 if biosolids are plowed in within 24 hours.

V_1 = 0.70 if biosolids are plowed in within 7 days.

■ ***Example 17.31***

Problem: The biosolids contain 21,000 mg/kg of organic nitrogen and 10,500 mg/kg of ammonia nitrogen. The biosolids are incorporated into the soil within 24 hr after application. What is the plant available nitrogen (PAN) per dry ton of solids?

Solution:

$$\text{PAN} = [(21{,}000 \text{ mg/kg} \times 0.20) + (10{,}500 \times 0.85)] \times 0.002 = 26.3 \text{ lb/dry ton}$$

17.6.11.2.3 Application Rate Based on Crop Nitrogen Requirement

In most cases, the application rate of domestic biosolids to crop lands will be controlled by the amount of nitrogen the crop requires. To determine the biosolids application rate based on the nitrogen requirement:

1. Use an agriculture handbook to determine the nitrogen requirement of the crop to be grown.
2. Determine the amount of sludge in dry tons required to provide this much nitrogen:

$$\text{Dry tons/ac} = \frac{\text{Plant Nitrogen Requirement (lb/ac)}}{\text{Plant Available Nitrogen (lb/dry ton)}} \tag{17.29}$$

■ *Example 17.32*

Problem: The crop to be planted on the land application site requires 150 lb of nitrogen per acre. What is the required biosolids application rate if the PAN of the biosolids is 30 lb/dry ton?

Solution:

$$\text{Biosolids Application Rate} = \frac{150 \text{ lb/ac}}{30 \text{ lb/dry ton}} = 5 \text{ dry tons/ac}$$

17.6.11.2.4 Metals Loading

When biosolids are land applied, metals concentrations are closely monitored and their loading on land application sites is calculated.

$$\begin{aligned}\text{Loading (lb/ac)} &= \text{Metals Concentration (mg/kg)} \times 0.002 \text{ lb/dry ton} \\ &\quad \times \text{Application Rate (dry tons/ac)}\end{aligned} \tag{17.30}$$

■ *Example 17.33*

Problem: The biosolids contain 14 mg/kg of lead. Biosolids are currently being applied to the site at a rate of 11 dry tons per acre. What is the metals loading rate for lead in pounds per acre?

Solution:

$$\text{Loading Rate} = 14 \text{ mg/kg} \times 0.002 \text{ lb/dry ton} \times 11 \text{ dry tons} = 0.31 \text{ lb/acre}$$

17.6.11.2.5 Maximum Allowable Applications Based on Metals Loading

If metals are present, they may limit the total number of applications a site can receive. Metals loading is normally expressed in terms of the maximum total amount of metal that can be applied to a site during its use:

$$\text{Applications} = \frac{\text{Maximum Allowable Cumulative Load (lb/ac)}}{\text{Metal Loading (lb/ac/application)}} \tag{17.31}$$

■ *Example 17.34*

Problem: The maximum allowable cumulative lead loading is 48.0 lb/ac. Based on the current loading of 0.35 lb/ac, how many applications of biosolids can be made to this site?

Solution:

$$\text{Applications} = \frac{48.0 \text{ lb/ac}}{0.35 \text{ lb/ac}} = 137$$

17.6.11.2.6 Site Life Based on Metals Loading

The maximum number of applications based on metals loading and the number of applications per year can be used to determine the maximum site life:

$$\text{Site Life (yr)} = \frac{\text{Maximum Allowable Applications}}{\text{Number of Applications Planned per Year}} \qquad (17.32)$$

■ ***Example 17.35***

Problem: Biosolids is currently applied to a site twice annually. Based on the lead content of the biosolids, the maximum number of applications is determined to be 135 applications. Based on the lead loading and the application rate, how many years can this site be used?

Solution:

$$\text{Site Life} = \frac{\text{135 applications}}{\text{2 applications per year}} = \text{68 years}$$

Note: When more than one metal is present, the calculations must be performed for each metal. The site life would then be the lowest value generated by these calculations.

17.7 CHAPTER REVIEW QUESTIONS

17.1 A sludge pump operates 30 min every 3 hr. The pump delivers 65 gpm. If the sludge is 5.2% solids and has a volatile matter content of 66%, how many pounds of volatile solids are removed from the settling tank each day?

17.2 Name three commonly used methods to thicken waste activated sludge.

17.3 Is a gravity thickener better at thickening primary or secondary sludge?

17.4 Name three sludge stabilization processes.

17.5 Name three general ways that sludge can be dewatered.

17.6 What two actions take place in a sludge drying bed?

17.7 An aerobic digester has a volume of 52,000 gal. The laboratory test indicates that 41 mg of lime were required to increase the pH of a 1-L sample of digesting sludge from 6.1 to the desired 7.3. How many pounds of lime must be added to the digester to increase the pH of the unit to 7.3?

17.8 The digester has a volume of 72,000 gal. Sludge is added to the digester at the rate of 2780 gpd. What is the sludge retention time in days?

17.9 What is the normal operating temperature of a heated anaerobic digester?

17.10 The supernatant contains 335 mg/L volatile acids and 1840 mg/L of alkalinity. What is the volatile acids-to-alkalinity ratio?

17.11 The digester is 45 ft in diameter and has a depth of 22 ft. Sludge is pumped to the digester at the rate of 4800 gpd. What is the sludge retention time?

17.12 Raw sludge pumped to a digester contains 70% volatile matter. The digested sludge removed from the digester contains 47% volatile matter. What is the percent volatile matter reduction?

17.13 Thickened thermally conditioned sludge is pumped to a vacuum filter at a rate of 30 gpm. The vacuum area of the filter is 10 ft wide with a drum diameter of 8.4 ft. If the sludge concentration is 12%, what is the filter yield in pounds per square foot? Assume the sludge weight is 8.34 lb/gal.

17.14 Liquids produced during solids treatment must be ____________.

17.15 The purpose(s) of sludge treatment is (are) ____________.

CHAPTER 18

WASTEWATER SAMPLING AND TESTING

18.1 INTRODUCTION

When anyone working in the environmental fields—environmental scientists, biologists, technical specialists, and water/wastewater operators—is planning a study that involves sampling, it is important, before initiating the study, to determine the objects of sampling. One important consideration is to determine whether sampling will be accomplished at a single point or at isolated points. Additionally, frequency of sampling must be determined; that is, will sampling be accomplished at hourly, daily, weekly, monthly, or at even longer intervals? Whatever sampling frequency is chosen, the entire process will probably continue over a protracted period. When a wastewater operator performs sampling, the decision-making considerations mentioned have already been addressed; it has already been determined where the samples are to be taken and the frequency of sampling, and the sampling will definitely continue over a protracted period—for as long as the wastestream continues to flow and the treatment process is continued.

Wastewater operators are required to take samples and test the samples to monitor overall plant and process performance to determine the effectiveness of treatment and to make corresponding system adjustments when necessary. Although only a few process control functions must actually be performed and only minimal analysis is required to monitor and report plant daily performance, the importance of sampling and testing in wastewater treatment operations cannot be overstated. Besides, sampling, testing, and recording the results are requirements of both state and federal laws.

In the following sections, wastewater sampling and testing requirements, information, and the knowledge required for certification at all classes or levels of licensure are covered. (More advanced technical information on biomonitoring, sampling, testing, and procedures is presented in Volume II of this handbook.)

18.2 WASTEWATER SAMPLING

Key Point: A representative sample is one that has the same chemical and biological composition as the wastewater it came from.

In wastewater sampling, the first critical step is to obtain good, untainted, valid information by collecting a representative sample. The second critical step in sampling is to follow a predetermined, plain-English, user-friendly, well-written sampling protocol. Although it is true that sample type and collection point must always be based on the test requirements and the particular information sought, it is also true that basic guidelines should be used for all sampling activities. Thus, the third critical step in sampling is to follow sampling rules. Sampling rules that should be followed anytime sampling is undertaken include:

- Samples must be collected from a well-mixed location.
- Sampling points must be clearly marked and easy to reach.
- Safety should always be considered when selecting a sampling point.
- Large, nonrepresentative objects must be discarded.
- No deposits, growths, or floating material should be included in the sample.
- All testing must begin as soon as possible after sample collection.
- Samples containing high concentrations of solids or large particles should be homogenized in a blender.
- Sample bottles and sample storage containers should be made of corrosion-resistant material, have leakproof tops, and be capable of withstanding repeated refrigeration and cleaning after use.
- Each sampling location should have a designated storage container used only for samples from that location.
- Appropriate safety procedures should always be followed when collecting samples (e.g., rubber gloves, washing after sampling, remaining within guardrails).

18.2.1 Sampling Devices and Containers

The tools of the trade for sampling performed by wastewater operators (and others) always include sampling devices and containers. It is important to ensure that sampling devices are corrosion resistant, easily cleaned, capable of collecting desired samples safely, and in accordance with test requirements. Whenever possible, a sampling device should be assigned to each sampling point. Sampling equipment must be cleaned on a regular basis to avoid contamination.

Note: Some tests require special equipment to ensure that the sample is representative. Dissolved oxygen and fecal coliform sampling requires special equipment and procedures to prevent collection of nonrepresentative samples. Sample containers may be specified for a particular test. If no container is specified, borosilicate glass or plastic containers may be used. Sample containers should be clean and free of soap or chemical residues.

18.2.2 Sample Types

The two basic types of samples are *grab samples* and *composite samples*. The type of sample taken depends on the specific test, the reason why the sample is being collected, and requirements stated in the plant discharge permit. A grab sample is a discrete sample collected at one time and one location. Grab samples are primarily used for any parameter whose concentration can change quickly, such as dissolved oxygen, pH, temperature, and total chlorine residual. They are representative only of the conditions at the time of collection. A composite sample consists of a series of individual grab samples taken at specified time intervals and in proportion to flow. The individual grab samples are mixed together in proportion to the flow rate at the time the sample was collected to form the composite sample. The composite sample represents the character of the water/wastewater over a period of time.

18.2.2.1 Composite Sampling Procedure and Calculation

When preparing oven-baked food, a cook pays close attention to setting the correct oven temperature. Usually, the cook sets the temperature at the correct setting and then moves on to some other chore—the oven thermostat makes sure that the food is cooked at the correct temperature, and that is that. Unlike the cook, in wastewater treatment plant operations the operator does not have the luxury of setting a plant parameter and then walking off and forgetting about it. To optimize plant operations, various adjustments to unit processes must be made on an ongoing basis. The operator makes unit process adjustments based on local knowledge (experience) and on lab test results; however, before lab tests can be performed, samples must be taken. Because knowledge of the procedure used to process composite samples is important (a basic requirement) to the water/wastewater operator, the actual procedure used is presented below.

18.2.2.1.1 Procedure

- Determine the total amount of sample required for all tests to be performed on the composite sample.
- Determine the average daily flow of the treatment system.

Note: Average daily flow can be determined by using several months of data, which will provide a more representative value.

- Calculate a proportioning factor:

$$\text{Proportioning Factor} = \frac{\text{Total Sample Volume Required (mm)}}{\text{No. of Samples Collected} \times \text{Avg. Daily Flow (MGD)}} \qquad (18.1)$$

Note: Round the proportioning factor to the nearest 50 units (e.g., 50,100, 150) to simplify calculation of the sample volume.

- Collect the individual samples in accordance with the schedule (e.g., once per hour, once per 15 minutes).
- Determine flow rate at the time the sample was collected.
- Calculate the specific amount to add to the composite container:

$$\text{Required Volume (mL)} = \text{Flow}^{T} \times \text{Proportioning Factor} \qquad (18.2)$$

  where T = time sample was collected

- Mix the individual sample thoroughly, measure the required volume, and add to composite storage container.
- Refrigerate composite samples throughout the collection period.

■ *Example 18.1*

Problem: The effluent testing will require 3825 mL of sample. The average daily flow is 4.25 MGD. Using the flows given below, calculate the amount of sample to be added at each of the times shown:

Time	Flow (MGD)
8 a.m.	3.88
9 a.m.	4.10
10 a.m.	5.05
11 a.m.	5.25
12 noon	3.80
1 p.m.	3.65
2 p.m.	3.20
3 p.m.	3.45
4 p.m.	4.10

Solution:

$$\text{Proportioning Factor} = \frac{3825\text{ mL}}{9\text{ Samples} \times 4.25\text{ MGD}} = 110 \text{ (round down to 100)}$$

$$\text{Volume}_{8\text{am}} = 3.88 \times 100 = 388 \text{ (400) mL}$$

$$\text{Volume}_{9\text{am}} = 4.10 \times 100 = 410 \text{ (410) mL}$$

$\text{Volume}_{10am} = 5.05 \times 100 = 505\ (500)\ \text{mL}$

$\text{Volume}_{11am} = 5.25 \times 100 = 525\ (530)\ \text{mL}$

$\text{Volume}_{12n} = 3.80 \times 100 = 380\ (380)\ \text{mL}$

$\text{Volume}_{1pm} = 3.65 \times 100 = 365\ (370)\ \text{mL}$

$\text{Volume}_{2pm} = 3.20 \times 100 = 320\ (320)\ \text{mL}$

$\text{Volume}_{3pm} = 3.45 \times 100 = 345\ (350)\ \text{mL}$

$\text{Volume}_{4pm} = 4.10 \times 100 = 410\ (410)\ \text{mL}$

18.3 WASTEWATER TEST METHODS*

This section describes general methods to help you understand better how each works in specific test kits. Always use the specific instructions included with the equipment and individual test kits. Most water analyses are conducted either by titrimetric analyses or colorimetric analyses. Both methods are easy to use and provide accurate results.

18.3.1 Titrimetric Methods

Titrimetric analyses are based on adding a solution of known strength (the titrant, which must have an exact known concentration) to a specific volume of a treated sample in the presence of an indicator. The indicator produces a color change indicating that the reaction is complete. Titrants are generally added by a *titrator* (microburet) or a precise glass pipet.

18.3.2 Colorimetric Methods

Colorimetric standards are prepared as a series of solutions with increasing known concentrations of the constituent to be analyzed. Two basic types of colorimetric tests are commonly used:

1. The pH test measures the concentration of hydrogen ions (the acidity of a solution) determined by the reaction of an indicator that varies in color depending on the hydrogen ion levels in the water.
2. Tests based on Beer's law determine the concentration of an element or compound. Simply, Beer's law states that the higher the concentration of a substance, the darker the color produced in the test reaction and therefore the more light absorbed. Assuming a constant viewpath, the absorption increases exponentially with concentration.

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* Material presented in this section is based on personal experience and adaptations from the American Water Works Association's *Standard Methods for the Examination of Water and Wastewater*, the *Federal Register*, and *The Monitor's Handbook* (LaMotte Co., Chestertown, MD, 1992).

18.3.3 Visual Methods

An octet comparator uses standards that are mounted in a plastic comparator block. It employs eight permanent translucent color standards and built-in filters to eliminate optical distortion. The sample is compared using either of two viewing windows. Two devices that can be used with the comparator are the bicolor reader, which neutralizes color or turbidity in water samples, and viewpath, which intensifies faint colors of low concentrations for easy distinction.

18.3.4 Electronic Methods

Although the human eye is capable of differentiating color intensity, interpretation is quite subjective. Electronic colorimeters consist of a light source that passes through a sample and is measured on a photodetector with an analog or digital readout. Besides electronic colorimeters, specific electronic instruments are manufactured for lab and field determination of many water quality factors, including pH, total dissolved solids (TDS)/conductivity, dissolved oxygen, temperature, and turbidity.

18.3.5 pH Measurement

pH is defined as the negative log of the hydrogen ion concentration of the solution. This is a measure of the ionized hydrogen in solution. Simply, it is the relative acidity or basicity of the solution. The chemical and physical properties and the reactivity of almost every component in water are dependent upon pH, which relates to corrosivity, contaminant solubility, and conductance of the water. pH has a secondary maximum contaminant level (MCL) set at 6.5 to 8.5.

18.3.5.1 Analytical and Equipment Considerations

The pH can be analyzed in the field or in the lab. If analyzed in the lab, it must be measured within 2 hours of sample collection, because the pH will change due to carbon dioxide in air that dissolves in the water, bringing the pH closer to 7. If your program requires a high degree of accuracy and precision in pH results, the pH should be measured with a laboratory-quality pH meter and electrode. Meters of this quality cost between $250 and $1000. Color comparators and pH “pocket pals” are suitable for most other purposes. The cost of either of these is approximately $50. The lower cost of the alternatives might be attractive if multiple samplers are used to sample several sites at the same time.

18.3.5.2 pH Meters

A pH meter measures the electric potential (millivolts) across an electrode when immersed in water. This electric potential is a function of the hydrogen ion activity in the sample; therefore, pH meters can display results in either millivolts (mV) or pH units.

