SECOND EDITION

Spellman's Standard Handbook *for* Wastewater Operators

VOLUME II

Intermediate Level

Frank R. Spellman

CRC Press
Taylor & Francis Group

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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.

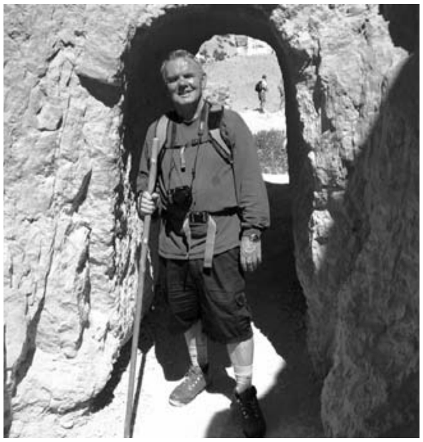
Contrary to popular belief (and simply put), treating wastewater is not just an art but both an art and a science. Treating wastewater successfully demands technical expertise, experience, and a broad range of available technologies, as well as an appreciation for and understanding of the fundamental 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

OPERATOR SAFETY

1.1 INTRODUCTION

Several statistical reports through the years have revealed that the wastewater treatment industry is an extremely unsafe occupational field. This less than stellar historical safety performance has continued to deteriorate, even in the age of the Occupational Safety and Health Act (OSH Act). The question is "Why is the wastewater treatment industry on-the-job injury rate so high?"

Several factors contribute to this high injury rate. In the first place, all of the major classifications of hazards exist at a wastewater treatment plant:

- Oxygen deficiency
- Physical injuries
- Toxic gases and vapors
- Infections
- Fire
- Explosion
- Electrocution

Along with having all of the major classifications of hazards present, the wastewater industry also has:

- Complex treatment systems
- Shift work
- New employees

- Liberal workers' compensation laws
- Absence of safety laws
- Absence of safe work practices and safety programs

Experience has shown that a lack of well-managed safety programs and safe work practices is the major reason why the wastewater treatment industry ranked near the top of the National Safety Council's 2005–2006 list of worst industries with regard to worker safety.

To further address the question of why the on-the-job injury rate is so high for wastewater workers, it is necessary to emphasize that workers involved with wastewater work have a high incidence of injury because of the *diversity* of duties required of them. The average wastewater worker must be a Jack or Jill of all trades. For example, operating the plant involves taking samples; operating, monitoring, and determining settings for chemical feed systems and high-pressure pumps; performing laboratory tests; and then recording the results in the plant daily operating log—all routine functions performed by most wastewater operators.

Then there are the nonroutine functions that cause additional problems; for example, the typical wastewater operator must not only perform the functions stated above but also make emergency repairs to systems (e.g., welding a broken machine part to keep the equipment online), perform material handling operations, make chemical additions to process flow, respond to hazardous materials emergencies, perform site landscaping duties, and carry out several other functions that are not usually part of the operator's job classification but are also required to maintain satisfactory plant operation and site appearance. Remember that the plant operator's job is to keep the plant running—keeping the plant running at 3:00 a.m. may require operators to perform mechanical tasks that they are not trained to do.

The wastewater operator is expected to be a diverse, multitalented, extremely capable individual who can do whatever is required to maintain smooth plant operation, which means that an assortment of safety considerations come into play during the operator's normal plant shift. For this reason, a wide variety of safety programs and safe work practices are required to address these diverse job functions and their associated hazards.

1.1.1 Plant Safety Person

To be successful, the primary lesson the wastewater treatment facility "safety person" must learn is to be an *advocate* for safe work conditions in the facility, not just a *regulator* of safe work conditions. Second, when an uninitiated person is thrown into the position of "safety person," he or she must quickly come to grips with the fact that on-the-job injuries are very real and can be frequent occurrences. On the other hand, it can take a lot longer time for the rookie "safety person" to realize that Grimaldi and Simonds (1989) put it right when they stated that, "Many (injurious) events, almost 9 out of 10 that occur in work places, … can be predicted" (p. 3). The point they made is that knowledge exists not only on how to predict injuries but also on how to prevent their occurrence.

"Where do I start?" This is a natural question for the new "safety person" to ask. Typically, someone is assigned the additional responsibility of safety person as a collateral duty. It is not unusual to find senior plant operators or chief operators who have been assigned this collateral duty. It would be difficult to find a more challenging or more mind-boggling collateral duty assignment than that of "safety person." This statement may seem strange to those managers who view safety as a duty that only requires someone to keep track of accident statistics, to conduct plant safety meetings, and perhaps place safety notices or safety posters on the plant bulletin boards. In this day and age of highly technical safety standards and government regulations, however, the safety person has much more to do than place posters on a bulletin board.

1.2 SAFETY STARTS AT THE TOP

Section 5(a) of Public Law 91-596 (December 29, 1970), the Occupational Safety and Health Act (OSH Act), requires that each employer:

1. Shall furnish to each of his employees employment and a place of employment which are free from recognized hazards that are causing or are likely to cause death or serious physical harm to his employees;
2. Shall comply with occupational safety and health standards promulgated under this Act.

1.3 SAFETY POLICY

When organizing a plant safety program, the first action the plant safety person should propose is that a formal organizational safety policy be written and approved by the general manager or other top plant manager. A well-written organizational safety policy should be the cornerstone of any organization's safety program. Various examples of safety policies used by Fortune 500 companies and others are available to model your own plant's safety policy after. The key to producing a powerful, tell-it-like-it-is safety policy is to keep it short, to the point, and germane to the overall goal. Many organizational safety policies are well written but are too lengthy, too philosophical. The major point to remember is that the organization's safety policy should be written not only so that it might be understood by every employee but also so that all employees will actually read it. An example of a short, to the point, and hard-hitting safety policy is provided in the following:

NO JOB IS SO CRITICAL AND
NO SERVICE IS SO URGENT
THAT WE CANNOT TAKE THE TIME
TO PERFORM OUR WORK SAFELY.

> While it is true that the major emphasis is on efficient operations, it is also true that this must be accomplished with a minimum of accidents and losses. I cannot overemphasize the importance that the Plant places on the health and well-being of each and every employee. The Plant's commitment to occupational health and safety is absolute. The Plant's safety goal is to integrate hazard control into all operations, including compliance with applicable standards. I encourage active leadership, direct participation, and enthusiastic support of the entire organization in supporting *our* safety programs and policies.
>
> **—General Manager**

1.4 SAFETY BUDGET

The safety budget is critical. No one ever said that safety is inexpensive; on the contrary, it is not unusual for safety divisions to expend six-figure budgets per year on safety and health programs and equipment for large wastewater organizations with large work forces. On the other hand, at smaller wastewater treatment facilities, where money for safety is either hard to find or nonexistent, the total safety budget might be limited to a few hundred dollars per year (which can also be the case in larger wastewater treatment facilities, which is understandable in the current economic climate where money is tight or nonexistent).