A pH meter consists of a *potentiometer*, which measures electric potential where it meets the water sample; a *reference electrode*, which provides a constant electric potential; and a *temperature compensating device*, which adjusts the readings according to the temperature of the sample (because pH varies with temperature). The reference and glass electrodes are frequently combined into a single probe called a *combination electrode.* A wide variety of meters is available, but the most important part of the pH meter is the electrode; thus, it is important to purchase a good, reliable electrode and follow the manufacturer's instructions for proper maintenance. Infrequently used or improperly maintained electrodes are subject to corrosion, which makes them highly inaccurate.

18.3.5.3 pH "Pocket Pals" and Color Comparators

pH "pocket pals" are electronic handheld "pens" that are dipped in the water, providing a digital readout of the pH. They can be calibrated to only one pH buffer. (Lab meters, on the other hand, can be calibrated to two or more buffer solutions and thus are more accurate over a wide range of pH measurements.) Color comparators involve adding a reagent to the sample that colors the sample water. The intensity of the color is proportional to the pH of the sample, then matched against a standard color chart. The color chart equates particular colors to associated pH values, which can be determined by matching the colors from the chart to the color of the sample. For instructions on how to collect and analyze samples, refer to *Standard Methods.*

18.3.6 Chlorine Residual Testing/Analysis

Chlorination is the most widely used means of disinfecting water in the United States. When chlorine gas is dissolved into (pure) water, it forms hypochlorous acid (HOCl), hypochlorite (OCl) ions, and hydrogen chloride (hydrochloric acid). The total concentration of HOCl and OCl ions is known as *free chlorine residual.* Currently, federal regulations cite the following approved methods for determination of total chlorine residual:

1. DPD (*N*,*N*-diethyl-*p*-phenylenediamine), spectrophotometric
2. DPD–FAS (ferrous ammonium sulfate) titration
3. Direct amperometric titration
4. Direct iodometric titration
5. Iodometric back titration
    - Starch iodine endpoint—iodine titrant
    - Starch iodine endpoint—iodate titrant
6. Amperometric endpoint
7. Chlorine electrode

All of these test procedures are approved methods and, unless prohibited by the plant's National Pollutant Discharge Elimination System (NPDES) discharge permit, can be used for effluent testing. Based on current most popular method usage in the United States, the discussion here is limited to:

1. DPD, spectrophotometric
2. DPD–FAS titration
3. Direct amperometric titration
4. Direct iodometric titration

Note: Treatment facilities required to meet nondetectable total chlorine residual limitations must use one of the test methods specified in the plant's NPDES discharge permit.

For information on any of the other approved methods, refer to the appropriate reference cited in the federal regulations.

18.3.6.1 DPD, Spectrophotometric

The DPD indicator reacts with chlorine to form a red color. The intensity of the color is directly proportional to the amount of chlorine present. This color intensity is measured using a colorimeter or spectrophotometer. This meter reading can be converted to a chlorine concentration using a graph developed by measuring the color intensity produced by solutions with precisely known concentrations of chlorine. In some cases, spectrophotometers or colorimeters are equipped with scales that display chlorine concentration directly. In these cases, there is no requirement to prepare a standard reference curve. If the direct reading colorimeter is not used, chemicals that are required to be used include:

1. Potassium dichromate solution (0.100 *N*)
2. Potassium iodine crystals
3. Standard ferrous ammonium sulfate solution (0.00282 *N*)
4. Concentrated phosphoric acid
5. Sulfuric acid solution (1 and 5 *N*)
6. Barium diphenylamine sulfonate (0.1%)

If an indicator is not used, the DPD indicator and phosphate buffer (a DPD prepared indicator includes a buffer and indicator) are required.

The test requires a direct readout colorimeter designed to meet the test specifications, a spectrophotometer (wavelength of 515 nm and light path of at least 1 cm), or a filter photometer with a filter having maximum transmission in the wavelength range of 490 to 520 nm and a light path of at least 1 cm. In addition, for direct readout colorimeter procedures, a sample test vial is required. When the direct readout colorimeter procedure is not used, the equipment required includes:

1. 250-mL Erlenmeyer flask
2. 10-mL measuring pipets
3. 15-mL test tubes
4. 1-mL pipets (graduated to 0.1 mL)
5. Sample cuvettes with 1-cm light path

Note: A cuvette is a small, often tubular laboratory vessel normally made of glass.

18.3.6.1.1 Procedure

For direct readout colorimeters, follow the procedure supplied by the manufacturer. The standard procedure when using a spectrophotometer or colorimeter is as follows:

1. Prepare a standard curve for total chlorine residual (TCR) concentrations from 0.05 to 4.0 mg/L (chlorine vs. percent transmittance). Instructions on how to prepare the TCR concentration curve or a standard curve are normally included in the spectrophotometer manufacturer's operating instructions.
2. Calibrate the colorimeter in accordance with the manufacturer's instructions using a laboratory-grade water blank.
3. To a clean test tube or cuvette, add one prepared indicator packet (or tablet) of the appropriate size to match the sample volume, or:
    - Pipet 0.5 mL phosphate buffer solution.
    - Pipet 0.5 mL DPD indicator solution.
    - Add 0.1 g KI (potassium iodide) crystals to a clean tube or cuvette.
4. Add 10 mL of sample to the cuvette.
5. Stopper the cuvette, and swirl to mix the contents well.
6. Let stand for 2 minutes.
7. Verify the wavelength of the spectrophotometer or colorimeter, and check and set the 0% T (transmittance) using the laboratory-grade water blank.
8. Place the cuvette in the instrument, read percent T, and record the reading.
9. Determine mg/L TCR from standard curve.

Note: Calculations are not required in this test because TCR (mg/L) is read directly from the meter or from the graph.

18.3.6.2 DPD–FAS Titration

The amount of ferrous ammonium sulfate solution required to just remove the red color from a total chlorine residual sample that has been treated with DPD indicator can be used to determine the concentration of chlorine in a sample. This is known as a titrimetric test procedure. The chemicals used in the test procedure include the following:

1. DPD prepared indicator (buffer and indicator together)
2. Potassium dichromate solution (0.100 *N*)
3. Potassium iodide crystals
4. Standard ferrous ammonium sulfate solution (0.00282 *N*)
5. Concentrated phosphoric acid
6. Sulfuric acid solution (1 and 5 *N*)
7. Barium diphenylamine sulfonate (0.1%)

Note: The DPD indicator or phosphate buffer is not required if a prepared indicator is used.

The equipment required for this test procedure includes the following:

1. 250-mL graduated cylinder
2. 5-mL measuring pipet
3. 500-mL Erlenmeyer flask
4. 50-mL buret (graduate to 0.1 mL)
5. Magnetic stirrer and stir bars

18.3.6.2.1 Procedure

1. Add the contents of a prepared indicator packet (or tablet) to the Erlenmeyer flask, or:
    - Pipet 5 mL phosphate buffer solution into an Erlenmeyer flask.
    - Pipet 5 mL DPD indicator solution into the flask.
    - Add 1 g KI crystals to the flask.
2. Add 100 mL of sample to the flask.
3. Swirl the flask to mix contents.
4. Let the flask stand for 2 minutes.
5. Titrate with FAS until the red color first disappears.
6. Record the amount of titrant.

The calculation required in this procedure is:

$$\text{TCR (mg/L)} = \text{FAS used (mL)} \tag{18.3}$$

18.3.6.3 Direct Amperometric Titration

In this test procedure, phenylarsine oxide (PAO) is added to a treated sample to determine when the test reaction has been completed. The volume of phenylarsine oxide used can then be used to calculate the TCR. The chemicals used include:

1. Phenylarsine oxide solution (0.00564 *N*)
2. Potassium dichromate solution (0.00564 *N*)
3. Potassium iodide solution (5%)
4. Acetate buffer solution (pH 4.0)
5. Standard arsenite solution (0.1 *N*)

The equipment required for this test procedure includes the following:

1. 250-mL graduated cylinder
2. 5-mL measuring pipets
3. Amperometric titrator

18.3.6.3.1 Procedure

1. Prepare amperometric titrator according to manufacturer.
2. Add 200-mL sample.
3. Place container on titrator stand and turn on mixer.
4. Add 1 g KI crystals or 1 mL KI solution.
5. Pipet 1 mL of pH 4 (acetate) buffer into the container.
6. Titrate with 0.0056-*N* PAO.

When conducting the test procedure, as the downscale endpoint is neared, slow titrant addition to 0.1-mL increments, and note titrant volume used after increment. When no needle movement is noted, the endpoint has been reached. Subtract the final increment from the buret reading to determine the final titrant volume. For this procedure, the only calculation normally required is:

$$\text{TCR (mg/L)} = \text{PAO used (mL)} \tag{18.4}$$

18.3.6.4 Direct Iodometric Titration

In this test, phenylarsine oxide (PAO) is added to a treated sample to a starch endpoint (blue to clear). The results of the titration are used to calculate the TCR of the sample. Chemicals used include the following:

- Phenylarsine oxide solution (0.00564 *N*)
- Potassium dichromate solution (0.00564 *N*)
- Potassium iodide crystals

- Acetate buffer solution (pH 4.0)
- Standard arsenite solution (.1 *N*)
- Starch indicator

The equipment required for this test procedure includes the following:

- 250-mL graduated cylinder
- 5-mL measuring pipets
- 500-mL Erlenmeyer flask
- 5-mL volumetric pipet
- 10-mL buret (graduated to 0.01 mL)
- 25-mL buret (graduate to 0.1 mL)
- Magnetic stirrer and stir bars

18.3.6.4.1 Procedure

1. Pipet 4 mL (acetate) buffer into an Erlenmeyer flask.
2. Add 1 g KI crystals to the flask.
3. Add 200 mL, 500 mL, or 1000 mL of sample.
4. Titrate with 0.00564-*N* sodium thiosulfate or PAO to pale yellow color.
5. Add 1 to 2 mL of starch solution.
6. Chlorine titrate until the blue color disappears.
7. Repeat steps 1 to 3 and steps 5 to 6 with an appropriate volume of laboratory-grade water for a negative blank. If no blue appears at step 5, titrate to the first appearance of blue color with 0.0282-*N* iodine solution, then back titrate with sodium thiosulfate for a positive blank.

18.3.6.4.2 Calculations

The calculations for this and similar procedures may be as simple as shown below, using Equation 18.4:

$$\text{TCR (mg/L)} = \text{PAO used (mL)}$$

In some instances, however, the calculations required to determine TCR using the direct iodometric titration method and iodometric back titration method may be a bit more complicated, as demonstrated by the following equations and examples.

- *Direct iodometric titration calculations*

$$\text{TCR (mg/L)} = \frac{\left[\begin{array}{l}\text{Titration used for sample (m/L)}\\ \pm\,\text{Titration used for blank (mL)}\end{array}\right] \times \text{Titration } N \times 35{,}450}{\text{Sample Volume (mL)}} \tag{18.5}$$

Note: A positive blank (+) is added to the titrant volume, and a negative blank (–) is subtracted from the titrant volume.

■ *Example 18.2*

Problem: Using the information provided below, determine TCR (mg/L):

mL of sample = 300 mL
Titrant used for sample = 2.8 mL
Titrant used for blank = +0.3 mL
Titrant normality = 0.00564 N

Solution:

$$\text{TCR} = \frac{(2.8\text{ mL} + 0.3\text{ mL}) \times 0.00564\ N \times 35{,}450}{300\text{ mL}} = 2.1\text{ mg/L}$$

- *Iodometric back titration calculations*

$$\text{TCR (mg/L)} = \frac{\begin{bmatrix}\text{Iodate added to blank (mL)} \\ -\text{ Iodate added to sample (mL)}\end{bmatrix} \times 200}{\text{Sample volume (mL)}} \tag{18.6}$$

■ *Example 18.3*

Problem: Using the information provided below, determine TCR (mg/L):

mL of sample = 200 mL
Iodate used for blank = 9.3 mL
Iodate used for sample = 7.0 mL

Solution:

$$\text{TCR (g/L)} = \frac{(9.3\text{ mL} - 7.0\text{ mL}) \times 200}{200\text{ mL}} = 2.3\text{ mg/L}$$

18.3.7 Dissolved Oxygen Testing

(This section and the sections that follow discuss several water quality factors that are routinely monitored in drinking water operations. Not covered are the actual test procedures used to analyze each water quality factor; instead, please refer to the latest edition of *Standard Methods* for the correct procedure to use in conducting these tests.)

A stream system used as a source of water produces and consumes oxygen. It gains oxygen from the atmosphere and from plants through photosynthesis. Churning running water dissolves more oxygen than still water does, such as in a reservoir behind a dam. Respiration by aquatic animals, decomposition, and various chemical reactions consume oxygen. Oxygen is actually poorly soluble in water. Its solubility is related to pressure and temperature. In water supply systems, dissolved oxygen (DO) in raw water is considered the necessary element to support life for many aquatic organisms. From the drinking water practitioner's point of view, DO is an important indicator of the water treatment process and an important factor in corrosivity.

Wastewater from sewage treatment plants often contains organic materials that are decomposed by microorganisms that use oxygen in the process. The amount of oxygen consumed by these organism in breaking down the waste is known as the biochemical oxygen demand (BOD). Other sources of oxygen-consuming waste include stormwater runoff from farmland or urban streets, feedlots, and failing septic systems.

Oxygen is measured in its dissolved form as dissolved oxygen. If more oxygen is consumed than produced, DO levels decline and some sensitive animals may move away, weaken, or die. DO levels fluctuate over a 24-hour period and seasonally, and they vary with water temperature and altitude. Cold water holds more oxygen than warm water (see Table 18.1), and water holds less oxygen at higher altitudes. Thermal discharges (such as water used to cool machinery in a manufacturing plant or a power plant) raise the temperature of water and lower its oxygen content. Aquatic animals are most vulnerable to lowered DO levels in the early morning on hot summer days, when stream flows are low, water temperatures are high, and aquatic plants have not been producing oxygen since sunset.

18.3.7.1 Sampling and Equipment Considerations

In contrast to lakes, where DO levels are most likely to vary vertically in the water column, changes in DO in rivers and streams move horizontally along the course of the waterway. This is especially true in smaller, shallow streams. In larger, deeper rivers, some vertical stratification of dissolved oxygen might occur. The DO levels in and below riffle areas, waterfalls, or dam spillways are typically higher than those in pools and slower-moving stretches. If you wanted to measure the effect of a dam, sampling for DO behind the dam immediately below the spillway and upstream of the dam would be important. Because DO levels are critical to fish, a good place to sample is in the pools that fish tend to favor, or in the spawning areas they use.

An hourly time profile of DO levels at a sampling site represents a valuable set of data, because it shows the change in DO levels from the low point (just before sunrise) to the high point (sometime near midday). This might not be practical for a volunteer monitoring program, though. Note the time of your DO sampling to help judge when in the daily cycle the data were collected. DO is measured in either milligrams per liter

TABLE 18.1 MAXIMUM DISSOLVED OXYGEN (DO) CONCENTRATIONS VS. TEMPERATURE VARIATIONS

Temperature (°C)	DO (mg/L)	Temperature (°C)	DO (mg/L)
0	14.60	23	8.56
1	14.19	24	8.40
2	13.81	25	8.24
3	13.44	26	8.09
4	13.09	27	7.95
5	12.75	28	7.81
6	12.43	29	7.67
7	12.12	30	7.54
8	11.83	31	7.41
9	11.55	32	7.28
10	11.27	33	7.16
11	11.01	34	7.05
12	10.76	35	6.93
13	10.52	36	6.82
14	10.29	37	6.71
15	10.07	38	6.61
16	9.85	39	6.51
17	9.65	40	6.41
18	9.45	41	6.31
19	9.26	42	6.22
20	9.07	43	6.13
21	8.90	44	6.04
22	8.72	45	5.95

(mg/L) or percent saturation, which is the amount of oxygen in a liter of water relative to the total amount of oxygen that the water can hold at that temperature.

Dissolved oxygen samples are collected using a special BOD bottle: a glass bottle with a “turtleneck” and a ground stopper. You can fill the bottle directly in the stream if the stream is wadeable or can be accessed by boat, or you can use a sampler dropped from a bridge or boat into water deep enough to submerse it. Samplers can be made or purchased.

18.3.7.2 Dissolved Oxygen Test Methods

Dissolved oxygen is measured primarily by using some variation of the Winkler method or a meter and probe.

18.3.7.2.1 Winkler Method (Azide Modification)

The Winkler method (azide modification) involves filling a sample bottle completely with water (no air is left to bias the test). The dissolved oxygen is then fixed using a series of reagents that form a titrated acid compound. Titration involves the drop-by-drop addition of a reagent that neutralizes the acid compound, causing a change in the color of the solution. The point at which the color changes is the endpoint, which reflects the amount of oxygen dissolved in the sample. The sample is usually fixed and titrated in the field at the sample site. Preparing the sample in the field and delivering it to a lab for titration is also possible. The azide modification method is best suited for relatively clean waters; otherwise, substances such as color, organics, suspended solids, sulfide, chlorine, and ferrous and ferric iron can interfere with test results. If fresh azide is used, nitrite will not interfere with the test. In testing, iodine is released in proportion to the amount of DO present in the sample. By using sodium thiosulfate with starch as the indicator, the sample can be titrated to determine the amount of DO present. The chemicals used include:

1. Manganese sulfate solution
2. Alkaline azide–iodide solution
3. Sulfuric acid, concentrated
4. Starch indicator
5. Sodium thiosulfate solution (0.025 *N*), phenylarsine solution (0.025 *N*), or potassium biniodate solution (0.025 *N*)
6. Distilled or deionized water

The equipment required for this test procedure includes the following:

1. Buret, graduated to 0.1 mL
2. Buret stand
3. 300-mL BOD bottles
4. 500-mL Erlenmeyer flasks
5. 1.0-mL pipets with elongated tips
6. Pipet bulb
7. 250-mL graduated cylinder
8. Laboratory-grade water rinse bottle
9. Magnetic stirrer and stir bars (optional)

The procedure for the Winkler method includes the following:

1. Collect sample in a 300-mL BOD bottle.
2. Add 1 mL manganous sulfate solution at the surface of the liquid.
3. Add 1 mL alkaline iodide–azide solution at the surface of the liquid.
4. Stopper the bottle, and mix by inverting the bottle.
5. Allow the floc to settle halfway in the bottle, remix, and allow to settle again.

6. Add 1 mL concentrated sulfuric acid at the surface of the liquid.
7. Restopper the bottle, rinse the top with laboratory-grade water, and mix until precipitate is dissolved.
8. The liquid in the bottle should appear clear and have an amber color.
9. Measure 201 mL from the BOD bottle into an Erlenmeyer flask.
10. Titrate with 0.025-*N* PAO or thiosulfate to a pale yellow color, and note the amount of titrant.
11. Add 1 mL of starch indicator solution.
12. Titrate until a blue color first disappears.
13. Record total amount of titrant.

18.3.7.2.2 Calculation

To calculate the DO concentration when the modified Winkler titration method is used:

$$\underset{\text{(mg/L)}}{\text{Dissolved Oxygen}} = \frac{\left[\text{Buret}_{\text{Final}}\ \text{(mL)} - \text{Buret}_{\text{Start}}\ \text{(mL)}\right] \times N \times 8000}{\text{Sample Volume (mL)}} \tag{18.7}$$

Note: Using a 200-mL sample and a 0.025-*N* titrant reduces this calculation to:

$$\text{Dissolved Oxygen (mg/L)} = \text{Titrant Used (mL)}$$

■ *Example 18.4*

Problem: The operator titrates a 200-mL DO sample. The buret reading at the start of the titration was 0.0 mL. At the end of the titration, the buret read 7.1 mL. The concentration of the titrating solution was 0.025 *N*. What was the DO concentration in mg/L?

Solution:

$$\text{Dissolved Oxygen} = \frac{(7.1\ \text{mL} - 0.0\ \text{mL}) \times 0.025 \times 8000}{200\ \text{mL}} = 7.1\ \text{mL}$$

Dissolved oxygen field kits using the Winkler method are relatively inexpensive, especially compared to a meter and probe. Field kits run between $35 and $200, and each kit comes with enough reagents to run 50 to 100 tests. Replacement reagents are inexpensive and come already measured in plastic pillows for each test. Reagents can also be purchased in larger quantities in bottles and measured out with a volumetric scoop. The advantage of the pillows is that they have a longer shelf life and are much less prone to contamination or spillage. Buying larger quantities in bottles has the advantage of considerably lower cost per test.

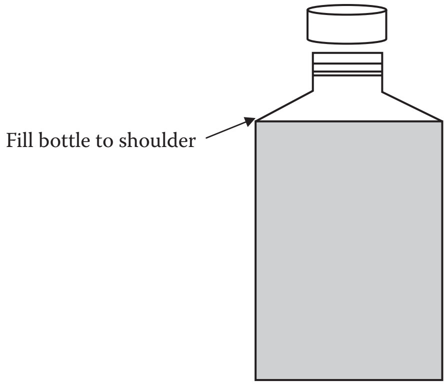

Figure 18.1 Typical sample bottle.

The major factor in the expense for the kits is the method of titration used—eyedropper or syringe-type titrator. Eyedropper and syringe-type titration is less precise than digital titration, because a larger drop of titrant is allowed to pass through the dropper opening, and on a microscale the drop size (and thus volume of titrant) can vary from drop to drop. A digital titrator or a buret (a long glass tube with a tapered tip like a pipet) allows much more precision and uniformity for titrant it allows to pass. If a high degree of accuracy and precision in the DO results is required, a digital titrator should be used, but a kit that uses an eyedropper-type or syringe-type titrator is suitable for most other purposes. The lower cost of this type of DO field kit might be attractive if several teams of samplers and testers are located at multiple sites at the same time.

18.3.7.3 Meter and Probe

A *dissolved oxygen meter* is an electronic device that converts signals from a probe placed in the water into units of DO in milligrams per liter. Most meters and probes also measure temperature. The probe is filled with a salt solution and has a selectively permeable membrane that allows DO to pass from the streamwater into the salt solution. The DO that has diffused into the salt solution changes the electric potential of the salt solution, and this change is sent by electric cable to the meter, which converts the signal to milligrams per liter on a scale that the user can read.

18.3.7.3.1 Methodology

If samples are to be collected for analysis in the laboratory, a special American Public Health Association (APHA) sampler, or the equivalent, must be used. If the sample is exposed or mixed with air during collection, test results can change dramatically; therefore, the sampling device must allow collection of a sample that is not mixed with atmospheric air and must allow for at least 3× bottle overflow (see Figure 18.1). Again, because the DO level in a sample can change quickly, only grab samples should be used for dissolved oxygen testing. Samples must be tested immediately (within 15 minutes) after collection.

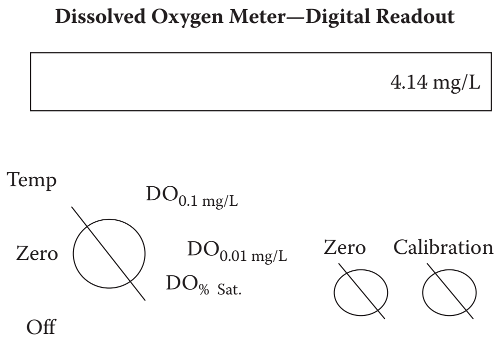

Figure 18.2 Meter control panel.

Note: Samples collected for analysis using the modified Winkler titration method may be preserved for up to 8 hours by adding 0.7 mL of concentrated sulfuric acid or by adding all the chemicals required by the procedure. Samples collected from the aeration tank of the activated sludge process must be preserved using a solution of copper sulfate–sulfamic acid to inhibit biological activity.

The advantage of using the DO oxygen meter method is that the meter can be used to determine DO concentration directly (see Figure 18.2). In the field, a direct reading can be obtained using a probe (see Figure 18.3), or samples can be collected for testing in the laboratory using a laboratory probe (see Figure 18.4).

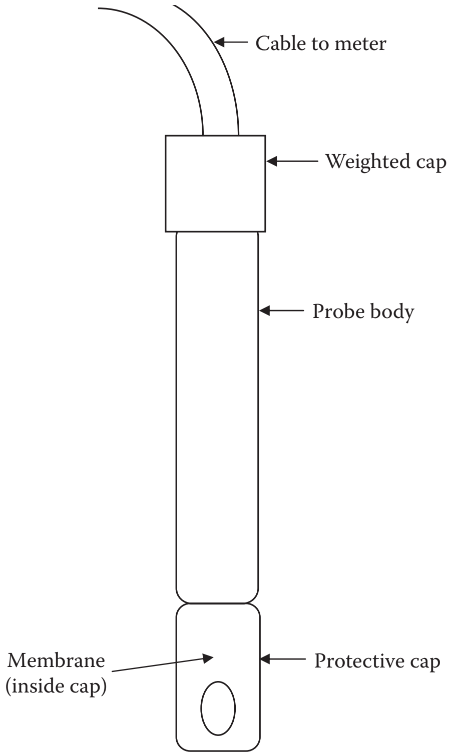

Figure 18.3 DO field probe.

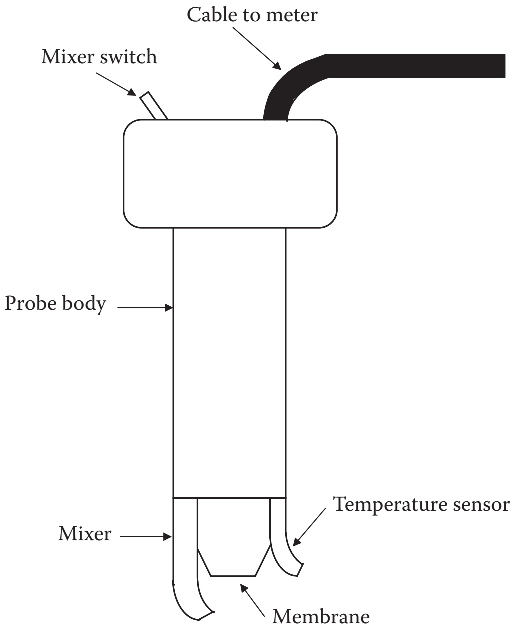

Figure 18.4 DO lab probe.

The probe used in the determination of DO consists of two electrodes, a membrane, and a membrane filling solution. Oxygen passes through the membrane into the filling solution and causes a change in the electrical current passing between the two electrodes. The change is measured and displayed as the concentration of DO. To be accurate, the probe membrane must be in proper operating condition, and the meter must be calibrated before use. The only chemical used in the DO meter method during normal operation is the electrode filling solution; however, in the Winkler DO method, chemicals are required for meter calibration.

Key Point: The field probe can be used for laboratory work by placing a stirrer in the bottom of the sample bottle, but the laboratory probe should never be used in any situation where the entire probe might be submerged.

Calibration prior to use is important. Both the meter and the probe must be calibrated to ensure accurate results. The frequency of calibration is dependent on the frequency of use; for example, if the meter is used once a day, then calibration should be performed before use. Three methods are available for calibration: saturated water, saturated air, and the Winkler method. It is important to note that, if the Winkler method is not used for routine calibration method, periodic checks using this method are recommended.

18.3.7.3.2 Procedure

It is important to keep in mind that the supplier's operating procedures for both the meter and probe should always be followed. Normally, the manufacturer's recommended procedure will include the following general steps:

1. Turn the DO meter on, and allow 15 minutes for it to warm up.
2. Turn the meter switch to zero, and adjust as needed.
3. Calibrate the meter using the saturated air, saturated water, or Winkler azide procedure for calibration.
4. Collect sample in 300-mL bottle, or place a field electrode directly in the stream.
5. Place the laboratory electrode in a BOD bottle without trapping air against the membrane, and turn on the stirrer.
6. Turn the meter switch to the temperature setting, and measure the temperature.
7. Turn the meter switch to DO mode, and allow 10 seconds for the meter reading to stabilize.
8. Read the DO mg/L from the meter, and record the results.

No calculation is necessary using this method because results are read directly from the meter.

Dissolved oxygen meters are expensive compared to field kits that use the titration method. Meter and probe combinations run between $500 and $1200, including a long cable to connect the probe to the meter. The advantage of a meter and probe is that DO and temperature can be quickly read at any point where the probe is inserted into the stream. DO levels can be measured at a certain point on a continuous basis. The results are read directly as milligrams per liter, unlike the titration methods, for which the final titration result might have to be converted by an equation to milligrams per liter. DO meters, however, are more fragile than field kits, and repairs to a damaged meter can be costly. The meter and probe must be carefully maintained, and must be calibrated before each sample run and, if many tests are done, between sampling. Because of the expense, a small water/wastewater facility might only have one meter and probe, which means that only one team of samplers can sample DO, and they must test all of the sites. With field kits, on the other hand, several teams can sample simultaneously.

18.3.8 Biochemical Oxygen Demand Testing

Biochemical oxygen demand (BOD) measures the amount of oxygen consumed by microorganisms in decomposing organic matter in streamwater. BOD also measures the chemical oxidation of inorganic matter (the extraction of oxygen from water via chemical reaction). A test is used to measure the amount of oxygen consumed by these organisms during a specified period of time (usually 5 days at 20°C). The rate of oxygen consumption in a stream is affected by a number of variables: temperature, pH, the presence of certain kinds of microorganisms, and the type of organic and inorganic material in the water.

Biochemical oxygen demand directly affects the amount of dissolved oxygen in water bodies—the greater the BOD, the more rapidly oxygen is depleted in the water body, leaving less oxygen available to higher forms of aquatic life. The consequences of high BOD are the same as those for low dissolved oxygen: Aquatic organisms become stressed, suffocate, and die. Most river waters used as water supplies have a BOD less than 7 mg/L; therefore, dilution is not necessary.

Sources of BOD include leaves and wood debris; dead plants and animals; animal manure; effluents from pulp and paper mills, wastewater treatment plants, feedlots, and food-processing plants; failing septic systems; and urban stormwater runoff.

Note: To evaluate the potential use of raw water as a drinking water supply, it is usually sampled, analyzed, and tested for biochemical oxygen demand when turbid, polluted water is the only source available.

18.3.8.1 Sampling Considerations

Biochemical oxygen demand is affected by the same factors that affect dissolved oxygen. Aeration of streamwater (e.g., by rapids and waterfalls) will accelerate the decomposition of organic and inorganic material; therefore, BOD levels at a sampling site with slower, deeper waters might be higher for a given column of organic and inorganic material than the levels for a similar site in highly aerated waters. Chlorine can also affect BOD measurement by inhibiting or killing the microorganisms that decompose the organic and inorganic matter in a sample. If sampling in chlorinated waters (such as those below the effluent from a sewage treatment plant), neutralizing the chlorine with sodium thiosulfate is necessary (see *Standard Methods*).

Biochemical oxygen demand measurement requires taking two samples at each site. One is tested immediately for dissolved oxygen; the second is incubated in the dark at 20°C for 5 days and then tested for dissolved oxygen remaining. The difference in oxygen levels (in mg/L) between the first test and the second test is the amount of BOD. This represents the amount of oxygen consumed by microorganisms and used to break down the organic matter present in the sample bottle during the incubation period. Because of the 5-day incubation, the tests are conducted in a laboratory.

Sometimes by the end of the 5-day incubation period, the dissolved oxygen level is zero. This is especially true for rivers and streams with a lot of organic pollution. Because knowing when the zero point was reached is not possible, determining the BOD level is also impossible. In this case, diluting the original sample by a factor that results in a final dissolved oxygen level of at least 2 mg/L is necessary. Special dilution water should be used for the dilutions (see *Standard Methods*).

Some experimentation is needed to determine the appropriate dilution factor for a particular sampling site. The result is the difference in dissolved oxygen between the first measurement and the second, after multiplying the second result by the dilution factor. *Standard Methods* prescribes all phases of procedures and calculations for BOD determination. A BOD test is not required for monitoring water supplies.

TABLE 18.2 BOD_5 TEST PROCEDURE

1. Fill two bottles with BOD dilution water; insert stoppers.
2. Place sample in two BOD bottles; fill with dilution water; insert stoppers.
3. Test for dissolved oxygen.
4. Incubate for 5 days.
5. Test for dissolved oxygen.
6. Add 1 mL $MnSO_4$ below the surface.
7. Add 1 mL alkaline KI below the surface.
8. Add 1 mL H_2SO_4.
9. Transfer 203 mL to flask.
10. Titrate with PAO or thiosulfate.

18.3.8.2 BOD_5 Sampling, Analysis, and Testing

The approved BOD sampling and analysis procedure measures the DO depletion (biological oxidation of organic matter in the sample) over a 5-day period under controlled conditions (20°C in the dark). The test is performed using a specified incubation time and temperature. Test results are used to determine plant loadings, plant efficiency, and compliance with NPDES effluent limitations; however, the duration of the test makes it difficult to use the data effectively for process control.

The standard BOD test does not differentiate between oxygen used to oxidize organic matter and that used to oxidize organic and ammonia nitrogen to more stable forms. Because many biological treatment plants now control treatment processes to achieve oxidation of the nitrogen compounds, it is possible that BOD test results for plant effluent and some process samples may produce BOD test results based on both carbon and nitrogen oxidation. To avoid this situation, a nitrification inhibitor can be added. When this is done, the test results are known as *carbonaceous BOD* (CBOD). A second uninhibited BOD should also be run whenever CBOD is determined.