When it comes to budgeting, management is concerned with the bottom line. It is often difficult for management to discern the value of safety in terms of the cost–benefit relationship. It is the safety person's function to enlighten management as to the significance of a sound safety program and how it relates to the organization's bottom line. This is not an easy undertaking. Additionally, making an argument for funding that does not exist can be extremely frustrating.

Sometimes, the plant safety person is able to present a strong case or argument for the additional funding to convince those who control finances to budget more money for safety. For example, the safety person must make the point to management that it is less expensive to incorporate safety into the organization than it is to compensate for the loss of life, medical expenses associated with serious injuries, hazardous materials incidents that affect the public, destruction of property, employees' lost time, workers' compensation expenses, possible violation of the plant's operating permit, and citations issued by OSHA or other regulators.

The plant safety person who is attempting to increase funding for safety must understand from the very beginning that, when organizational money is spent, upper management wants results. It wants to see what its money has bought. For the designated safety person, this is a critical area. Some might call it "blowing your own horn." In reality, it should be called "communicating success to the extreme." When OSHA inspects one of the organization's facilities, for example, and can find little wrong (nothing that can be cited), then this information must be passed on to upper management. Upper management must get the message that its commitment to spending money on safety has paid off; the organization has saved money, and it has prevented fines and embarrassment. More importantly, a strong commitment to an effective safety program can and will prevent fatalities and injuries. When talking about the organization's bottom line, the safety person must convince upper management that the organization's real bottom line is maintaining the health and well-being of its employees. If upper management's bottom line is putting financial gain before protecting the employees, then the organization does not need a safety person and the appropriate safety funding; instead, it needs very deep pockets to pay for very expert legal counsel.

1.5 SAFETY PERSON'S AUTHORITY

The degree and extent of the safety person's authority is important; for example, the safety person must have the authority to conduct in-house audits. These safety audits are designed to reveal unsafe conditions and practices. More importantly, these audits must be followed up. In other words, the safety person must have the authority and the backing of upper management to ensure that supervisors correct deficiencies that are found during the audit. The safety person must have the authority to shut down work in progress on the spot, immediately, whenever unsafe work practices or unsafe conditions are discovered. Although this type of authority is important, it should also be stressed that this is latent authority—authority that is reserved and only to be used with great discretion. Remember, the safety person must take on the persona of "Good Neighbor Sam," not that of a Gestapo agent.

The safety person must have the authority to convene plantwide mandatory training sessions. Training is at the heart of safety. Employees cannot be expected to abide by safe work practices if they have not been properly trained on what is required of them. Safety training is more effective whenever the training is provided by those who are expert in the subject matter and by those who take on a personal approach. The organization's safety person must be viewed by supervisors and employees as part of the organization. This can be accomplished if the safety person takes an active role in learning the plant operation.

In large organizations where a number of employees may be working at several different locations, it is important to train supervisors so they will be able to recognize safety hazards and to take the correct remedial actions. Additionally, well-trained supervisors should augment the safety person's effort in providing employee safety training. Training provided by a worker's immediate supervisor, who is competent in the subject matter, is often more effective than training provided by other officials.

The importance of using supervisors in safety training cannot be overstated. To train workers on the proper and safe performance of assigned duties, input from the technical expert (i.e., the supervisor) for each job function is critical. Moreover, when supervisors are asked for their input and advice in formulating safe work practices, they generally buy into the overall safety program. Thus, these same supervisors often become valuable allies of the safety person and strong supporters of the organization's safety effort.

1.6 ACCIDENT INVESTIGATIONS

The plant safety person must have the authority to properly perform other functions, such as accident investigations. Accident investigations can turn up causal factors that point to a disregard of established safety rules or safe work practices or to disobedience of direct orders, all of which are going to lay the finger of blame on someone. Caution is advised here, and the safety person must tread a fine line. His or her intention should be to determine the cause, recommend remedial action, and follow up to ensure that corrective procedures have been put in place.

The safety person should never perform investigations in a dictatorial manner. The safety person must be professional, tactful, efficient, observant, and thoughtful and should never target individuals for blame. *Dragnet's* Joe Friday said it best: "Just the facts, ma'am." The organizational safety person should stick to gathering and reporting the facts only.

1.7 SAFETY RULES

After implementing an organizational safety policy, one of the first items on the newly assigned safety person's agenda should be the generation and incorporation of the organization's safety rules. Before submitting a list of safety rules to higher authority for approval, the safety person should think through what he or she is proposing. Rules are everywhere. All through our lives we have functioned according to some set of rules. Workers generally do not like rules. This is especially the case when the rules are unclear and arbitrary. When putting the plant's safety rules together, it is wise for the plant safety person to abide by the old acronym KISS ("keep it simple, stupid!").

Safety rules should be straightforward, easily understood, and limited to as few in number as possible. Concocting volumes of complicated safety rules will result in much wasted effort and adding another dust collector to the shelf. Employees will not read, follow, or abide by rules that occupy voluminous manuals or any rule they deem stupid or unnecessary. Additionally, supervisors will have difficulty in enforcing too many rules.

The best safety rules are those that can be read and understood in short order; for example, the organizational safety rules shown below are short and to the point:

SAFETY RULES

Employees should familiarize themselves with and observe all safety rules.

1. Wear hard hats at all times in designated areas.
2. Wear safety glasses when chipping, hammering, pounding, cutting grass, grinding, and using power tools.
3. Wear appropriate safety goggles and a face shield when handling chemicals.
4. Wear safety goggles and a dust mask when entering an incinerator or when handling ash.
5. Wear safety shoes.
6. Wear a safety harness and lifeline when working in or around an enclosed manhole, pipe, or tank or anywhere else where there is no other adequate protection against falling or retrieval.
7. Wear a life jacket when working in or around open water or chemical basins.
8. Test for a safe atmosphere with gas detection equipment before entering an enclosed manhole, pipe, tank, wet well, or any area subject to an explosive, oxygen-deficient, or toxic atmosphere.
9. Wear self-contained breathing apparatus when entering an enclosed manhole, pipe, tank, wet well, or any area subject to an oxygen-deficient or a toxic atmosphere not proven safe by testing.
10. Ventilate with a portable ventilation blower before entering an enclosed manhole, pipe, tank, or wet well.
11. Place barricades around all open access hatches, manholes, pipe trenches, and excavations left unattended.
12. Wear appropriate goggles, face mask, and gloves when burning or welding.
13. Wear appropriate eye and hand protection when opening a hot incinerator access or air door.
14. Wear hearing protection where designated.
15. Wear seat belts when driving plant vehicles.

The safety rules shown above are not and cannot be effective unless the organization provides enforcement. It is best to provide enforcement in the form of both punishment and praise. Punishment should be given, depending upon the severity of the infraction, to those employees who disregard or disobey safety rules. Moreover, when a good safety effort is observed, praise should be provided in the form of letters of commendation and appropriate notations on the worker's performance record.

1.8 SAFETY COMMITTEE OR COUNCIL

When working with upper management in the formulation of the organization's safety program, it is important to set up a safety committee or council. The safety committee can provide valuable assistance to the plant safety person. The safety committee should be composed of a cross-section of the organization's workforce. Additionally, the safety committee should consist of a combination of senior managers as well as employees at mid-grade supervisory levels. If the organization is unionized, then a designated union representative must be assigned.