When taking a BOD sample, no special sampling container is required. Either a grab or composite sample can be used. BOD_5 samples can be preserved by refrigeration at or below 4°C (not frozen); composite samples must be refrigerated during collection. The maximum holding time for preserved samples is 48 hours. Using the incubation of dissolved approved test method, a sample is mixed with dilution water in several different concentrations (dilutions). The dilution water contains nutrients and materials to provide optimum environment. Chemicals used include dissolved oxygen, ferric chloride, magnesium sulfate, calcium chloride, phosphate buffer, and ammonium chloride.

Key Point: Remember that all chemicals can be dangerous if not used properly and in accordance with the recommended procedures. Review the appropriate sections of the material safety data sheet (MSDS) for each chemical to determine the proper methods for handling and for safety precautions that should be taken.

Sometimes it is necessary to add (seed) healthy organisms to the sample. The DO levels of the dilution and the dilution water are determined. If seed material is used, a series of dilutions of seed material must also be prepared. The dilutions and dilution blanks are incubated in the dark for 5 days at 20 ± 1°C. At the end of 5 days, the DO level of each dilution and the dilution blanks is determined.

For the test results to be valid, certain criteria must be achieved. These test criteria are listed as follows:

1. Dilution water blank DO change must be ≤0.2 mg/L.
2. Initial DO must be >7.0 mg/L but ≤9.0 mg/L (or saturation at 20°C and test elevation).
3. Sample dilution DO depletion must be ≥2.0 mg/L.
4. Sample dilution residual DO must be ≥1.0 mg/L.
5. Sample dilution initial DO must be ≥7.0 mg/L.
6. Seed correction should be ≥0.6 but ≤1.0 mg/L.

The BOD_5 test procedure consists of 10 steps (for unchlorinated water), as shown in Table 18.2.

Note: BOD_5 is calculated individually for all sample dilutions that meet the criteria. The reported result is the average of the BOD_5 of each valid sample dilution.

18.3.8.3 BOD_5 Calculation (Unseeded)

Unlike the direct reading instrument used in the DO analysis, BOD results require calculation. Several criteria are used when selecting which BOD_5 dilutions should be used for calculating test results. Consult a laboratory testing reference manual (such as *Standard Methods*) for this information.

Currently, there are two basic calculations for BOD_5. The first is used for samples that have not been seeded. The second must be used whenever BOD_5 samples are seeded. In this section, we illustrate the calculation procedure for unseeded samples:

$$\text{BOD}_5\ \text{(Unseeded)} = \frac{\left[\text{DO}_{\text{start}}\ \text{(mg/L)} - \text{DO}_{\text{final}}\ \text{(mg/L)}\right] \times 300\ \text{mL}}{\text{Sample Volume (mL)}} \tag{18.8}$$

- ***Example 18.5***

Problem: The BOD_5 test is completed. Bottle 1 of the test had a DO of 7.1 mg/L at the start of the test. After 5 days, bottle 1 had a DO of 2.9 mg/L. Bottle 1 contained 120 mg/L of sample.

Solution:

$$\text{BOD}_5\ \text{(Unseeded)} = \frac{(7.1\ \text{mg/L} - 2.9\ \text{mg/L}) \times 300\ \text{mL}}{120\ \text{mL}} = 10.5\ \text{mg/L}$$

18.3.8.4 BOD_5 Calculation (Seeded)

If the BOD_5 sample has been exposed to conditions that could reduce the number of healthy, active organisms, the sample must be seeded with organisms. Seeding requires use of a correction factor to remove the BOD_5 contribution of the seed material:

$$\text{Seed Correction} = \frac{\text{Seed Material BOD}_5 \times \text{Seed in Dilution (mL)}}{300\text{ mL}} \tag{18.9}$$

$$\begin{array}{c}\text{BOD}_5\\ \text{(Seeded)}\end{array} = \frac{\left\{\left[\text{DO}_{\text{start}}\ \text{(mg/L)} - \text{DO}_{\text{final}}\ \text{(mg/L)}\right] - \text{Seed Correction}\right\} \times 300}{\text{Sample Volume (mL)}} \tag{18.10}$$

■ ***Example 18.6***

Problem: Using the data provided below, determine the BOD_5:

BOD_5 of seed material = 90 mg/L
Dilution #1 seed material = 3 mL
Sample = 100 mL
Start DO = 7.6 mg/L
Final DO = 2.7 mg/L

Solution:

$$\text{Seed Correction} = \frac{90\text{ mg/L} \times 3\text{ mL}}{300\text{ mL}} = 0.90\text{ mg/L}$$

$$\text{BOD}_5\ \text{(Seeded)} = \frac{\left[(7.6\text{ mg/L} - 2.7\text{ mg/L}) - 0.90\right] \times 300}{100\text{ mL}} = 12\text{ mg/L}$$

18.3.9 Solids Measurement

Solids in water are defined as any matter that remains as residue upon evaporation and drying at 103°C. They are separated into two classes: suspended solids and dissolved solids.

$$\begin{aligned}\text{Total Solids} &= \text{Suspended Solids (nonfilterable residue)}\\ &\quad + \text{Dissolved Solids (filterable residue)}\end{aligned}$$

As shown above, *total solids* are dissolved solids plus suspended and settleable solids in water. In natural freshwater bodies, dissolved solids consist of calcium, chlorides, nitrate, phosphorus, iron, sulfur, and other ions—particles that will pass through a filter with pores of around 2 µm (0.002 cm) in size. Suspended solids include silt and clay particles, plankton, algae, fine organic debris, and other particulate matter. These are particles that will not pass through a 2-µm filter.

The concentration of total dissolved solids affects the water balance in the cells of aquatic organisms. An organism placed in water with a very low level of solids (distilled water, for example) swells because water tends to move into its cells, which have a higher concentration of solids. An organism placed in water with a high concentration of solids shrinks somewhat, because the water in its cells tends to move out. This in turn affects the organism's ability to maintain the proper cell density, making it difficult for it to maintain its position in the water column. It might float up or sink down to a depth to which it is not adapted, and it might not survive.

Higher concentrations of suspended solids can serve as carriers of toxics, which readily cling to suspended particles. This is particularly a concern where pesticides are being used on irrigated crops. Where solids are high, pesticide concentrations may increase well beyond those of the original application as the irrigation water travels down irrigation ditches. Higher levels of solids can also clog irrigation devices and might become so high that irrigated plant roots will lose water rather than gain it.

A high concentration of total solids will make drinking water unpalatable and could have an adverse effect on people who are not used to drinking such water. Levels of total solids that are too high or too low can also reduce the efficiency of wastewater treatment plants, as well as the operation of industrial processes that use raw water.

Total solids affect water clarity. Higher solids decrease the passage of light through water, thereby slowing photosynthesis by aquatic plants. Water heats up more rapidly and holds more heat; this, in turn, might adversely affect aquatic life adapted to a lower temperature regime. Sources of total solids include industrial discharges, sewage, fertilizers, road runoff, and soil erosion. Total solids are measured in milligrams per liter.

18.3.9.1 Solids Sampling and Equipment Considerations

When conducting solids testing, many things can affect the accuracy of the test or result in wide variations in results for a single sample:

1. Drying temperature
2. Length of drying time
3. Condition of desiccator and desiccant
4. A lack of consistency among nonrepresentative samples in the test procedure
5. Failure to achieve constant weight prior to calculating results

Several precautions can be taken to improve the reliability of test results:

1. Use extreme care when measuring samples, weighing materials, and drying or cooling samples.
2. Check and regulate oven and furnace temperatures frequently to maintain the desired range.
3. Use an indicator drying agent in the desiccator that changes color when it is no longer good; change or regenerate the desiccant when necessary.
4. Keep the desiccator cover greased with the appropriate type of grease; this will seal the desiccator and prevent moisture from entering the desiccator as the test glassware cools.
5. Check ceramic glassware for cracks and glass fiber filters for possible holes. A hole in a glass filter will cause solids to pass through and give inaccurate results.
6. Follow manufacturers' recommendations for the care and operation of analytical balances.

Total solids are important to measure in areas where discharges from sewage treatment plants, industrial plants, or extensive crop irrigation may occur. In particular, streams and rivers in arid regions where water is scarce and evaporation is high tend to have higher concentrations of solids and are more readily affected by the human introduction of solids from land-use activities.

Total solids measurements can be useful as an indicator of the effects of runoff from construction, agricultural practices, logging activities, sewage treatment plant discharges, and other sources. As with turbidity, concentrations often increase sharply during rainfall, especially in developed watersheds. They can also rise sharply during dry weather if earth-disturbing activities occur in or near the stream without erosion control practices in place. Regular monitoring of total solids can help detect trends that might indicate increasing erosion in developing watersheds. Total solids are closely related to stream flow and velocity and should be correlated with these factors. Any change in total solids over time should be measured at the same site at the same flow.

Total solids are measured by weighing the amount of solids present in a known volume of sample; this is accomplished by weighing a beaker, filling it with a known volume, evaporating the water in an oven and completely drying the residue, then weighing the beaker with the residue. The total solids concentration is equal to the difference between the weight of the beaker with the residue and the weight of the beaker without it. Because the residue is so light in weight, the lab needs a balance that is sensitive to weights in the range of 0.0001 g. Balances of this type are called *analytical* or *Mettler balances*, and they are expensive (around $3000). The technique requires that the beakers be kept in a desiccator, a sealed glass container containing material that absorbs moisture and ensures that the weighing is not biased by water condensing on the beaker. Some desiccants change color to indicate moisture content. Measurement of total solids cannot be done in the field. Samples must be collected using clean glass or plastic bottles or Whirl-Pak® bags and taken to a laboratory where the test can be run.

18.3.9.2 Total Suspended Solids

The term *solids* refers to any material suspended or dissolved in water and wastewater. Although normal domestic wastewater contains a very small amount of solids (usually less than 0.1%), most treatment processes are designed specifically to remove or convert solids to a form that can be removed or discharged without causing environmental harm. In sampling for total suspended solids (TSS), samples may be either grab or composite and can be collected in either glass or plastic containers. TSS samples can be preserved by refrigeration at or below 4°C (not frozen); however, composite samples must be refrigerated during collection. The maximum holding time for preserved samples is 7 days.

18.3.9.2.1 Test Procedure

To conduct a TSS test, a well-mixed measured sample is poured into a filtration apparatus and, with the aid of a vacuum pump or aspirator, is drawn through a preweighted glass fiber filter. After filtration, the glass filter is dried at 103 to 105°C, cooled, and reweighed. The increase in weight of the filter and solids compared to the filter alone represents the total suspended solids. An example of the specific test procedure used for total suspended solids is given below.

1. Select a sample volume that will yield between 10 and 200 mg of residue with a filtration time of 10 minutes or less.

Note: If filtration time exceeds 10 minutes, increase filter area or decrease volume to reduce filtration time.

Note: For nonhomogeneous samples or samples with very high solids concentrations (e.g., raw wastewater or mixed liquor), use a larger filter to ensure that a representative sample volume can be filtered.

2. Place the preweighed glass fiber filter on the filtration assembly in a filter flask.
3. Mix the sample well, and measure the selected volume of sample.
4. Apply suction to the filter flask, and wet the filter with a small amount of laboratory-grade water to seal it.
5. Pour the selected sample volume into the filtration apparatus.
6. Draw the sample through the filter.
7. Rinse the measuring device into the filtration apparatus with three successive 10-mL portions of laboratory-grade water. Allow complete drainage between rinsings.
8. Continue suction for 3 minutes after filtration of the final rinse is completed.
9. Remove the glass filter from the filtration assembly (membrane filter funnel or clean Gooch crucible). If using the large disks and membrane filter assembly, transfer the glass filter to a support (aluminum pan or evaporating dish) for drying.

10. Place the glass filter with solids and support (pan, dish, or crucible) in a drying oven.
11. Dry the filter and solids to a constant weight at 103 to 105°C (at least 1 hour).
12. Cool to room temperature in a desiccator.
13. Weigh the filter, solids, and support, and record the constant weight in the test record.

18.3.9.2.2 TSS Calculations

To determine the total suspended solids concentration in milligrams per liter, we use the following equations:

1. To determine the weight of dry solids in grams:

$$\text{Dry Solids (g)} = \text{Weight of dry solids and filter (g)} - \text{Weight of dry filter (g)} \tag{18.11}$$

2. To determine the weight of dry solids in milligrams:

$$\text{Dry Solids (mg)} = \text{Weight of dry solids and filter (mg)} - \text{Weight of dry filter (mg)} \tag{18.12}$$

3. To determine the TSS concentration in milligrams per liter:

$$\text{TSS (mg/L)} = \frac{\text{Dry Solids (mg)} \times 1000\text{ mL}}{\text{Sample Volume (mL)}} \tag{18.13}$$

■ ***Example 18.7***

Problem: Using the data provided below, calculate total suspended solids (TSS):

Sample volume = 250 mL

Weight of dry solids and filter = 2.305 g

Weight of dry filter = 2.297 g

Solution:

$$\text{Dry Solids (g)} = 2.305\text{ g} - 2.297\text{ g} = 0.008\text{ g}$$

$$\text{Dry Solids (mg)} = 0.008\text{ g} \times 1000\text{ mg/g} = 8\text{ mg}$$

$$\text{TSS} = \frac{8.0 \times 1000\text{ mL/L}}{250\text{ mL}} = 32.0\text{ mg/L}$$

18.3.9.3 Volatile Suspended Solids Testing

When the total suspended solids are ignited at 550 ± 50°C, the volatile (organic) suspended solids of the sample are converted to water vapor and carbon dioxide and are released to the atmosphere. The solids that remain after the ignition (ash) are the inorganic or fixed solids. In addition to the equipment and supplies required for the total suspended solids test, you need the following:

1. Muffle furnace (550 ± 50°C)
2. Ceramic dishes
3. Furnace tongs
4. Insulated gloves

18.3.9.3.1 Test Procedure

An example of the test procedure used for volatile suspended solids is given below:

1. Place the weighed filter with solids and support from the total suspended solids test in the muffle furnace.
2. Ignite the filter, solids, and support at 550 ± 50°C for 15 to 20 minutes.
3. Remove the ignited solids, filter, and support from the furnace, and partially air cool.
4. Cool to room temperature in a desiccator.
5. Weigh the ignited solids, filter, and support on an analytical balance.
6. Record the weight of the ignited solids, filter, and support.

18.3.9.3.2 Total Volatile Suspended Solids Calculations

Calculating the total volatile suspended solids (TVSS) requires knowing the weight of the dry solids, filter, and support in grams (A) and the weight of the ignited solids, filter, and support in grams (C):

$$\text{TVSS (mg/L)} = \frac{(A - C) \times 1000\text{ mg/g} \times 1000\text{ mL/L}}{\text{Sample Volume (mL)}} \tag{18.14}$$

■ *Example 18.8*

Problem: Using the data provided below, calculate the total volatile suspended solids:

Weight of dried solids, filter, and support = 1.6530 g

Weight of ignited solids, filter, and support = 1.6330 g

Solution:

$$\text{TVSS} = \frac{(1.6530\text{ g} - 1.6330\text{ g}) \times 1000\text{ mg/g} \times 1000\text{ mL}}{100\text{ mL}}$$

$$= \frac{0.02 \times 1{,}000{,}000\text{ mg/L}}{100} = 200\text{ mg/L}$$

Note: *Total fixed suspended solids* (TFSS) is the difference between the total volatile suspended solids (TVSS) and the total suspended solids (TSS) concentrations:

$$\text{TFSS (mg/L)} = \text{TSS} - \text{TVSS} \tag{18.15}$$

- ***Example 18.9***

Problem: Calculate TFSS given the following data:

Total suspended solids (TSS) = 202 mg/L

Total volatile suspended solids (TVSS) = 200 mg/L

Solution:

$$\text{TFSS} = 202\text{ mg/L} - 200\text{ mg/L} = 2\text{ mg/L}$$

18.4 CHAPTER REVIEW QUESTIONS

18.1 How soon after the sample is collected must the pH be tested?

18.2 The operator titrates a 200-mL dissolved oxygen sample. The buret reading at the start of the titration was 0.0 mL. At the end of the titration, the buret read 7.1 mL. The concentration of the titration solution was 0025. What is the DO concentration in mg/L?

18.3 What is a grab sample?

18.4 Dissolved oxygen samples collected from the aeration tank and carried back to the lab for testing must be preserved by adding ________________.

18.5 When is it necessary to use a grab sample?

18.6 If a grab sample is to be used to evaluate plant performance, when should the influent and effluent samples be collected?

18.7 What is a composite sample?

18.8 Why is a composite sample more representative of the average characteristics of the wastewater?

18.9 List three rules for sample collection.

18.10 The approved method for pH testing requires ________________.

18.11 Who specifies the sample type, preservation method, and test method for effluent samples?

18.12 The *Guidelines Establishing Test Procedures for the Analysis of Pollutants Under the Clean Water Act* is a/an ______________ regulation.

18.13 The average daily flow is 7.66 MGD, and the effluent testing will require 3000 mL of sample. What is the proportioning factor if a 24-hour composite sample is to be collected?