1.9 WORKER INPUT

Safety officials sometimes overlook a valuable resource that is always present in any organization: *workers*. Some would argue that workers not only make up the organization but are the organization. Safety persons are hired primarily to protect workers from injury, but they sometimes forget this mission of ensuring that workers have a safe place to work. Workers also have a role in maintaining their own safety, which many may find surprising. At the beginning of this chapter, part of the OSH Act was stated, the part dealing with an employer's responsibilities under the Act. It may surprise many people, and almost always the workers, to learn that according to the OSH Act:

> Section 5(b) mandates that each *employee* shall comply with occupational safety and health standards and all rules, regulations, and orders issued pursuant to this Act which are applicable to his own actions and conduct.

Several organizational safety programs, policies, manuals, or directives specifically define who is responsible for safety. When the reader reviews such programs, policies, manuals, or directives, it usually is clear whom has been made responsible for safety; however, when specific personnel are designated as being responsible for safety, the reader might wonder about the rest of the organization's personnel. Aren't these personnel also responsible for safety? Shouldn't everyone share this responsibility?

Providing a safe place to work can be better accomplished when all organizational personnel have input, especially the workers—the rank and file. Input can be in the form of discussion between the worker and the supervisor. Input can also be in the form of discussion between the worker and the work center's safety committee member. On occasion, workers provide input directly to the safety person.

1.10 ACCIDENT REPORTING

The organizational safety person should ensure that supervisors prepare and maintain records for reporting worker injuries and accident investigations. In the wastewater industry, where exposure to various microorganisms (some that are harmful to humans) in the wastewater stream is a routine occurrence, even the most minor scratch, cut, or abrasion should immediately be reported to the supervisor. Some would say that it is burdensome for the supervisor and the safety person to process paperwork that details minor on-the-job injuries. This might be the case in other industries, but in wastewater treatment plants where exposure to sanitary wastewater and industrial waste is a daily occurrence, it is important to require employees to report all injuries, no matter how minor.

1.11 SAFETY AUDITS

Safety audits or inspections can be a valuable tool for detecting worksite hazards that may lead to worker injury. The obvious purpose of safety audits is to identify and correct workplace hazards. Not surprisingly a newly assigned safety person is sometimes apprehensive about conducting safety audits of the organization's facilities, not wanting to antagonize the site supervisor. Moreover, without previous safety inspection experience, the rookie safety person may feel that he or she lacks the knowledge and expertise required to conduct safety inspections.

One question that the new safety person might ask is "What do I inspect for?" Although it is true that each worksite is different from others, it is also true that types of safety hazards generally fall into the same categories, no matter the size of a facility. There are exceptions to this rule, however. For example, the hazards inherent in a nuclear facility are not the same as the hazards present in a wastewater treatment plant.

Those concerned about conducting safety audits in wastewater treatment plants should refer to several excellent publications that discuss the topic in detail. Several of these publications are listed in the reference section of this text. Additionally, the potential auditor should do a number of things prior to conducting the audit. The first thing to do is to become familiar with the facility and operation to be audited, particularly with respect to the types of hazards that are normally present at the facility. The auditor should determine whether the facility handles and uses hazardous materials, for example.

Wastewater treatment plants possess most of the industrial hazards that are present in other industrial settings. A short list of some of the typical hazards that are present at wastewater treatment plants includes:

1. Machinery
2. Flammable/combustible materials
3. Walking and work surfaces
4. Welding, cutting, and brazing operations
5. Electrical equipment and appliances
6. Ladders and scaffolds
7. Compressed gases

8. Materials handling and storage
9. Hand and portable power tools
10. Process-generated hazardous and toxic substances (e.g., methane and hydrogen sulfide)

A valuable tool to use when conducting the safety audit is a safety inspection checklist. If your organization does not have a safety inspection checklist, one should be generated as soon as possible. Once the organization's safety checklist is generated, the safety person should consider this document as a living document that will continue to grow as time passes.

1.12 COMMUNICATION

The importance of training and documentation of the training that has been completed must be stressed. Another area that is equally as important as training workers and documentation of the training is the area of *communication*. Communication is addressed in the OSHA Hazard Communication (HAZCOM) standard. The HAZCOM standard requires employees who might be exposed to hazardous material to have full knowledge of the hazards. Safety communication goes beyond HAZCOM, however. Getting safety information out to supervisors and workers is critical; for example, to facilitate the scheduling of safety training it is prudent to publish a schedule far in advance of the actual training dates. It might be wise to develop an organizational publication titled *Safety Training/Medical Exam/Inspection Schedule*, which can be published quarterly or annually. This schedule should provide a day by day, month by month account of when safety training is scheduled. Supervisors like to know far in advance what is scheduled in the future so they can plan appropriately.

The bottom line on safety communication is that the supervisors and workers need to be informed. It is true that too much information can defeat the intended purpose, but it is also true that too little information may lead to accidents.

1.13 SAFETY PROGRAMS

There are two types of safety programs: *organizational safety programs* and *individual safety programs*. An organizational safety program is the plant's *entire* safety program, which consists of policy, organization, and the safety and health plan. Individual safety programs are *specific* safety programs (e.g., hazard communication, confined space entry, lockout/tagout, respiratory protection, and other safety programs) that are part of the organizational safety program. Individual safety programs are designed to achieve specific objectives. Each individual safety program states a plan of action for the enlistment and maintenance of support from all members of each particular area with regard to safety on the job. To be effective, the plant's individual safety programs must be understandable and their requirements must be clearly defined. Moreover, the plant's individual safety programs must be *enforceable*. Without enforcement, safety cannot and will not become part of the organization's culture.

Some of the OSHA safety programs are required at all facilities. In the safety program design phase, keep in mind that writing a safety program to comply with a particular mandate is only part of the requirement. Employees must be *trained* on the organization's safety programs. As a matter of fact, more than 100 specific training programs are mandated by OSHA, Environmental Protection Agency (EPA), and Department of Transportation (DOT) regulations. The key thing to remember is that these training programs are not optional; if your employees perform tasks covered by these regulations, you must provide the specified safety training. Before further discussing the training of workers to meet compliance, let's take a look at the safety programs that might be needed for a particular wastewater facility.

1.13.1 Hazard Communication: The Right to Know Law (29 CFR 1910.1200)

If your workers come into contact with hazardous chemicals in your workplace, OSHA mandates that they have a "right to know" what chemicals they are working with or around. This employee "right to know" requirement is formally known as the OSHA Hazard Communication (HAZCOM) standard. This standard requires that the manufacturers, importers, and distributors of hazardous chemicals must transmit important information to employees in the form of container labels and material safety data sheets (MSDSs). The information contained on the label or MSDS sheet must clearly state the possible physical or health hazards of each chemical.