18.14 The proportioning factor is 100, and the flow at the time the sample is collected (7 a.m.) is 4.66 MGD. How many milliliters of sample should be added to the composite sample container at 7 a.m.?

18.15 What is the maximum holding time and recommended preservation technique for BOD_5 samples?

18.16 The dissolve oxygen meter requires calibration at least once per ______________.

18.17 What is the difference between the BOD_5 and the $CBOD_5$ test?

18.18 Why is seeding required for samples with high or low pH or chlorinated samples?

18.19 What is the acceptable range of seed correction?

18.20 What is the acceptable preservation method for suspended solids samples?

18.21 Most solids test methods are based on changes in weight. What can cause changes in weight during the testing procedure?

CHAPTER 19

PERMITS, RECORDS, AND REPORTS

19.1 INTRODUCTION

Permits, records, and reports play a significant role in wastewater treatment operations. In fact, with regard to permits, one of the first things any new operator quickly learns is the importance of “making permit” each month. This chapter briefly covers National Pollutant Discharge Elimination System (NPDES) permits and other pertinent records and reports with which the wastewater operator must be familiar.

Note: The discussion that follows is general in nature; it does not necessarily apply to any state in particular but instead is an overview of permits, records, and reports that are an important part of wastewater treatment plant operations. For specific guidance on requirements for your locality, refer to your state water control board or other authorized state agency for information. In this handbook, the term *board* represents the state-reporting agency.

19.2 DEFINITIONS

Several definitions should be understood before we discuss the permit requirements for records and reporting:

Average daily limitation—The highest allowable average over a 24-hour period, calculated by adding all of the values measured during the period and dividing the sum by the number of values determined during the period.

Average hourly limitation—The highest allowable average for a 60-minute period, calculated by adding all of the values measured during the period and dividing the sum by the number of values determined during the period.

Average monthly limitation—The highest allowable average over a calendar month, calculated by adding all of the daily values measured during the month and dividing the sum by number of daily values measured during the month.

Average weekly limitation—The highest allowable average over a calendar week, calculated by adding all of the daily values measured during the calendar week and dividing the sum by the number of daily values determined during the week.

Daily discharge—The discharge of a pollutant measured during a calendar day or any 24-hour period that reasonably represents the calendar for the purpose of sampling. For pollutants with limitations expressed in units of weight, the daily discharge is calculated as the total mass of the pollutant discharged over the day. For pollutants with limitations expressed in other units, the daily discharge is calculated as the average measurement of the pollutant over the day.

Discharge monitoring report—Forms for use in reporting self-monitoring results of the permittee.

Discharge permit—State Pollutant Discharge Elimination System (SPDES) permit that specifies the terms and conditions under which a point source discharge to state waters is permitted.

Effluent limitation—Any restriction by the state board on quantities, discharge rates, or concentrations of pollutants discharged from point sources into state waters.

Maximum daily discharge—The highest allowable value for a daily discharge.

Maximum discharge—The highest allowable value for any single measurement.

Minimum discharge—The lowest allowable value for any single measurement.

Point source—Any discernible, defined, and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, vessel, or other floating craft from which pollutants are or may be discharged. This definition does not include return flows from irrigated agricultural land.

19.3 NPDES PERMITS

In the United States, all treatment facilities that discharge to state waters must have a discharge permit issued by the state water control board or other appropriate state agency. This permit is known on the national level as the National Pollutant Discharge Elimination System (NPDES) permit and on the state level as the State Pollutant Discharge

Elimination System (SPDES) permit. The permit states the specific conditions that must be met to legally discharge treated wastewater to state waters. The permit contains general requirements (applying to every discharger) and specific requirements (applying only to the point source specified in the permit). A general permit is a discharge permit, which covers a specified class of dischargers. It is developed to allow dischargers with the specified category to discharge under specified conditions. All discharge permits contain general conditions. These conditions are standard for all dischargers and cover a broad series of requirements. Read the general conditions of the treatment facility's permit carefully. Permittees must retain certain records, including those discussed below.

Key Point: All records must be kept at least 3 years (longer at the request of the State Board.

19.3.1 Monitoring

- Date, time, and exact place of sampling or measurements
- Names of the individuals performing sampling or measurement
- Dates and times analyses were performed
- Names of the individuals who performed the analyses
- Analytical techniques or methods used
- Observations, readings, calculations, bench data, and results
- Instrument calibration and maintenance
- Original strip chart recordings for continuous monitoring
- Information used to develop reports required by the permit
- Data used to complete the permit application

19.3.2 Reporting

Generally, reporting must be made under the following conditions or situations (requirements may vary depending on the state regulatory body with reporting authority):

Unusual or extraordinary discharge reports—Notify the board by telephone within 24 hours of occurrence and submit a written report within 5 days. The report must include:

- Description of the noncompliance and its cause
- Noncompliance date, time, and duration
- Steps planned/taken to reduce/eliminate the problem
- Steps planned/taken to prevent reoccurrence of the problem

Anticipated noncompliance—Notify the board at least 10 days in advance of any changes to the facility or activity that may result in noncompliance.

Compliance schedules—Report compliance or noncompliance with any requirements contained in compliance schedules no later than 14 days following the scheduled date for completion of the requirement.

24-hour reporting—Any noncompliance that may adversely affect state waters or may endanger public health must be reported orally with 24 hours of the time the permittee becomes aware of the condition. A written report must be submitted within 5 days.

Discharge monitoring reports (DMRs)—These report self-monitoring data generated during a specified period (normally 1 month). When completing the DMR, remember:

- More frequent monitoring must be reported.
- All results must be used to complete reported values.
- Pollutants monitored by an approved method but not required by the permit must be reported.
- No blocks on the form should be left blank.
- Averages are arithmetic unless noted otherwise.
- Appropriate significant figures should be used.
- All bypasses and overflows must be reported.
- The licensed operator must sign the report.
- A responsible official must sign the report.
- Department must receive reports by the 10th of the next month.

19.4 SAMPLING AND TESTING

The general requirements of the permit specify minimum sampling and testing that must be performed on the plant discharge. Moreover, the permit will specify the frequency of sampling, sample type, and length of time for composite samples. Unless a specific method is required by the permit, all sample preservation and analysis must be in compliance with the requirements set forth in the federal regulations *Guidelines Establishing Test Procedures for the Analysis of Pollutants Under the Clean Water Act* (40 CFR 136).

Key Point: All samples and measurements must be representative of the nature and quantity of the discharge.

19.4.1 Effluent Limitations

The permit sets numerical limitations on specific parameters contained in the plant discharge. Limits may be expressed as:

- Average monthly quantity (kg/day)
- Average monthly concentration (mg/L)
- Average weekly quantity (kg/day)
- Average weekly concentration (mg/L)

- Daily quantity (kg/day)
- Daily concentration (mg/L)
- Hourly average concentration (mg/L)
- Instantaneous minimum concentration (mg/L)
- Instantaneous maximum concentration (mg/L)

19.4.2 Compliance Schedules

If the facility requires additional construction or other modifications to fully comply with the final effluent limitations, the permit will contain a schedule of events to be completed to achieve full compliance.

19.4.3 Special Conditions

Any special requirements or conditions set for approval of the discharge are contained in this section. Special conditions may include:

- Monitoring required to determine effluent toxicity
- Pretreatment program requirements

19.4.4 Licensed Operator Requirements

The permit will specify, based on the treatment system complexity and the volume of flow treated, the minimum license classification required by the designated responsible charge operator.

19.4.5 Chlorination/Dechlorination Reporting

Several reporting systems apply to chlorination or chlorination followed by dechlorination. It is best to review this section of the specific permit for guidance. If confused, contact the appropriate state regulatory agency.

19.5 REPORTING CALCULATIONS

Failure to accurately calculate report data will result in violations of the permit. The basic calculations associated with completing the DMR are covered below.

19.5.1 Average Monthly Concentration

The average monthly concentration (AMC) is the average of the results of all tests performed during the month:

$$\text{AMC (mg/L)} = \frac{\text{Test}_1 + \text{Test}_2 + \text{Test}_3 + \ldots + \text{Test}_n}{\text{Number of tests during the month}} \tag{19.1}$$

19.5.2 Average Weekly Concentration

The average weekly concentration (AWC) is the result of all of the tests performed during a calendar week. A calendar week must start on Sunday and end on Saturday and be completely within the reporting month. A weekly average is not computed for any week that does not meet these criteria.

$$\text{AWC (mg/L)} = \frac{\text{Test}_1 + \text{Test}_2 + \text{Test}_3 + \ldots + \text{Test}_n}{\text{Number of tests during calendar week}} \tag{19.2}$$

19.5.3 Average Hourly Concentration

The average hourly concentration (AHC) is the average of all of the test results collected during a 60-minute period.

$$\text{AHC (mg/L)} = \frac{\text{Test}_1 + \text{Test}_2 + \text{Test}_3 + \ldots + \text{Test}_n}{\text{Number of tests during a 60-minute period}} \tag{19.3}$$

19.5.4 Daily Quantity

Daily quantity is the quantity of a pollutant in kilograms per day discharged during a 24-hour period:

$$\begin{aligned}\text{Daily Quantity (kg/day)} &= \text{Concentration (mg/L)} \times \text{Flow (MGD)} \\ &\quad \times 3.785 \text{ kg/mg/L/MG}\end{aligned} \tag{19.4}$$

19.5.5 Average Monthly Quantity (AMQ)

Average monthly quantity (AMQ) is the average of all of the individual daily quantities determined during the month:

$$\text{AMQ (kg/day)} = \frac{DQ_1 + DQ_2 + DQ_3 + \ldots + DQ_n}{\text{Number of tests during month}} \tag{19.5}$$

19.5.6 Average Weekly Quantity

The average weekly quantity (AWQ) is the average of all of the daily quantities determined during a calendar week. A calendar week must start on Sunday and end on Saturday and be completely within the reporting month. A weekly average is not computed for any week that does not meet these criteria:

$$\text{AWQ (kg/day)} = \frac{DQ_1 + DQ_2 + DQ_3 + \ldots + DQ_n}{\text{Number of tests during calendar week}} \tag{19.6}$$

19.5.7 Minimum Concentration

The minimum concentration is the lowest instantaneous value recorded during the reporting period.

19.5.8 Maximum Concentration

The maximum concentration is the highest instantaneous value recorded during the reporting period.

19.5.9 Bacteriological Reporting

Bacteriological reporting is used for reporting fecal coliform test results. To make this calculation the geometric mean calculation is used, and all monthly geometric means are computed using all of the test values. Note that weekly geometric means are computed using the same selection criteria discussed for average weekly concentration and quantity calculations. The easiest way to make this calculation is to use a calculator that can perform logarithmic (log) or *n*th root functions:

$$\text{Geometric Mean} = \text{Antilog}\left(\frac{\log X_1 + \log X_2 + \log X_3 + \ldots\ \log X_n}{\text{Number of Tests}}\right) \tag{19.7}$$

or

$$\text{Geometric Mean} = \sqrt[n]{X_1 \times X_2 \times \ldots \times X_n}$$

19.6 CHAPTER REVIEW QUESTIONS

Use the data in the chart below for the following questions:

Date	Day (MGD)	Flow (mg/L)	BOD_5 (kg/day)	BOD_5 (mg/L)	TSS (kg/day)	TSS (mg/L)	pH	DO
1	F	5.27	10.5	209.4	11.1	221.4	6.5	7.10
2	Sa	4.99	—	—	—	—	7.2	7.00
3	S	5.40	—	—	—	—	7.0	7.40
4	M	5.71	27.0	583.5	20.0	432.2	7.2	7.00
5	T	6.46	—	—	—	—	6.2	7.30
6	W	5.91	9.4	210.3	4.6	102.9	5.2	7.00
7	Th	5.09	—	—	—	—	5.0	7.00
8	F	5.89	14.3	—	20.3	452.6	6.0	7.20
9	Sa	5.31	—	—	—	—	6.6	7.20
10	S	5.82	—	—	—	—	7.0	7.10
11	M	6.42	4.2	102.1	5.3	128.8	6.1	7.26
12	T	5.72	—	—	—	—	5.6	7.30
13	W	5.12	21.5	416.7	4.3	83.3	5.5	7.40

Date	Day (MGD)	Flow (mg/L)	BOD_5 (kg/day)	BOD_5 (mg/L)	TSS (kg/day)	TSS (mg/L)	pH	DO
14	Th	6.09	—	—	—	—	5.4	7.30
15	F	5.08	15.7	301.9	11.8	226.9	5.0	7.35
16	Sa	6.22	—	—	—	—	5.3	7.55
17	S	5.44	—	—	—	—	5.3	7.10
18	M	5.99	21.7	492.0	17.3	392.2	6.3	7.41
19	T	6.83	—	—	—	—	5.4	7.25
20	W	5.53	48.3	1011	75.9	1588.7	4.5	6.88
21	Th	5.38	—	—	—	—	5.5	7.00
22	F	6.07	73.3	1684.1	48.7	1118.9	5.2	7.33
23	Sa	5.71	—	—	—	—	5.5	7.12
24	S	5.40	—	—	—	—	6.1	7.37
25	M	5.18	13.0	254.9	25.5	500.0	6.2	7.36
26	T	6.09	—	—	—	—	5.0	6.35
27	W	6.09	17.2	396.5	32.2	742.2	4.9	7.10
28	Th	7.08	—	—	—	—	5.1	6.40
29	F	5.36	41.8	848.0	55.7	1130	5.6	7.25
30	Sa	5.48	—	—	—	—	6.0	7.23
31	S	5.08	—	—	—	—	6.0	7.17

19.1 What was the daily quantity of BOD_5 on day 8?

19.2 What was the monthly average concentration of total suspended solids? If the permit specifies an average concentration of 27 mg/L, how many times did the plant violate its permit limit?

19.3 The plant permit specifies a maximum quantity (weekly average) of 980.4 kg/day. How many times did the plant effluent violate the maximum quantity for BOD_5 during the month?

19.4 What was the highest weekly average BOD_5 and total suspended solids concentration?

19.5 The permit specifies a minimum dissolved oxygen concentration of 6.0 mg/L. How many times did the effluent violate the permit limit for dissolved oxygen?

19.6 The plant's permit specifies a maximum pH concentration of 9.0 and minimum concentration of 6.5. How many times did the plant effluent violate the permit limit? What should be recorded in the maximum and minimum columns on the DMR?

19.7 Who must sign the DMR?

19.8 If an effluent test is performed more frequently than required by the permit, the extra tests ☐*do*/☐*do not* need to be included in the DMR.

CHAPTER 20

FINAL REVIEW EXAM

20.1 INTRODUCTION

Now that you have read each chapter and completed the chapter review questions, you can test your overall knowledge of the material contained in Volume I of the handbook by completing the following review examination. For the questions you have difficulty answering or that you answer wrong, review the pertinent sections containing the applicable subject matter. Successful review and completion of all of the requirements specified in this edition of the handbook should prepare you for the Class IV/Grade I licensing examinations and should set the stage for successful completion of the Class III/Grade II examinations. For those operators preparing for the Class III/Grade II and Class II/Grade III licensing exams, review and completion of the requirements in Volume II of these handbooks are highly recommended.

Unlike the actual state licensure examinations, which contain an assortment of different types of questions (e.g., multiple choice, true/false, essay, question completion), the final review examinations presented in each handbook require a written response to each question. I have formatted the examinations this way because experience has shown me that when studying for an exam (any exam), it is always best to write out the answer (for retention purposes). Moreover, when studying for an exam, it is best to view only the correct answer instead of several different choices that might be confused as being the correct answer, which could lead to the test taker selecting the wrong answer on the licensure exam—and you only want the correct answer! Upon completion of the final review exam, check your answers with those given in Appendix B.

20.2 REVIEW EXAM

20.1 Give three reasons for treating wastewater.

20.2 Name two types of solids based on physical characteristics.

20.3 Define *organic* and *inorganic*.

20.4 Name four types of microorganisms that may be present in wastewater.

20.5 When organic matter is decomposed aerobically, what materials are produced?

20.6 Name three materials or pollutants that are not removed by the natural purification process.

20.7 What are the used water and solids from a community that flow to a treatment plant called?

20.8 Where do disease-causing bacteria in wastewater come from?

20.9 What does the term *pathogenic* mean?

20.10 What is wastewater called that comes from households?

20.11 What is wastewater called that comes from industrial complexes?

Use the following data for Question 20.12 through Question 20.17:

Primary settling
Number = 2
Length = 180 ft
Width = 110 ft
Water depth = 12 ft

Aeration tank
Number = 4
Length = 210 ft
Width = 90 ft
Water depth = 14 ft

Secondary settling tank
Number = 4
Diameter = 120 ft
Water depth = 18 ft

20.12 The effluent weir on the secondary settling tank is located along the outer edge of the tank. What is the weir length in feet for each settling tank?

20.13 What is the surface area of each of the primary settling tanks in square feet?

20.14 What is the volume of each of the aeration tanks in cubic feet?

20.15 You wish to install a fence around each aeration tank to prevent falls into the tanks. How many feet of fence must be ordered?

20.16 The secondary settling tanks consist of a cylindrical section 18 ft deep and a cone-shaped bottom that has a depth of 8 ft. What is the total volume of each settling tank in cubic feet?

20.17 The lab test indicates that a 500-g sample of sludge contains 22 g of solids. What is the percent solids in the sludge sample?

20.18 The depth of water in the grit channel is 28 in. What is the depth in feet?

20.19 The operator withdraws 5250 gal of solids from the digester. How many pounds of solids have been removed?

20.20 Sludge added to the digester causes a 1920 ft^3 change in the volume of sludge in the digester. How many gallons of sludge have been added?

20.21 The plant effluent contains 30 mg/L of solids. The effluent flow rate is 3.40 MGD. How many pounds per day of solids are discharged?

20.22 The plant effluent contains 25 mg/L BOD_5. The effluent flow rate is 7.25 MGD. How many kilograms per day of BOD_5 are being discharged?

20.23 The operator wishes to remove 3280 lb of solids per day from the activated sludge process. The waste activated sludge concentration is 3250 mg/L. What is the required flow rate in million gallons per day?

20.24 Plant influent includes an industrial flow that contains 240 mg/L BOD. The industrial flow is 0.72 MGD. What is the population equivalent for the industrial contribution in people per day?

20.25 The label of hypochlorite solution states that the specific gravity of the solution is 1.1288. What is the weight of 1 gal of the hypochlorite solution?

Use the following data for Question 20.26 through Question 20.29:

Plant influent
Flow = 6.40 MGD
Suspended solids = 370 mg/L
BOD = 230 mg/L

Primary effluent
Flow = 8.40 MGD
Suspended solids = 130 mg/L
BOD = 170 mg/L

Activated sludge effluent
Flow = 8.34 mg/L
Suspended solids = 18 mg/L
BOD = 22 mg/L

Anaerobic digester
Solids in = 6.6%
Solids out = 13.5%
Volatile matter in = 66.5%
Volatile matter out = 48.9%

20.26 What is the plant percent removal for BOD_5?

20.27 What is the plant percent removal for TSS?

20.28 What is the primary treatment percent removal for BOD_5?

20.29 What is the percent volatile matter reduction in the digestion process?

Use the following data for Question 20.30 through Question 20.32:

Plant influent
Flow = 8.40 MGD

Grit channel
Number = 2
Channel length = 40 ft
Channel width = 3 ft
Water depth = 2.5 ft

Primary settling
Number = 2
Length = 140 ft
Width = 100 ft
Water depth = 12 ft

Anaerobic digester
Flow = 19,000 gpd
Volume = 115,000 ft^3

20.30 What is the hydraulic detention time in hours for primary settling when both tanks are in service?

20.31 What is the hydraulic detention time in the grit channel in minutes when both channels are in service?

20.32 What is the hydraulic detention time of the anaerobic digester in days?

20.33 What is the purpose of the bar screen?

20.34 What two methods are available for cleaning a bar screen?

20.35 Name two ways to dispose of screenings.

20.36 What must be done to the cutters in a comminutor to ensure proper operation?

20.37 The comminutor jams frequently. A review of the maintenance records indicates that the cutters were changed approximately 2 weeks ago, and the cutter alignment was checked yesterday. What are the possible causes for the continued jamming problem? What actions would you recommend to identify the specific cause?

20.38 What is grit? Give three examples of material that is considered to be grit.

20.39 The plant has three channels in service. Each channel is 2 ft wide and has a water depth of 3 ft. What is the velocity (fps) in the channel when the flow rate is 8.0 MGD?

20.40 The grit from the aerated grit channel has a strong hydrogen sulfide odor upon standing in a storage container. What does this indicate, and what action should be taken to correct the problem?

20.41 What is the purpose of primary treatment?

20.42 What is the purpose of the settling tank in the secondary or biological treatment process?

20.43 The circular settling tank is 90 ft in diameter and has a depth of 12 ft. The effluent weir extends around the circumference of the tank. The flow rate is 2.25 MGD. What is the detention time in hours, surface loading rate in gpd/ft^2, and weir overflow rate in gpd/ft?

Use the following data for Question 20.44 through Question 20.51:

Plant effluent
Flow = 0.44 MGD
Suspended solids = 370 mg/L
BOD = 380 mg/L

Population of town = 2850

Industrial contribution
Flow = 0.039 MGD
Suspended solids = 650 mg/L
BOD = 970 mg/L

Pond
Length = 1500 ft
Width = 1100 ft
Operating depth = 4.1 ft

20.44 What is the pond area in acres?

20.45 What is the pond volume in acre-feet?

20.46 What is the influent flow rate to acre-feet per day?

20.47 What is the influent flow rate in acre-inches per day?

20.48 What is the pond hydraulic detention time in days?

20.49 What is the pond hydraulic loading in inches/day?

20.50 What is the pond organic loading in pounds of BOD per acre per day?

20.51 What is the current population loading (including the industrial contributions)?

20.52 Give three classifications of ponds based on their location in the treatment system.

20.53 Describe the processes occurring in a raw sewage stabilization pond (facultative).

20.54 How do changes in the season affect the quality of the discharge from a stabilization pond?

20.55 What is the advantage of using mechanical or diffused aeration equipment to provide oxygen?

20.56 Describe how the dissolved oxygen level of the pond changes during the day.

20.57 What is the purpose of the polishing pond?

Use the following data for Question 20.58 through Question 20.62:

Plant effluent
Flow = 2.40 MGD
Suspended solids = 205 mg/L
BOD_5 = 196 mg/L

Trickling filters
Number = 2
Diameter = 90 ft
Media depth = 8 ft

Recirculation ratio = 1.5:1.0

20.58 What is the total flow in each filter in million gallons per day? (Assume that the flow is equally split.)

20.59 What will the total flow to each filter be in million gallons per day if the operator changes the recirculation rate to 0.7:1.0? (Assume that the flow is equally split between the two filters.)

20.60 What is the hydraulic loading in gallons per day per square foot for each filter at the 1.5:1.0 recirculation ratio? (Assume that the flow is equally split between the two filters.)

20.61 What would the hydraulic loading in gallons per day per square foot be for each filter at a 0.75:1.0 recirculation ratio? (Assume that the flow is equally split between the two filters.)

20.62 What would the organic loading in pounds of BOD per 1000 ft^3 for each filter be at a 0.80:1.0 recirculation ratio? (Assume that the flow is equally split between the filters.)

20.63 Name three main parts of the trickling filter, and give the purposes of each part.

20.64 Name three classifications of trickling filters, and identify the classification that produces the highest quality effluent.

Use the following data for Question 2.65 through Question 20.67:

RBC influent

Flow = 8.40 MGD
Suspended solids = 150 mg/L
BOD_5 = 190 mg/L

RBC design

Number of stages = 8
Media area, Stage 1 = 250,000 ft^2
Media area, Stage 2 = 220,000 ft^2
Media area, Stages 3 to 8 = 150,000 ft^2 each
K factor = 0.55
Hydraulic loading = 7.1 gpd/ft^2
SOL = 6.5 lb BOD/1000 ft^2

20.65 What is the hydraulic loading in gpd/ft^2?

20.66 What is the total organic loading (TOL) in pounds of BOD/day/1000 ft^2?

20.67 What is the soluble BOD organic loading (SOL) in pounds of BOD/day/1000 ft^2 of media?

20.68 Describe the process occurring in the rotating biological contactor process.

20.69 What makes the RBC process similar to the trickling filter?

20.70 Describe the appearance of the slime when the RBC is operating properly. What happens if the RBC is exposed to a wastewater containing high amounts of sulfur?

Use the following data for Question 20.71 through Question 20.75:

Influent

Flow = 2.10 MGD
BOD = 230 mg/L
TSS = 370 mg/L

Primary effluent

Flow = 2.10 MGD
BOD = 175 mg/L
TSS = 130 mg/L

Activated sludge process effluent

Flow = 2.10 MGD

BOD = 22 mg/L

TSS = 18 mg/L

Aeration tank

Volume = 1,255,000 gal

MLSS = 2750 mg/L

MLVSS = 1850 mg/L

SSV test

Sample = 2000 mL

30 minutes = 1750 mL

60 minutes = 1050 mL

Waste

Flow = 0.090 MGD

Solids = 6120 mg/L

Volatile = 66%

Return

Flow = 0.50 MGD

Solids = 5750 mg/L

Settling tank

Volume = 880,000 gal

Desired F/M ratio = 0.25 lb/lb

Desired MCRT = 6.5 days

20.71 What is the percent of SSV_{30}?

20.72 What is the SSV_{60} in mL/L?

20.73 Using the SSV_{30} in mL/L, what is the sludge volume index?

20.74 What is the food-to-microorganism (F/M) ratio?

20.75 What is the mean cell residence time in days? (Assume that the clarifier solids concentration equals the aeration tank MLSS.)

20.76 Microscopic examination reveals a predominance of rotifers. What process adjustment does this indicate is required?

20.77 Increasing the wasting rate will ____________ the MLSS, ____________ the return concentration, ____________ the MCRT, ____________ the F/M ratio, and ____________ the SVI.

20.78 The plant adds 320 lb/day of dry hypochlorite powder to the plant effluent. The hypochlorite powder is 45% available chlorine. What is the chlorine feed rate in pounds per day?

20.79 The plant uses liquid HTH, which is 67.9% available chlorine and has a specific gravity of 1.18. The required feed rate to comply with the plant's discharge permit total residual chlorine limit is 285 lb/day. What is the required flow rate for HTH solution in gallons per day?

20.80 The plant currently uses 45.8 lb of chlorine per day. Assuming that the chlorine usage will increase by 10% during the next year, how many 2000-lb cylinders of chlorine will be needed for the year (365 days)?

20.81 The plant has six 2000-lb cylinders on hand. The current dose of chlorine being used to disinfect the effluent is 6.2 mg/L. The average effluent flow rate is 2.25 MGD. Allowing 15 days for ordering and shipment, when should the next order for chlorine be made?

20.82 The plant feeds 38 lb of chlorine per day and uses 150-lb cylinders. Chlorine use is expected to increase by 11% next year. The chlorine supplier has stated that the current price of chlorine ($0.170 per pound) will increase by 7.5% next year. How much money should the town budget for its chlorine purchase for the next year (365 days)?

20.83 What is the difference between disinfection and sterilization?

20.84 To be effective, chlorine must be added to satisfy the ____________ and produce a ________________ mg/L ________________ for at least ________________ minutes at design flow rates.

20.85 Elemental chlorine gas is ________________ in color and is ________________ times heavier than air.

20.86 The sludge pump operates 30 minutes every 3 hours. The pump delivers 70 gpm. If the sludge is 5.1% solids and has a volatile matter content of 66%, how many pounds of volatile solids are removed from the settling tank each day?

20.87 The aerobic digester has a volume of 63,000 gal. The laboratory test indicates that 41 mg of lime were required to increase the pH of a 1-L sample of digesting sludge from 6.0 to the desired 7.1. How many pounds of lime must be added to the digester to increase the pH of the unit to 7.1?

20.88 The digester has a volume of 73,500 gal. Sludge is added to the digester at the rate of 2750 gal/day. What is the sludge retention time in days?

20.89 What is the normal operating temperature of a heated anaerobic digester? What is the maximum change that should be made in a day to avoid reductions in gas production?

20.90 The supernatant contains 340 mg/L volatile acids and 1830 mg/L alkalinity. What is the volatile acids-to-alkalinity ratio?

20.91 The digester is 50 ft in diameter and has a depth of 25 ft. Sludge is pumped to the digester at rate of 6000 gal/day. What is the sludge retention time?

20.92 The raw sludge pumped to the digester contains 72% volatile matter. The digested sludge removed from the digester contains 48% volatile matter. What is the percent volatile matter reduction?

20.93 Who must sign the DMR?

20.94 What does NPDES stand for?

20.95 How can primary sludge be freshened going into a gravity thickener?

20.96 What are the two most important factors affecting the operation of a centrifuge?

20.97 A vacuum filter, in order to be effective, requires what type of sludge conditioning?

20.98 A neutral solution has what pH value?

20.99 Why is the seeded BOD test required for some samples?

20.100 What is the foremost advantage of the COD over the BOD?

APPENDIX A

ANSWERS TO CHAPTER REVIEW QUESTIONS

CHAPTER 2 REVIEW QUESTIONS

2.1 Matching answers

1. o
2. c
3. t
4. j
5. s
6. p
7. d
8. i
9. e
10. q
11. u
12. k
13. a
14. v
15. r
16. w
17. l
18. x
19. m
20. y
21. f
22. b
23. z
24. h
25. n
26. g

CHAPTER 3 REVIEW QUESTIONS

3.1 0

3.2 $C = D\pi$: 140 ft × 3.14 = 440 ft

3.3 $A = LD$: 120 ft × 60 ft = 7200 ft^2

3.4 20 ft + 5 ft, D = 80 ft
0.785 × 80 ft × 80 ft × 20 ft = 100,480 ft^3
0.262 × 80 ft × 80 ft × 5 ft = 8384 ft^3
Total = 108,864 ft^3

3.5 6.5%/100 × 8000 × 8.34 = 4337 lb

3.6 20 g × 100/600 g = 3.3%

3.7 20 g × 100/500 g = 4%

3.8 3.14 × 100 ft = 3.14 ft

3.9 130 ft × 110 ft = 14,300 ft^2

3.10 250 × 110 ft × 14 ft = 385,000 ft^3

3.11 (2 × 250 ft) + (2 × 110 ft) = 720 ft × 4 = 2880 ft

3.12 0.784 × 100 ft × 100 ft × 18 ft = 141,300 ft^3
0.262 × 100 ft × 100 ft × 10 ft = 26,200 ft^3
Total = 167,500 ft^3

3.13 32 mg/L

3.14 Day 8, 34.7 mg/L; Day 9, 31.0 mg/L

CHAPTER 4 REVIEW QUESTIONS

4.1 36 in. ÷ 12 in./ft = 3 ft

4.2 5269 gal × 8.34 lb/gal = 43,943 lb

4.3 1996 ft^3 × 7.48 gal/ft^3 = 14,930 gal

4.4 35 mg/L × 3.69 MGD × 8.34 lb/MG/mg/L = 1077 lb/day

4.5 26 mg/L × 7.25 MGD × 3.785 kg/mg/L/MG = 713 kg/day

4.6 3540 lb/day ÷ (3524 mg/L × 8.34 lb/MG/mg/L) = 0.120 MG

4.7 $$\frac{(235\ \text{mg/L} \times 0.70\ \text{MGD} \times 8.35\ \text{lb/MG/mg/L})}{(0.17\ \text{lb BOD}_5/\text{person})} = 8070\ \text{people}$$

4.8 BOD = 0.21 lb/capita/day; SS = 0.28 lb/capita/day

$$\text{Per capita BOD}_5\ \text{conc.} = \frac{0.21\ \text{lb/capita/day} \times 108\ \text{gal/M gal}}{8.34\ \text{lb/MG/mg/L} \times 110\ \text{gal/capita/day}} = 229\ \text{mg/L}$$

$$\text{Per capita SS conc.} = \frac{0.28\ \text{lb/capita/day} \times 106\ \text{gal/M gal}}{8.34\ \text{lb/MG/mg/L} \times 110\ \text{gal/capita/day}} = 305\ \text{mg/L}$$

4.9 8.34 lb/gal × 1.1545 = 9.63 lb/gal

CHAPTER 5 REVIEW QUESTIONS

5.1 $$\frac{(225\text{ mg/L} - 24\text{ mg/L}) \times 100}{225\text{ mg/L}} = 89\%$$

5.2 $$\frac{(350\text{ mg/L} - 17\text{ mg/L}) \times 100}{350\text{ mg/L}} = 95\%$$

5.3 $$\frac{(225\text{ mg/L} - 175\text{ mg/L}) \times 100}{225\text{ mg/L}} = 22\%$$

5.4 $$\frac{(350\text{ mg/L} - 144\text{ mg/L}) \times 100}{350\text{ mg/L}} = 59\%$$

5.5 $$\frac{(0.663 - 0.491) \times 100}{0.663 - (0.663 \times 0.491)} = 51\%$$

CHAPTER 6 REVIEW QUESTIONS

6.1 Tank Volume = 70 ft × 16 ft × 10 ft × 7.48 gal/ft^3 = 83,776 gal

1.35 MGD = 1,350,000 gal/1 day

Det. Time = 83,776 gal × 1 day/1,350,000 gal × 24 hr/day = 1.5 hr

6.2 $$\frac{(0.663 - 0.491) \times 100}{0.663 - (0.663 \times 0.491)} = 51\%$$

6.3 $$\frac{600\text{ ft} \times 4\text{ ft} \times 2.6\text{ ft} \times 2\text{ channels} \times 7.48\text{ gal/ft}^3 \times 1440\text{ min/day}}{8.40\text{ MGD} \times 1{,}000{,}000\text{ gal/MG}} = 1.6\text{ min}$$

6.4 $$\frac{110{,}000\text{ ft}^3 \times 7.48\text{ gal/ft}^3}{19{,}000\text{ gpd}} = 43\text{ days}$$

CHAPTER 7 REVIEW QUESTIONS

7.1 Secondary maximum contaminant levels

7.2 Transpiration

7.3 Surface water

7.4 Agriculture, municipal wastewater plants, habitat and hydrologic modifications, resource extraction, and urban runoff and storm sewers

7.5 Solids content

7.6 Turbidity

7.7 Universal solvent

7.8 Alkalinity

7.9 Neutral state

7.10 Lead

7.11 The amount of organic matter that can be biologically oxidized under controlled conditions (5 days at 20°C in the dark)

7.12 Human and animal wastes (body discharges); household waste (e.g., garbage, paper, cleaning materials); industrial waste (waste material from industrial processes)

7.13 *Organic* indicates matter that is made up mainly of carbon, hydrogen, and oxygen and will decompose into mainly carbon dioxide and water at 550°C. *Inorganic* indicates mineral matter that is made up of elements such as aluminum, iron, sodium, or chlorine (substances that will not be destroyed when burned at 550°C).