1.13.2 Control of Hazardous Energy: Lockout/Tagout (29 CFR 1910.147)

Lockout/tagout refers to the control of energy. These energy sources include electrical, chemical, hydraulic, pneumatic, thermal, and potential energy (e.g., energy that is stored in a compressed spring). Lockout/tagout *procedures* are designed to prevent accidents and injuries caused by the accidental release of energy. All wastewater treatment facilities are required to have a written lockout/tagout procedure. Lockout/tagout procedures can prevent needless deaths and serious injuries to workers. The plant's lockout/tagout procedure *must* be the only acceptable method used to de-energize equipment and machinery and control the release of potentially hazardous energy.

1.13.3 Confined Space Entry (29 CFR 1910.146)

Confined space entry and the wastewater treatment and collection industry go hand in hand. Facilities where confined space entry occurs must have a confined space program. Whether the confined space is a contact tank, aeration basin, clarifier, pumping station wet well, bar screen trunk, pipe, sewer, manhole, storage vessel, tunnel, boiler, reactor, tank, or a large excavation where repairs to a damaged interceptor or collection line are undertaken, proper confined space entry procedures are essential to protect the worker. Several thousand injuries occur each year in confined spaces. OSHA (1993) defined a confined space as any space that:

- Has limited or restricted means of entry or exit
- Is large enough for an employee to enter and perform assigned work
- Is not designed for continuous worker occupancy

Hazards common to confined spaces include:

- Atmospheric conditions
- Engulfment
- Internal configuration
- Physical hazards

The primary consideration for confined spaces is oxygen deficiency. Normal air contains about 20.8% oxygen by volume. OSHA indicates that the minimum safe level is 19.5% and defines the maximum safe level as 25%. (Remember that an atmosphere too rich in oxygen can cause fires and explosions.)

The potential for combustibility also makes confined space entry hazardous. Gases and vapors are often trapped in confined spaces. These built-up gases or vapors can be easily ignited by friction, cigarettes, or sparks from hot work equipment.

In addition to a lack of oxygen and combustibility, another factor that can make a confined space extremely dangerous is toxic air contaminants. Toxic air contaminants such as methane, hydrogen sulfide, cleaning solvents, and coating vapors are a constant threat to those who work in wastewater treatment and collection. Some toxic air contaminants can cause problems due to irritation of the respiratory system; others can be much more serious, as they can cut off the person's oxygen supply or enter the lungs and asphyxiate that person.

Engulfment is a problem, too. Engulfment is defined as the surrounding and effective capture of a person by finely divided particulate matter or a liquid. To gain a better understanding of engulfment and the potential hazard, consider the following example. If you have ever worked on a farm where grains such as wheat and corn are grown, you are probably quite familiar with grain silos. Grain silos can be extremely dangerous for a number of reasons. Fine grain dust is always an explosion hazard, and grain silos are also engulfment hazards due to the grain being stored inside the silo. Personnel can enter the compartment below the storage area, but grain that is unexpectedly released from the upper compartment can engulf a person inside that compartment, and survival is doubtful. Industry safety records document the many incidents where farmers and helpers have died due to engulfment in silos.

In the wastewater treatment plant or collection system, engulfment is also a very real possibility; for example, a clarifier that is emptied for maintenance but is not properly locked out could trap the workers inside if the wastestream, under pressure, were to inadvertently enter the clarifier basin and rise in level at more than 10 feet per minute. Additionally, collection crews are at risk when working inside an interceptor line that is not properly locked or tagged out and blinded or blanked with flanges. The sudden release of the wastestream into the area they are working in could engulf them. Engulfment can also occur in pumping or lift station wet wells. Additionally, in excavation work, engulfment can trap and crush or suffocate workers deep inside a trench that suddenly collapses.

Physical hazards can also make a confined space entry hazardous. Physical hazards include machines such as rotating blades or agitators. Moving parts in confined spaces must be locked or tagged out before entry is made. Heat stress is another physical hazard often precipitated by confined space entry. This should not be surprising when one considers the nature of the atmosphere that is contained in a confined space. It is not unusual for confined space atmospheres to have temperatures well above ambient. In addition to the normal heat sink qualities of some confined spaces, the heat stress problem is greatly exacerbated when someone enters the confined space wearing all of the proper personal protective equipment, such as self-contained breathing apparatus.

Noise is another physical hazard that most people ignore or do not think about when confined space entry is made. Noise actually reverberates in confined spaces and can cause permanent hearing loss. Hearing protection may be required to protect those entering a confined space. Another physical hazard in confined spaces is falls. Falls in confined spaces can be fatal. Falls are common because confined spaces are usually entered via ladders. Ladders are inherently dangerous, and their danger is magnified exponentially when used in confined spaces.

When improper confined space entry procedures are used in a space with an undetected contaminant present, a common thread runs through all of these incidents—that is, fatalities are almost always the result. Confined spaces can be very unforgiving. Unfortunately, experience has shown that confined space mishaps often result in the deaths of more than one individual due to what the author refers to as the *John Wayne syndrome*. For example, it is not unusual for someone who finds a victim unconscious in a wet well to attempt heroic rescue efforts to free the victim, with total disregard for his or her own safety. Thus, the John Wayne syndrome has caused the confined space tragedy to become a multiple-victim incident.

Confined space entry relies on additional safety programs to ensure safe entry. As pointed out earlier, a confined space should not be entered unless proper lockout/tagout procedures have been effected to prevent engulfment and the accidental energizing of machinery. In addition to lockout/tagout procedures, another important OSHA safety program that must be followed to ensure safe confined space entry is an effective respiratory protection program.

It cannot be overstated that, to ensure safe confined space entry, it is necessary to assemble a sound confined space entry program for your facility, beginning with a written program. The written confined space entry program should include entry procedures, lockout/tagout procedures, ventilation procedures, air testing procedures, rescue procedures, personal protective equipment required, and confined space permit procedures or requirements for confined space that can only be entered by permit. Confined space permit requirements not only should clearly detail how to fill out a confined space permit but should also designate who is authorized to fill out the permit. All confined spaces must be labeled. OSHA is quite specific about confined space labeling. It is not necessary to expend large sums of money on fancy labels. The confined space labeling can be painted on a wall or access hatch or cover. Stenciling the label in heavy black letters is also a technique that works.

Thus far, this discussion has specifically addressed confined spaces that are to be entered by permit only. It should be noted, however, that OSHA discusses two types of confined spaces: *non-permit* and *permit-required confined spaces*. Non-permit confined spaces are those that do not contain physical or atmospheric hazards that could cause death or serious physical harm. Generally, non-permit confined spaces are those that are continuously ventilated, have more than one way in or out, and have no history of hazardous atmosphere. To determine whether a confined space is a non-permit or permit-required space requires professional judgment. When in doubt, consider the space a permit-required confined space.

1.13.4 Respiratory Protection (29 CFR 1910.134)

It may not always be obvious to workers when a respirator is required. Whenever workers must enter a confined space or other vessel for maintenance, entry should not be made until the atmosphere (air) within the confined space or vessel is tested for the presence of flammable agents, oxygen content, and the presence of toxic agents, such as hydrogen sulfide, methane, and carbon monoxide, among others. A lack of oxygen is the most common cause of deaths during confined space entry. To prevent fire or explosion, fuel storage tanks that have contained flammable materials are frequently inerted or purged with various gases such as nitrogen prior to allowing personnel to enter the space to perform the required maintenance. Purging the tanks prevents fires due to welding or spark-making activities, but a worker who enters this space without a proper respirator will be quickly overcome from lack of oxygen.