7.14 Dissolved and suspended

7.15 Water from street drains, parking lots, roof drains, etc., which can hydraulically overload the plant

7.16 Domestic, sanitary, and industrial

7.17 Prevent disease, protect aquatic organisms, and protect water quality.

CHAPTER 8 REVIEW QUESTIONS

8.1 Algae, bacteria, rotifers, viruses, protozoa

8.2 Pathogenic organisms

8.3 Carbon dioxide, stable solids, more organisms

8.4 Color turns gray, solids settle, DO decreases rapidly, fish disappear, microorganism population increases rapidly.

8.5 Zone of active decomposition

8.6 Process can return to degradation or active decomposition zones.

8.7 Inorganic solids, toxic materials, and pathogenic organisms.

8.8 Proper pH, adequate supply of organic mater (biodegradable), adequate supply of oxygen, enough nutrients, no toxic matter, enough water

8.9 Bacteria, viruses, protozoa

8.10 During rain storms

8.11 No

8.12 Binary fission

8.13 Spheres, rods, spirals

8.14 Typhoid, cholera, gastroenteritis

8.15 Amoebic dysentery, giardiasis

8.16 Cyst

8.17 Host

8.18 Clog screens, machinery; cause taste and odor problems

8.19 No, bacteria is Machiavellian—it is a survivor.

CHAPTER 9 REVIEW QUESTIONS

9.1 669.9 $ft^3 \times 7.48$ gal/$ft^3 = 5011$ gal

9.2 (1) 120 lb – 85 lb = 35 lb; (2) specific gravity = 120/35 = 3.4

9.3 (1) 8.34 lb/gal × 0.91 = 7.59 lb/gal; (2) 1270 gal × 7.59 lb/gal = 9639 lb

9.4 65 ft × 0.433 psi/ft = 28.1 psi

9.5 Height in feet = 14 psi ÷ 0.433 psi/ft = 32.3 ft

9.6 Static head = Discharge Elevation – Supply Elevation
2566 ft – 2133 ft = 433 ft

CHAPTER 10 REVIEW QUESTIONS

10.1 Positive-displacement

10.2 High-viscosity

10.3 Positive displacement

10.4 High

10.5 High

10.6 Eye

10.7 Static, dynamic

10.8 Shut off

10.9 $V^2/2g$

10.10 Total head

10.11 Head capacity, efficiency, horsepower demand

10.12 Water

10.13 Suction lift

10.14 Elevation head

10.15 Water horsepower and pump efficiency

10.16 Centrifugal force

10.17 Stuffing box

10.18 Impeller

10.19 Rings, impeller

10.20 Casing

CHAPTER 11 REVIEW QUESTION

11.1 To lift the wastewater to provide energy for continued flow to the treatment plant

CHAPTER 12 REVIEW QUESTIONS

12.1 To protect the plant equipment and remove materials that are not affected by treatment

12.2 To remove large solids (rags, sticks, rocks, etc.)

12.3 Manual, mechanical

12.4 Burial, incineration, grinding, and return to flow

12.5 Sharpen and align

12.6 Rate of flow, depth of the wastewater in the channel, width of the channel, and number of channels in service

12.7 $$V = \frac{8.0\text{ MGD} \times 1.55\text{ cfs/MGD}}{3\text{ channels} \times 2\text{ ft} \times 3\text{ ft}} = .69\text{ fps}$$

12.8 Reduce odors, freshen septic wastes, reduce BOD_5, prevent corrosion, improve settling and flotation

12.9 To prevent the excessive pump wear caused by grit and to prevent it from taking up valuable space in downstream units

12.10 1 ft/s

12.11 1.4 ft/s

12.12 $$\frac{4.5\text{ MG}}{1\text{ day}} \times \frac{1\text{ day}}{24\text{ hr}} \times \frac{84\text{ hr}}{1} = 15.75\text{ MG};\quad \frac{4\text{ ft} \times 5\text{ ft} \times 2\text{ ft}}{15.75\text{ MG}} = 2.5\text{ ft}^3\text{/MG}$$

12.13 Anaerobic

12.14 Flow rate in open channels

12.15 Decrease slowly, then return to saturation slowly

12.16 Slow the wastewater so the heavy inorganic material will settle out.

12.17 Remove settleable solids

CHAPTER 13 REVIEW QUESTIONS

13.1 To reduce settleable and floatable solids

13.2 $$VM = 75\text{ gpm} \times \frac{20\text{ min}}{3\text{ hr}} \times \frac{24\text{ hr}}{\text{day}} \times \frac{5.5\%}{100} \times \frac{66\%}{100} \times \frac{8.34\text{ lb}}{\text{gal}} = 3633\text{ lb/day}$$

13.3 $$\frac{0.785 \times 80\text{ ft} \times 80\text{ ft} \times 12\text{ ft} \times 7.48\text{ gal/ft}^3 \times 24\text{ hr/day}}{2.6\text{ MGD} \times 1{,}000{,}000\text{ gal/MG}} = 4.2\text{ hr}$$

Note: 1 to 3 hr is recommended; obviously, 4.2 hr exceeds this limit.

$$\frac{2.6\text{ MGD} \times 1{,}000{,}000\text{ gal/MG}}{0.785 \times 80\text{ ft} \times 80\text{ ft}} = 517.5\text{ gpd/ft}^2$$

$$\frac{2.6\text{ MGD} \times 1{,}000{,}000\text{ gal/MG}}{3.14 \times 80\text{ ft}} = 10{,}350\text{ gpd/ft}$$

13.4 Operate sludge pumping often enough to prevent large amounts of septic solids on the surface of the settling tank while maintaining a percent sludge solids of 4 to 8%.

13.5 To prevent floatable solids (scum) from leaving the tank

13.6 90 to 95% of the settleable solids

13.7 1.5 to 2.5 hr

13.8 Surface = 80 ft × 20 ft = 1600 ft^2

$$\text{Surface Overflow Rate} = \frac{1{,}500{,}000\text{ gpd}}{1600\text{ ft}^2} = 937.5\text{ gpd/ft}^2$$

13.9 $$\text{WOR} = \frac{1{,}250{,}000\text{ gpd}}{80\text{ ft}} = 15{,}625\text{ gpd/ft}$$

13.10 Tank Volume = 80 ft × 20 ft × 12 ft × 7.48 gal/ft^3 = 143,616 gal

$$\text{Detention Time} = 3 \times 143{,}616\text{ gal} \times \frac{1\text{ day}}{5{,}000{,}000} \times \frac{24\text{ hr}}{1\text{ day}} \times \frac{60\text{ min}}{1\text{ hr}}$$

$$= 124\text{ min}$$

$$\text{SOR} = \frac{5{,}000{,}000\text{ gpd}}{3 \times 80\text{ ft} \times 20\text{ ft}} = 1042\text{ gpd/ft}^2$$

$$\text{WOR} = \frac{5{,}000{,}000\text{ gpd}}{3 \times 86\text{ ft}} = 19{,}380\text{ gpd/ft}^2$$

13.11 2.8 hr

CHAPTER 14 REVIEW QUESTIONS

14.1 Facultative ponds

14.2 Stabilization pond, oxidation pond, polishing pond

14.3 Settling, anaerobic digestion of settled solids, aerobic/anaerobic decompositions of dissolved and colloidal organic solids by bacteria producing stable solids and carbon dioxide, photosynthesis production of oxygen by algae

14.4 Summer effluent is high in solids (algae) and low in BOD_5; winter effluent is low in solids and high in BOD_5.

14.5 $609 \text{ ft} \times 425 \text{ ft} \times 6 \text{ ft} \times \dfrac{7.48 \text{ gal}}{1 \text{ ft}^3} = 13{,}161{,}000 \text{ gal}$

$$13{,}161{,}060 \text{ gal} \times \frac{1 \text{ day}}{300{,}000 \text{ gal}} = 43.9 \text{ days}$$

14.6 $730 \text{ ft} \times 410 \text{ ft} \times \dfrac{1 \text{ ac}}{43{,}560 \text{ ft}^2} = 6.87 \text{ acre}$

$$\frac{0.66 \text{ ac-ft/day}}{6.87 \text{ ac}} = 0.096 \text{ in./day}$$

14.7 (1) Distribution to spread the wastewater evenly over the media; (2) media to support the biological growth; (3) underdrains to collect the flow and transport it out of the filter, provide ventilation, and support the media

14.8 Standard rate, high rate, roughing

14.9 Standard rate

14.10 To provide additional oxygen, reduce organic loading, improve sloughing, reduce odors, eliminate filter flies

14.11 Total = 2.3 MGD × (1.0 + 0.80) = 4.1 MGD

14.12 To remove sloughings from the wastewater prior to discharge

14.13 Arm movement, distribution, orifice clogging, odors, operational problem indications

14.14 0.288 MGD + 0.366 MGD = 0.654 MGD

Surface Area = $0.785 \times (90 \text{ ft})^2 = 6359 \text{ ft}^2$

$$\frac{654{,}000 \text{ gpd}}{6359 \text{ ft}^2} = 103 \text{ gpd/ft}^2$$

14.15 4.30 MGD ÷ 3.0 MGD = 1.43 MGD

14.16 A series of plastic disks placed side by side on a shaft; the disks are suspended in a channel of wastewater and rotate through the wastewater.

14.17 Slime on disks collects organic solids from the wastewater; organisms biologically oxidize the materials to produce stable solids. As the disk moves through the air, oxygen is transferred to the slime to keep it aerobic. Excess solids are removed as sloughings as the disk moves through the wastewater.

14.18 No. An RBC must follow primary settling in order to remove the settleable solids. An RBC is designed to treat only soluble material.

14.19 White biomass indicates filamentous bacteria growth.

14.20 Standard density and high density.

14.21 The biological growth is attached to the media.

14.22 The unit is normally covered and maintains the same temperature throughout the year.

14.23 Gray, shaggy, translucent is normal. Sulfur will cause slime to become white and chalky in appearance.

14.24 Nitrification is occurring in the later stages of the process.

14.25 $\frac{425{,}000 \text{ gpd}}{200{,}000 \text{ ft}^2} = 2.25 \text{ gpd/ft}^2$

CHAPTER 15 REVIEW QUESTIONS

15.1 Provides the needed oxygen for the microorganisms and the required mixing to put the food and microorganisms together

15.2 Activated sludge

15.3 Mixed liquor

15.4 Food, oxygen, and organisms

15.5 To remove BOD

15.6 Mechanical and diffused

15.7 Aeration tank color, foam, odors, settling tank capacity, solids loss, aeration rates, process control tests, etc.

15.8 $\text{SSV}_{60} = \frac{1300 \text{ mL} \times 1000}{2200 \text{ mL}} = 591 \text{ mL}$

15.9 $\text{SVI} = \frac{420 \times 1000 \text{ gpd}}{2245 \text{ mL}} = 187$

15.10 Waste = 8185 mg/L × 0.069 MGD × 8.34 = 4710 lb/day

15.11 Contact stabilization

15.12 Gravity thickening, dissolved air flotation thickening, and sludge concentration (belt thickener)

CHAPTER 16 REVIEW QUESTIONS

16.1 *Disinfection* destroys pathogenic organisms; *sterilization* destroys all organisms.

16.2 Demand; 1; residual; 30

16.3 Yellow green; 2.5

16.4 Chlorine is a toxic substance.

16.5 $\text{Dose} = \frac{400 \text{ lb/day}}{(5.55 \text{ MGD} \times 8.34)} = 8.64 \text{ mg/L}$

16.6 7.1 mg/L

16.7 May be required by plant's permit because chlorine is very toxic to aquatic organisms and must be removed to prevent stream damage

16.8 HTH/day × 0.42 Available Chlorine = 147 lb Chlorine/day

16.9 $$\frac{290\text{ lb Chlorine/day}}{0.69\%\text{ Available Chlorine}\times 8.34\text{ lb/gal}\times 1.18} = 42.7\text{ gpd}$$

16.10 $$\frac{45.7\text{ lb/day}\times 1.10\times 365\text{ days}}{2000\text{ lb/container}} = 9.2\text{, or 10 containers}$$

16.11 Chlorine and its byproducts (e.g., chloramines) are very toxic.

CHAPTER 17 REVIEW QUESTIONS

17.1 30 min/cycle × (24 hr ÷ 3 hr/cycle) × 65 gpm × 8.34 lb/gal × .052 × .66 = 4465 lb/day

17.2 Gravity thickeners, flotation thickeners, sludge concentrators

17.3 Primary sludge

17.4 Aerobic digesters, anaerobic digesters, composting, heat treatment, chlorine oxidation, lime stabilization

17.5 Sand drying beds, vacuum filtration, belt filtering, centrifuges, incineration

17.6 Drainage and evaporation

17.7 $$\frac{41\text{ mg}\times 52{,}000\text{ gal}\times 3.785\text{ L/gal}}{1\text{ L}\times 454\text{ g/lb}\times 1000\text{ mg/g}} = 18\text{ lb}$$

17.8 72,000 gal ÷ 2780 gpd = 26 days

17.9 90 to 95°F

17.10 335 mg/L ÷ 1840 mg/L = 0.18 lb

17.11 $$\frac{0.785\times 45\text{ ft}\times 5\text{ ft}\times 22\text{ ft}\times 7.48\text{ gal/ft}^3}{4800\text{ gpd}} = 54.5\text{ days}$$

17.12 $$\frac{(0.70-0.47)\times 100}{0.70-(0.70\times 0.47)} = 62\%$$

17.13 $$\text{Area} = 3.14\times 10\text{ ft}\times 8.4\text{ ft} = 263.8\text{ ft}^2$$

$$\frac{30\text{ gal}}{1\text{ min}}\times\frac{60\text{ min}}{1\text{ hr}}\times\frac{8.34\text{ lb}}{1\text{ gal}}\times\frac{12\%}{100\%} = 1801.4\text{ lb/hr}$$

$$\frac{1801.4}{263.8} = 6.8\text{ lb/hr/ft}^2$$

17.14 Returned to the plant for treatment

17.15 Reduce sludge volume, stabilize organic matter, and recover organic matter for use in the plant.

CHAPTER 18 REVIEW QUESTIONS

18.1 15 minutes

18.2 $$\text{DO} = \frac{(7.1\text{ mL} - 0.0\text{ mL}) \times 0.025\ N \times 8000}{200\text{ mL}} = 7.1\text{ mg/L}$$

18.3 A sample collected all at one time, representative of the conditions only at the time taken

18.4 10 mL/L of copper sulfate–sulfanic acid solution

18.5 For pH, dissolved oxygen, total residual chlorine, fecal coliform, and any test required by NPDES permit for grab samples

18.6 At different times to allow for the time it takes for wastewater to pass through treatment units

18.7 A series of samples collected over a specified period of time in proportion to flow

18.8 Composite samples reflect conditions in wastewater over a period of time.

18.9 Collect from well-mixed locations, clearly mark sampling points, and choose easy locations to read; sample should have no large or unusual particles nor deposits, growths, or floating materials; use corrosion-resistant containers; follow safety procedures; test samples as soon as possible.

18.10 A meter, reference electrode, and glass electrode

18.11 USEPA regulation (40 CFR 136) and the plant's permit

18.12 USEPA

18.13 3000 mL ÷ (24 samples × 7.66 MGD) = 16.3

18.14 mL of sample = 100 × 4.66 MGD = 466, or 470 mL

18.15 48 hours when preserved using refrigeration at 4°C.