Key Point: Before workers are issued respirators that are to be worn on the job, the employer must properly protect those workers by training them in proper respirator use. This training must include a discussion of the type of respirator that is to be worn for the particular hazard to be guarded against. Additionally, each worker must know the limitations and maintenance and cleaning requirements for proper respirator use.

Normal breathing air contains about 21% oxygen, by volume. A typical worker's total lung volume is about 5.5 liters. During normal breathing, each inspiration and expiration involves about 500 mL of air. Of this 500 mL, about 140 to 160 mL occupies the tracheobronchial tree, where no interchange of oxygen takes place with the blood; therefore, only 340 to 350 mL of air is actually exchanged in each inhalation. Alveolar (air sack) air, which comes from deep within the lungs, contains only about 11 to 12% oxygen when it is exhaled, but when combined with air remaining in the tracheobronchial tree the net exhaled composition is about 16%. When the concentration of air being inhaled drops below 16% oxygen, symptoms of distress will occur. Loss of consciousness can occur at oxygen levels below 11%. Breathing will cease if the oxygen concentration falls below 6 to 7%.

Employers in occupational settings are required by OSHA to establish and administer an effective written respiratory protection program. This requirement is vital when you consider that the most common route of entry of chemicals and toxic substances into the body is by inhalation. Respirators are frequently used in the wastewater treatment and collection industry. If your facility requires the use of respirators, then your facility must have a written respiratory protection program and abide by the OSHA requirements for respirator use. A respiratory protection program, for example, is required for confined space entry, for change-out of chlorine cylinders or tank cars, or for sandblasting, coating, or other similar operations.

Along with a written program, OSHA also requires that a workplace assessment be made to determine which respiratory hazards are present and if the potential for respiratory hazards exists. From this determination, the employer must provide the correct type of respirator to protect workers. The workplace assessment should be accomplished by a knowledgeable person who is familiar with the workplace, with working conditions, and with workplace hazards.

The three basic kinds of respirators are air-purifying, supplied-air, and self-contained breathing apparatus (SCBA). *Air-purifying respirators* clean contaminated air before it is inhaled. There are different types of air-purifying respirators. One type removes particles from the inhaled air; these respirators are designed to filter out dusts, mists, sprays, and fumes. The gas and vapor type of air-purifying respirator is designed to absorb or chemically remove gases and vapors.

Air-purifying respirators have limitations. Probably the most significant limitation is the fact that these respirators do *not* provide a supply of respirable air. Second, air-purifying respirators do not protect the user from all types of hazards, as not all dangerous substances can be safely filtered out of the atmosphere. A third limitation is the filtering media. Filters can and do become clogged, and they have a limited lifespan.

In some cases it is more desirable to use the *supplied-air respirator*, which supplies air from an outside source. Supplied-air respirators are used whenever there is not enough oxygen present or when the concentration that is present is immediately dangerous to life or health (IDLH). An IDLH atmosphere is defined as a very hazardous atmosphere where exposure can cause serious injury or death in a short period of time. Two kinds of supplied-air respirators are available. The *air-line type of supplied-air respirator* delivers clean, compressed air from a stationary source delivered through a pressurized hose. The *hose mask type* supplies clean, noncompressed air through a strong hose to a respiratory inlet covering. Air may be supplied with a motor or a hand-operated blower.

The supplied-air respirator has limitations. The biggest disadvantage of supplied-air respirators is that losing the source of respirable air supplied to the respirator inlet covering voids any protection to the wearer. Moreover, mobility might be restricted by the inconvenience and length of the air-supply hose (which cannot exceed 300 feet). Adequate protection may not be provided in certain highly toxic environments. The air intake of the device used must be fed uncontaminated air, which might not be available.

When mobility is an issue and when respiratory protection against all breathing hazards is required, the *self-contained breathing apparatus* (SCBA) type of breathing device is required. Although the use of SCBA allows more freedom and protection than the other types of respirators, it must be kept in mind that it is important to monitor the amount of air used and the amount still available for use in the worker's air cylinder.

Selecting the correct type of respirator to wear is only one of several considerations involved with respiratory protection. Because it does little good (and could be disastrous) to have workers wear respirators not suited for the hazard they are to be exposed to, OSHA requires the employer to ensure that the proper respirator is selected for the hazard involved. An employee, for example, who chooses to wear a half-face-mask, air-purifying type of respirator in a confined space that has an atmosphere composed of 100% carbon dioxide will become another confined space fatality. Thus, employers must ensure that they provide their workers with the correct type of respirator to protect them from the respiratory hazards they are or might be exposed to.

Wearing the correct respirator is important, but making sure that the respirator actually fits is just as important. OSHA requires that workers who are designated to wear respirators in the workplace are to be given respirator fit tests. The purpose of respirator fit-testing is to provide the worker with a face seal on a respirator that provides the most protective and comfortable fit. The two types of respirator fit tests are *quantitative* and *qualitative*. In both tests, a harmless smoke, gas, vapor, or aerosol is used to test for fit.

In a quantitative fit test, the person to be tested is instructed to don his or her respirator and is then placed inside an enclosure for exposure to a test agent (irritant smoke, banana oil, or saccharin). The worker is carefully monitored and observed during a quantitative fit test to determine if any of the test agent is entering the worker's mask. In a quantitative test, special instrumentation is used and the test is generally performed by an industrial hygienist or safety professional who has extensive training in this area. The special instrumentation and equipment required to perform quantitative fit tests are expensive.

In the qualitative test, which is the test most commonly administered in general industry, the person performing the fit test knows the worker has a good fit if the worker cannot sense the agent when it is released in close proximity to the worker's breathing zone (between the shoulders and top of head). The qualitative fit test is not as accurate as the quantitative fit test in measuring the worker's ability to wear a respirator because qualitative fit tests rely on the wearer's subjective response, so it may not be entirely reliable. The qualitative fit test is, however, much easier to administer, less expensive, and easily performed in the field.

At the minimum, before using a respirator, users must test their respirators by performing their own pre-use self-fit tests. Workers must test the positive and negative seal of their masks each time they use a respirator. This is accomplished by performing positive and negative pressure tests. During the *positive pressure test*, the user closes the respirator's exhalation valve and breathes out gently into the facepiece. This should cause the facepiece to bulge out slightly. If no air leaks out, the user has a good fit. During the *negative pressure test*, users cover both filter cartridges with the palms of their hands and inhale slightly to partially collapse the mask. This negative pressure is held for 10 seconds. If no air leaks into the mask, it can be assumed that the mask is fitting properly.

To retain their original effectiveness, respirators must be periodically cleaned (disinfected) and properly stored. The provisions for cleaning and proper storage of respirators must be included in the organization's written respiratory protection program. Respirators should be cleaned after each use. When performing the cleaning operation it is always best to follow the manufacturer's instructions. Keep in mind that caution must be exercised whenever respirators are cleaned. Certain detergents and solvents will not only damage the facepieces but could also damage the respirator casing.