18.16 Day

18.17 In the CBOD test, the nitrogenous oxygen demand is eliminated.

18.18 To ensure that healthy organisms are available

18.19 0.6 to 1.0 mg/L

18.20 Refrigerate at 4°C

18.21 Absorption of water during cooling, contaminants, fingerprints, etc.

CHAPTER 19 REVIEW QUESTIONS

19.1 14.3 mg/L × 5.89 MGD × 3.786 kg/MG/mg/L = 318.8 kg

19.2 Total 332.7; average = 332.7/13 = 25.6 (no violation)

19.3 Week 1, 370.9 kg/day Week 3, 1062.4 kg/day (violation)

Week 2, 273.4 kg/day Week 4, 499.8 kg/day

19.4

	BOD$_5$ (mg/L)	TSS (mg/L)
Week 1	16.9	15.0
Week 2	13.8	7.1
Week 3	47.8	47.3
Week 4	24.0	37.8

19.5 No violation occurred.

19.6 Minimum = 4.5 and maximum = 7.2; 25 exceptions (violations) occurred

19.7 The licensed operator and the responsible official

19.8 DO

APPENDIX B

ANSWERS TO FINAL REVIEW EXAM (CHAPTER 20)

20.1 Prevent disease, protect aquatic organisms, protect water quality

20.2 Dissolved and suspended

20.3 *Organic* indicates that the matter is made up mainly of carbon, hydrogen, and oxygen and will decompose into mainly carbon dioxide and water at 550°C.

20.4 Algae, bacteria, protozoa, rotifers, virus

20.5 Carbon dioxide, water, more organism, stable solids

20.6 Toxic matter, inorganic dissolved solids, pathogenic organisms

20.7 Raw effluent

20.8 From body wastes of humans who have disease

20.9 Disease-causing

20.10 Domestic waste

20.11 Industrial waste

20.12 $3.14 \times 120\text{ ft} = 377\text{ ft}$

20.13 $180\text{ ft} \times 110\text{ ft} = 19{,}800\text{ ft}^3$

20.14 $210\text{ ft} \times 90\text{ ft} \times 14\text{ ft} = 264{,}600\text{ ft}^3$

20.15 $[(2 \times 210\text{ ft}) + (2 \times 90\text{ ft})] \times 4 = 2400\text{ ft}$

20.16 $0.785 \times 120\text{ ft} \times 120\text{ ft} \times 18\text{ ft} = 203{,}472\text{ ft}^3$

$203{,}472\text{ ft}^3 + 30{,}182.4\text{ ft}^3 = 233{,}654.4\text{ ft}^3$

20.17 $(22\text{ g} \times 100) \div 500\text{ g} = 4.4\%$

20.18 2.3 ft

20.19 5250 gal × 8.34 lb/gal = 43,785 lb

20.20 1920 ft^3 × 7.48 gal/ft^3 = 14,362 gal

20.21 30 mg/L × 3.40 MGD × 8.34 lb/MG/mg/L = 850.7 lb/day

20.22 5 mg/L × 7.25 MGD × 3.785 kg/MG/mg/L = 686 kg/day

20.23 $$\frac{3280\text{ lb/day}}{3250\text{ mg/L}\times 8.34\text{ lb/MG/mg/L}} = 0.121\text{ MGD}$$

20.24 $$\frac{240\text{ mg/L}\times 0.72\text{ MGD}\times 8.34\text{ lb/MG/mg/L}}{0.17\text{ lb BOD}_5\text{/person/day}} = 8477\text{ people}$$

20.25 8.34 lb/gal × 1.1288 = 9.41 lb/gal

20.26 $$\frac{(230\text{ mg/L} - 22\text{ mg/L})\times 100}{230\text{ mg/L}} = 90.4\%$$

20.27 $$\frac{(370\text{ mg/L} - 18\text{ mg/L})\times 100}{370\text{ mg/L}} = 95.1\%$$

20.28 $$\frac{(230\text{ mg/L} - 170\text{ mg/L})\times 100}{230\text{ mg/L}} = 26\%$$

20.29 $$\frac{(0.665 - 0.489)\times 100}{0.665 - (0.665\times 0.489)} = 52\%$$

20.30 $$\frac{140\text{ ft}\times 100\text{ ft}\times 12\text{ ft}\times 2\text{ tanks}\times 7.48\text{ gal/ft}^3\times 24\text{ hr/day}}{8.40\text{ MGD}\times 1{,}000{,}000\text{ MGD}} = 7.2\text{ hr}$$

20.31 $$\frac{40\text{ ft}\times 3\text{ ft}\times 2.5\text{ ft}\times 2\text{ channels}\times 7.48\text{ gal/ft}^3\times 1440\text{ min/day}}{8.40\text{ MGD}\times 1{,}000{,}000\text{ MGD}}$$
$$= 0.77\text{ min}$$

20.32 $$\frac{115{,}000\times 7.48\text{ gal/ft}^3}{19{,}000\text{ gpd}} = 45\text{ days}$$

20.33 To remove large objects

20.34 Manual and mechanical cleaners

20.35 Burial in an approved landfill; incineration

20.36 Cutter must be sharpened and/or replaced when needed; cutter alignment must be adjusted as needed.

20.37 Because the cutters have been replaced and the alignment has been checked, the most likely cause is excessive solids in the plant effluent. Corrective actions would include identifying the source, implementing or creating a sewer use ordinance, or installing a bar screen upstream of the comminutor to decrease the load it receives.

20.38 Grit is heavy inorganic matter. Examples include sand, gravel, metal filings, egg shells, coffee grounds, etc.

20.39 $$\frac{8.0\text{ MGD} \times 1.55\text{ cfs/MGD}}{3\text{ channels} \times 2\text{ ft} \times 3\text{ ft}} = 0.7\text{ fps}$$

20.40 There is a large amount of organic matter in the grit. The aeration rate must be increased to prevent settling of the organic solids.

20.41 To remove settleable and flotable solids

20.42 To remove the settleable solids formed by the biological activity

20.43 $$\frac{0.785 \times 90\text{ ft} \times 90\text{ ft} \times 12 \times 7.48\text{ gal/ft}^3 \times 24\text{ hr/day}}{2.25\text{ MGD} \times 1{,}000{,}000\text{ gal/MG}} = 6.1\text{ hr}$$

$$\frac{2.25\text{ MGD} \times 1{,}000{,}000\text{ gal/MG}}{0.785 \times 90\text{ ft} \times 90\text{ ft}} = 354\text{ gpd/ft}^2$$

$$\frac{2.25\text{ MGD} \times 1{,}000{,}000\text{ gal/MG}}{3.14 \times 90\text{ ft}} = 7962\text{ gpd/ft}$$

20.44 $$\frac{1500\text{ ft} \times 1100\text{ ft}}{43{,}560\text{ ft}^3\text{/ac-ft}} = 37.9\text{ acres}$$

20.45 $$\frac{1500\text{ ft} \times 1100\text{ ft} \times 4.1\text{ ft}}{43{,}560\text{ ft}^3\text{/ac-ft}} = 155.3\text{ ac-ft}$$

20.46 0.44 MGD × 3.069 ac-ft/MG = 1.35 ac-ft/day

20.47 0.44 MGD × 36.8 ac-in./MG = 16.2 ac-in./day

20.48 155.3 ac-ft ÷ 1.35 ac-ft/day = 115 days

20.49 16.2 ac-in./day ÷ 37.9 acres = 0.43 in./day

20.50 $$\frac{380\text{ mg/L} \times 0.44\text{ MGD} \times 8.34\text{ lb/MG/mg/L}}{37.9\text{ acres}} = 36.8\text{ lb BOD}_5\text{/ac/day}$$

20.51 $$\frac{970\text{ mg/L} \times 0.039\text{ MGD} \times 8.34\text{ lb/MG/mg/L}}{0.17\text{ lb BOD}_5\text{/PE}} = 1855\text{ PE}$$

20.52 Stabilization pond, oxidation pond, polishing pond

20.53 Settling, anaerobic digestion of settled solids, aerobic/anaerobic decomposition of dissolved and colloidal organic solids by bacteria producing stable solids and carbon dioxide, photosynthesis production of oxygen by algae

20.54 Summer effluent is high in solids (algae) and low in BOD_5; winter effluent is low in solids and high in BOD_5.

20.55 Eliminates wide diurnal and seasonal variation in pond DO

20.56 Increases during the daylight hours and decreases during darkness

20.57 Reduces fecal coliform, BOD_5, TSS, and nutrient levels

20.58 $$\frac{2.40\text{ MGD} \times (1.0 + 1.5)}{2} = 3.0\text{ MGD}$$

20.59 $$\frac{2.40\text{ MGD} \times (1.0 + 0.70)}{2} = 2.04\text{ MGD}$$

20.60 $$\frac{2.40\text{ MGD} \times (1.0 + 1.5) \times 1{,}000{,}000\text{ gal/MG}}{0.785 \times 90\text{ ft} \times 90\text{ ft} \times 2} = 472\text{ gpd/ft}^2$$

20.61 $$\frac{2.40\text{ MGD} \times (1.0 + 0.75) \times 1{,}000{,}000\text{ gal/MG}}{0.785 \times 90\text{ ft} \times 90\text{ ft} \times 2} = 330\text{ gpd/ft}^2$$

20.62 $$\frac{\begin{array}{c}196\text{ mg/L} \times 240\text{ MGD}\\ \times 8.34\text{ lb/MG/mg/L} \times 1000\end{array}}{2\text{ filters } \times 0.785 \times 90\text{ ft} \times 90\text{ ft} \times 8\text{ ft}} = 38.6\text{ lb BOD}_5/1000\text{ ft}^3$$

20.63 Distribution system to distribute the hydraulic and organic loading evenly over the filter media; media to support the biological growth; underdrains to collect and remove treated wastewater and sloughings from the filter to provide ventilation

20.64 Standard (best effluent quality), high rate, roughing

20.65 $$250{,}000\text{ ft}^2 + 220{,}000\text{ ft}^2 + (6 \times 150{,}000\text{ ft}^2) = 1{,}370{,}000\text{ ft}^2$$

$$\frac{840\text{ MGD} \times 1{,}000{,}000\text{ gal/MG}}{1{,}370{,}000\text{ ft}^2} = 6.1\text{ gpd/ft}^2$$

20.66 $$\frac{190\text{ mg/L} \times 8.40\text{ MGD} \times 8.34\text{ lb/MG/mg/L} \times 1000}{1{,}370{,}000\text{ ft}^2}$$

$$= 9.72\text{ lb BOD}_5/\text{day}/1000\text{ ft}^2$$

20.67 $$190\text{ mg/L} - (150\text{ mg/L} \times 0.55) = 107\text{ mg/L}$$

$$\text{SOL} = \frac{107\text{ mg/L} \times 8.40\text{ MGD} \times 8.34\text{ lb/MG/mg/L}}{1{,}370{,}000\text{ ft}^2}$$

$$= 5.5\text{ lb BOD}_5/\text{day}/1000\text{ ft}^2$$

20.68 Disks covered with biological growth rotate in wastewater. Organisms collect food during submergence. Oxygen is transferred during exposure to air. Organisms oxidize organic matter. Waste products and sloughings are discharged to wastewater flow for removal in settling tank.

20.69 The use of fixed film biological organisms

20.70 Normal, gray and shaggy; high sulfur, chalky and white

20.71 (1750 mL × 100) ÷ 2000 mL = 88%

20.72 1050 mL ÷ 2 L = 525 mL/L

20.73 1750 mL ÷ 2 L = 875 mL/L

(875 mL × 1000) ÷ 2750 mg/L = 318

20.74 $$\frac{175\text{ mg/L} \times 2.10\text{ MGD} \times 8.34}{1850\text{ mg/L} \times 1.255\text{ MG} \times 8.34} = 0.16\text{ lb BOD}_5/\text{lb MLVSS}$$

20.75 $$\frac{2750\text{ mg/L} \times (1.255\text{ MG} + 0.88\text{ MG}) \times 8.34}{(6120\text{ mg/L} \times 0.090\text{ MGD} \times 8.34) + (18\text{ mg/L} \times 2.10\text{ MGD} \times 8.34)} = 10.0\text{ days}$$

20.76 Increase waste rate.

20.77 Decrease; decrease; decrease; increases; increase

20.78 320 lb Hypochlorite × 0.45 Available Chlorine = 144 lb Chlorine/day

20.79 $$\frac{285\text{ lb Chlorine/day}}{0.679\%\text{ Available Chlorine} \times 8.34\text{ lb/gal} \times 1.18} = 42.7\text{ gpd}$$

20.80 $$\frac{45.8\text{ lb/day} \times 1.10 \times 365\text{ days}}{2000\text{ lb/containers}} = 9.2\text{, or 10 containers}$$

20.81 $$\frac{6\text{ containers} \times 2000\text{ lb/container}}{6.2\text{ mg/L} \times 2.25\text{ MGD} \times 8.34\text{ lb/MG/mg/L}} = 88\text{ days}$$

20.82 $$\frac{38\text{ lb/day} \times 1.11 \times 365\text{ days}}{150\text{ lb/cylinder}} = 102.6\text{, or 103 cylinders}$$

$$103\text{ cylinders} \times 150\text{ lb/cycle} \times \$0.17\text{/lb} \times 1.075 = \$2823.49$$

20.83 *Disinfection* destroys pathogenic organisms; *sterilization* destroys all organisms.

20.84 Demand; 1; residual; 30

20.85 Yellow–green; 2.5

20.86 $$30\text{ min/cycle} \times (24\text{ hr} \div 3\text{ hr/cycle}) \times 70\text{ gpm} \times 8.34\text{ lb/gal} \times 0.051 \times 0.66 = 4716\text{ lb/day}$$

20.87 $$\frac{41\text{ mg} \times 63{,}000\text{ gal} \times 3785\text{ L/gal}}{1\text{ L} \times 454\text{ g/lb} \times 1000\text{ mg/g}} = 21.5\text{ lb}$$

20.88 73,500 gal ÷ 2750 gpd = 27 days

20.89 90 to 95°F; maximum change should be 1° per day.

20.90 340 mg/L ÷ 1830 mg/L = 0.19 mg/L

20.91 $$\frac{0.785 \times 50\text{ ft} \times 50\text{ ft} \times 25\text{ ft} \times 7.48\text{ gal/ft}^3}{6000\text{ gpd}} = 61.2\text{ days}$$

20.92 $$\frac{(0.72 - 0.48) \times 100}{0.72 - (0.72 \times 0.48)} = 64.1\%$$

20.93 The licensed operator and the responsible official

20.94 National Pollutant Discharge Elimination System

20.95 By increasing the primary sludge pumping rate or by adding dilution water

20.96 Flow rate of the sludge going into the unit; pounds or kilograms of solids in the influent

20.97 Thermal conditioning

20.98 7.0 pH

20.99 Because the microorganisms have been killed or are absent

20.100 The time to do the test (3 hours vs. 5 days)

APPENDIX C

FORMULAE

AREA (FT²)

Rectangular Tank

$$A = L \times W$$

Circular Tank

$$A = \pi r^2 \text{ or } A = 0.785\ D^2$$

VOLUME (FT³)

Rectangular Tank

$$V = \mathrm{L} \times W \times H$$

Circular Tank

$$V = \pi r^2 \times H \text{ or } 0.785\ D^2 \times H$$

FLOW (CFS)

Gallons per day (gpd) = Gallons per minute (gpm) × 1440 min/day

Gallons per day (gpd) = Gallons per hour × 24 hr/day

Million gallons per day (MGD) = (Gallons per day)/1,000,000

DOSE

$$\text{Pounds (lb)} = \text{ppm} \times \text{MG} \times 8.34\ \text{lb/gal}$$

$$\text{Parts per million (ppm)} = \text{lb}/(\text{MG} \times 8.34\ \text{lb/gal})$$

EFFICIENCY (% REMOVAL)

$$\text{Efficiency} = \frac{(\text{Influent} - \text{Effluent})}{\text{Influent}} \times 100$$

WEIR LOADING (OVERFLOW RATE)

$$\text{Weir Loading} = \frac{\text{Total gallons per day}}{\text{Length of weir}}$$

SURFACE SETTLING RATE

$$\text{Surface Settling Rate} = \frac{\text{Total gallons per day}}{\text{Surface area of tank}}$$

DETENTION TIME (HOURS)

$$\text{Detention Time (hr)} = \frac{\text{Capacity of tank (gal)} \times 24\ \text{hr/day}}{\text{Flow rate (gpd)}}$$

HORSEPOWER

$$\text{Horsepower} = \frac{\text{Gallons per minute} \times \text{head (ft)}}{3960 \times \text{total efficiency}}$$

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