After use and cleaning, a respirator should be properly stored. Respirators are subject to damage when stored in bright sunlight. Moreover, respirators can become contaminated or damaged whenever they are exposed to dirt, grease, oil, solvents, or other contaminants that can render the respirator useless and create a serious health hazard for the user.

Speaking of the user's health, OSHA states that not everyone can wear a respirator. Anyone assigned to a job requiring a respirator must first have a medical examination and be cleared by a medical doctor for respirator use. OSHA is very straightforward on this issue and states that no one should be assigned a task requiring the use of respirators unless found physically able to do the work while wearing the respirator. Follow-up medical examinations are also required—usually at no longer than 5-year intervals, depending on the age of the worker. If the worker is 40 years or older, annual medical examinations should be required. The ultimate decision on what the actual frequency of re-examination is to be made by a physician.

The medical screening procedure used widely in preplacement and medical surveillance testing of a worker's medical suitability to wear respirators is the *pulmonary function test* or *spirometry*. The pulmonary function test measures two important parameters: FVC (forced vital capacity) and FEV_1 (forced expiratory volume in 1 second). FVC measures the worker's vital capacity when air is exhaled as rapidly and forcefully as possible. The vital capacity (lung volume) is the amount of air that can be exhaled after a maximal inspiration. FVC decreases with the loss of lung volume that occurs in restrictive lung diseases resulting from exposure to various fibrogenic dusts such as asbestos and silica. FEV_1 measures the amount of air that the worker is able to expire in the first second. FEV_1 divided by FVC (FEV_1/FVC) decreases in obstructive disease due to cigarettes, asthma, or exposure to chemicals, among others. The American National Standards Institute recommends that the FVC should be measured as 80% or greater and FEV_1 as 70% or greater. If the FVC is less than 80% or the FEV_1 is less than 70%, restriction from respirator use should be considered; however, the ultimate decision on whether or not the worker is disqualified from respirator use for medical reasons must be made by competent medical authority. The safety practitioner must keep in mind that, although the pulmonary function test is an excellent screening tool, it is not the definitive test or statement as to whether one is medically fit or not; again, only competent medical authority can make this decision. Pulmonary function testing can also provide the employer with baseline data against which an assessment can be made regarding any physiological changes in respirator wearers that might occur with the passage of time.

Before the organizational safety person performs pulmonary function tests on employees, two requirements are necessary. First, the safety person must be formally trained as a National Institute for Occupational Safety and Health (NIOSH) pulmonary function technician. This training usually can be completed in not more than 3 days at a NIOSH-approved training center. Moreover, serving as a pulmonary function technician does not require a medical degree or background. The second requirement is equipment. Spirometers are available from various vendors and usually can be purchased for less than $3000.

A final word on pulmonary function testing. Experience has shown that workers generally look forward to this test. This is especially the case for those employees who are active cigarette smokers and those who have recently given up smoking. When workers can receive graphic illustrations or parameters that indicate what is going on inside their lungs, they are interested. It can be very gratifying to observe workers who have given up cigarette smoking as a direct result of their annual pulmonary function tests. Persuading workers to give up cigarettes not only helps workers maintain their good health but also helps to significantly reduce their sick leave requests.

1.13.5 Hearing Conservation (29 CFR 1910.95)

A potential hazard of the workplace that is often overlooked is excessive noise. Noise is usually defined as any unwanted sound. Sound is caused by rapid fluctuations of air pressure on the eardrum of the listener. Sound may be unwanted for several reasons, including its contribution to hearing loss, its adverse effects on human physiology, its interference with normal conversation, or its being just a plain nuisance. Sound is measured in decibels (dB). The decibel is a dimensionless unit used to express physical intensity or sound pressure levels. If sound is intensified by 10 dB, it seems to human hearing as if the sound intensity has approximately doubled. A reduction by 10 dB makes it seem as if the intensity has been reduced by half. The reference point for noise level measurement is 0 dBA, which is the threshold of hearing for a young child with very good hearing. The threshold of pain for humans is 120 to 125 dBA. The "A" part of dBA is determined by using instruments used to measure sound levels. The instruments used have a measuring scale designed to resemble sound that the human ear is sensitive to (A-weighted sound level).

Noise is a workplace problem. Along with possibly causing permanent or temporary hearing loss, noise also affects the nervous system. Anyone who has worked at a wastewater treatment plant or pumping station knows that the wastewater treatment process produces noise: from the low barely audible hum of fractional horsepower electric motors to the din created by 300-horsepower aeration blowers and diesel engines, the spectrum of noise intensity at a wastewater treatment facility or pumping station is wide. Hearing loss is a common workplace injury that is often ignored. As a matter of record, it was not uncommon in the past for workers to accept partial hearing loss as a cost of working in a noisy workplace, including a wastewater treatment plant. Times have changed, however. OSHA recognizes noise for what it really is. Noise is an occupational hazard that can cause temporary or permanent hearing loss, stress, and other physical problems.

Because noise is a workplace hazard OSHA has established criteria for protecting workers' hearing. The main factors related to hearing loss are intensity, time of duration of exposure, and repeated impact noise. It is the continuous exposure to high-level noise that must be avoided. With increased time of exposure, there is a corresponding increase in harm done.

In order to protect workers and to abide by OSHA requirements, wastewater facilities need to incorporate a hearing conservation program into their overall safety program whenever sounds generated in the workplace are irritating to workers. When a worker needs to raise his or her voice to shout to be heard by someone closer than a foot away, that worker is being exposed to noise levels that are too high. Moreover, whenever the measured sound levels reach 85 dB or higher for an 8-hour time period, a hearing conservation program is required by OSHA.

When implementing a hearing conservation program, the plant safety person usually asks the same standard question: "Where do I start?" The first step is to conduct a noise survey of the plant site, including pumping stations and maintenance centers. This noise survey should be conducted using a calibrated sound meter. Each building at each facility should be surveyed for sound. Keep in mind that even administrative office areas, at times, can contain high noise levels.

When conducting the plant sound level survey it is important to remember that various machines might not be online and in operation at the particular moment the survey is conducted. It is impossible to conduct a sound level survey that will provide a true picture of actual noise levels unless all machinery is running.

While conducting the plant sound level survey, it is wise to draw a rough map of the layout of each building. On this map, include pictorial representations of each noise-making machine or device. When testing for sound level, start at the machine and work around the machine; it is important to survey the entire area around the machine. Moreover, the sound level survey should be conducted at varying distances from each machine. Sound measured at a certain distance from the source in open air is reduced by about 6 dB for each doubling of that distance. Sound is reduced less when it spreads inside a room. The point is that by moving away from the sound source the sound level is reduced.

When measuring for noise level, measure the sound level close to the pump, motor, or blower (within 2 feet) and then move outward from the device by doubling the distance from the machine (e.g., 4 feet, 8 feet, and 16 feet). On the rough sketch, at the particular machine being measured, draw concentric circles at each distance and record the meter readings on each circle.

The concentric circle approach aids in two significant ways. First, by knowing the sound level for varying distances from the noise source it is possible to label or mark off high noise areas and direct routine traffic away from the noise. Second, the noise level mapping system also provides a reference for future comparisons. In some cases, where it has been noted that an appreciable increase in decibel level occurs (as measured by the sound level meter), you will be able to point this out to the plant superintendent. This can be important information. The increase in decibel level might indicate, for example, that the motor bearings or perhaps a drive belt is about to fail. Maintenance personnel may later determine that failure of some machine component was indeed imminent. Thus, a sound level survey can pay off in more ways than one.

After conducting the plantwide noise survey and entering the findings on the map, the plant safety person should then compare the measured readings with the 85-dB rule. If any of the measured readings are equal to or exceed 85 decibels and workers could be exposed to these levels for 8 hours (or less if the noise level is higher), then a written hearing conservation program is required. The written hearing conservation program should include several parts. To begin with, it should include

TABLE 1.1 OSHA PERMISSIBLE EXPOSURE LEVELS FOR WORKPLACE NOISE

Sound Level (dB)	Maximum Time of Exposure (hr)
85 (program required)	8
90 (hearing protection required)	8
92	6
95	4
97	3
100	2
102	1.5
105	1
110	0.5
115	0.25

an introduction stating the OSHA requirements. The program objectives should be clearly stated. Designation of responsibilities should be included, with a statement that the program requires good direction, management, supervision, and conduct at all work levels within the plant site. Include a section that defines key terms. One part of the written hearing conservation program should identify the exact locations at the plant site where the noise hazards exist. When these noise hazard areas have been identified, the written program should require labeling or marking of these areas. OSHA's permissible noise exposures are listed in Table 1.1.

When it has been determined what type of noise hazard warning will be used and where each sign is to be posted, the next item that should be included in the hearing conservation program is an evaluation of engineering and administrative controls. Incorporating engineering and administrative controls into your hearing conservation program should be looked at closely. In the world of safety, it is always best, if possible and feasible, to try to engineer out a safety hazard instead of guarding against it. Engineering out the noise problem might include such things as installing mufflers on air-exhaust nozzles or isolating a machine. If the noise source cannot be damped, then perhaps something can be done about the noise path. Placing sound-absorbent enclosures around noisy equipment is a modification that can be easily accomplished. As a last engineering control measure, protecting the receiver of the noise is another solution. This can be accomplished by constructing an enclosure around the employee's workstation.

When engineering controls are not possible, feasible, or cost effective, then administrative controls are called for. The primary administrative control used to protect workers from unwanted sound or noise is to issue each worker hearing protection devices. Hearing protection devices include earplugs and earmuffs. Earplugs offer the most protection, and properly installed foam earplugs are the most effective. Earmuffs fit over the outside of the ear. Many workers feel that earmuffs provide more protection than earplugs, but this is usually not the case. Earmuffs are only as good as the seal they provide around the ear. In extremely noisy environments it might be wise to recommend *double hearing protection*: wearing both ear plugs and earmuffs at the same time.

Another important area that needs to be addressed in the plant hearing conservation program is the designation of *audiometric evaluation* procedures. OSHA requires employers with facilities where noise exposure equals or exceeds an average of 85 dB over an 8-hour period to provide their employees with audiometric testing. Wastewater treatment plant safety officials can ensure that audiometric examinations are conducted by either performing the tests themselves or by hiring a local medical contractor to perform the tests. If the evaluation is conducted in-house, the audiometric technician must be properly trained. NIOSH-approved training centers offer audiometric technician or occupational hearing conservationist training throughout the country. This training usually can be completed in 3 days, and the trainee is not required to have a medical background. Moreover, audiometric equipment is readily available to purchase at reasonable prices. The plant safety person must keep in mind that audiometric testing must be conducted in a noise-free environment (e.g., in an audiometric testing booth).

Whatever audiometric testing approach the plant safety person decides to implement, in-house testing or hiring a medical contractor, the audiometric testing procedure has some requirements that are mandatory. For example, each employee who might be exposed to noise levels at or greater than 85 dB must be given a baseline audiometric test. The audiometric test should be conducted only when the worker has not been exposed to workplace noise for at least 14 hours. Testing must be performed by a certified audiometric technician using a calibrated audiometer (annual requirement) in an environment of less than 40 dBA. Six months after receiving the baseline audiometric test, the worker should be tested again and then annually thereafter. All new employees should be given the baseline audiometric test within 6 months of their hire date. Any worker who experiences a temporary or permanent threshold shift should be retested within 60 days. A temporary threshold shift (TTS) represents auditory fatigue caused by excessive exposure to noise. TTS is transient but its presence is undesirable. A permanent threshold shift (PTS), on the other hand, is a more serious hearing disability. As the name implies, PTS can result in permanent loss of hearing acuity and should be rigorously guarded against. If the follow-up audiometric test suggests a permanent threshold shift rather than temporary threshold shift, the worker must be referred to a physician for evaluation as to whether or not the damage is permanent. All cases of occupational-related hearing loss must be recorded on the OSHA Form 300 log, and the plant's hearing conservation program must receive oversight guidance from a licensed audiologist.

Because hearing loss is such a gradual process, it is often ignored by the worker and the supervisor. This is why training is so critical. Like all safety programs, the programs are only as good as the training that is provided with the program. As part of a hearing conservation program not only is training critical but so are supervision and management. An effective hearing conservation program cannot be established without a written program, worker training, and effective supervisory management. It has often been said that leaders should lead by example; that is, the worker will not wear the hearing protection devices unless the leader leads the way by wearing hearing protection devices and ensuring that the workers also wear them. Hearing loss liability continues to be a costly proposition for many high-noise industries. By incorporating an effective hearing conservation program into the organizational safety program you will reduce worker hearing loss and liability for the loss.

1.13.6 Personal Protective Equipment (29 CFR 1910.132 and 1910.138)

Recognizing the importance of personal protective equipment (PPE), on October 5, 1994, the revised OSHA personal protective equipment standard went into effect in workplaces throughout the United States. It is important to note that OSHA stresses that PPE should *not* be used as a substitute for engineering, work practice, and/or administrative controls. PPE should be used in conjunction with these controls to provide for worker safety and health in the workplace, as backup or secondary protection.

The PPE addressed in the OSHA standard specifically deals with protective equipment designed to protect many parts of a worker's body, including eyes, face, head, hands, and feet. PPE for respiratory protection and hearing conservation is addressed in other OSHA standards and has already been discussed in this text.

The specific part of the PPE regulation that applies to a particular organization varies, depending primarily on the *types of hazards* present in the workplace environment. The PPE regulation is known as an OSHA "performance standard." A performance standard mandates that protection shall be provided by the employer to the employee but the employer is allowed to meet the minimum requirements as determined by experience/performance as specified by the organization's safety person.

In general, the OSHA PPE standard covers three important areas:

- Hazard assessment of the workplace and certification
- Selection of PPE
- Worker PPE training and certification

Before addressing the individual areas concerning PPE it must be reiterated that OSHA's goal is to use PPE in conjunction with other controls to protect workers. Remember, PPE is simply designed to create a barrier between the worker and workplace hazards; *it does not remove the hazard from the workplace.*

The first step to be taken in determining the types of PPE that are needed at the plant site is conducting a hazard assessment survey of the workplace to determine if hazards that require the use of PPE are present or are likely to be present. If the plantwide hazard assessment survey shows that hazards, or the likelihood of hazards, are possible, employers must select and have affected employees use *properly fitted* PPE suitable for protection from the existing hazards. Standby PPE protection should be on hand in case potential hazards become actual hazards.

For PPE to be effective it must be properly selected. To aid the employer in the selection process, each employer is required to perform the workplace hazard assessment mentioned earlier. Each employer must prepare a written *certification of hazard assessment*, which at a minimum contains the following information:

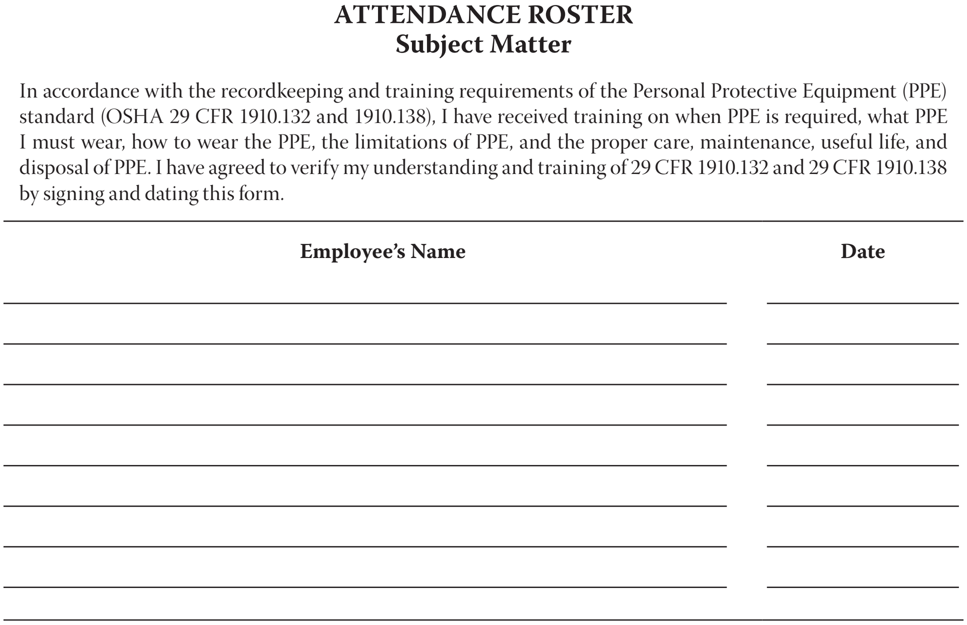
- Location of the workplace evaluated
- Details of the hazards assessed
- The person certifying the evaluation
- Dates of hazard assessments

Once the workplace hazard assessment has been completed, the employer is required to select and require each employee to use the correct PPE. For PPE to be effective in hazard control, workers must be aware of the importance of their role in the proper fitting and wearing of it. Moreover, the appropriate PPE for each workplace must be *clearly described* to each worker in that area. Work areas where hazardous operations such as welding and chemical handling take place must be labeled for the hazard and for the PPE that is required.

According to the Bureau of Labor Statistics' injury reports, a significant number of workers who are injured on the job have never been trained in the proper use of PPE. Worker training is absolutely essential in the proper use of PPE. Workers must be trained to know when to wear PPE. They must know what PPE to wear and how to wear it, they must understand the limitations of PPE, and they must be trained in the proper care, maintenance, useful life, and disposal of PPE. Once the worker has demonstrated an understanding of PPE training, the safety person must verify the worker's certification in writing.

Another word about training: By now you have picked up on the fact that the author feels that the importance of training cannot be overemphasized. Important as training is it is just as important to ensure that training that is completed is documented. Training completed but not properly documented is training that was never done; that is, if you can not demonstrate to OSHA in writing that training was accomplished, then, in the regulator's view, it was not.

To verify the effectiveness of PPE training or any other safety training it is always prudent to give a test or quiz at the end of each training presentation. This test or quiz should be straightforward and on the subject matter that was taught. The test should be written in such a manner that all workers will be able to easily understand its content. The test should be reviewed, and all questions that were incorrectly answered



ATTENDANCE ROSTER
Subject Matter

In accordance with the recordkeeping and training requirements of the Personal Protective Equipment (PPE) standard (OSHA 29 CFR 1910.132 and 1910.138), I have received training on when PPE is required, what PPE I must wear, how to wear the PPE, the limitations of PPE, and the proper care, maintenance, useful life, and disposal of PPE. I have agreed to verify my understanding and training of 29 CFR 1910.132 and 29 CFR 1910.138 by signing and dating this form.

Employee's Name	Date

Figure 1.1 An attendance roster not only is used to verify an employee's attendance at a particular safety training session but also serves as verification that the employee understood the training. This form or a similar form should be used for all safety training sessions and should be filed in the workplace master training file.

should be answered correctly. This will ensure that the worker who may have incorrectly answered any question does not leave the training area without knowing the correct answer. Workers who have difficulty with reading and writing should be administered oral tests. The safety person should use discretion whenever this practice is followed. The idea is to test the worker's comprehension of the subject matter and not to embarrass the worker.

Upon the successful completion of PPE or any other safety training it is a good idea to present each worker with some type of certificate of completion. As a matter of fact, according to OSHA regulations, employees undergoing PPE training must be given written *certificates of employee training* to verify that they have received and understand the required information. This certification must contain the employee's name, the date of the training, and the subject of certification. Remember, training that is not documented is training that was never accomplished—this is the view that OSHA and the courts will take. In addition to testing and certifying workers who have completed safety training it is prudent to have each worker sign and date an attendance roster. Figure 1.1 shows one version of an attendance roster.

The OSHA PPE standard addresses the protection of four distinct areas: eye and face, head, hands, and feet. The eye and face protection part of the standard requires that workers be provided with eye and face protection whenever they are required to work with:

- Liquid chemicals
- Hazardous gases
- Flying particles
- Molten metals
- Injurious radiant energy

OSHA requires that the eye protection devices provided must:

- Provide adequate protection against the particular hazard for which they are designed.
- Be reasonably comfortable when worn under the designated conditions.
- Fit snugly without interfering with the movements or vision of the wearer.
- Be durable.
- Be capable of being disinfected.
- Be easily cleanable.
- Be kept clean and in good repair.

Several types of eye and face protection are available, including:

- Safety glasses
- Goggles
- Face shields
- Full hoods
- Welding helmets

Safety glasses are the basic form of eye protection. OSHA now requires protective eye coverage from the front and the sides any time there is a hazard from flying objects. This coverage can be accomplished by using safety glasses with attached side shields or by using detachable side protectors.

A common misunderstanding is that most workers think that a face shield is eye protection. Face shields are designed to protect the worker's face; they are not eye protection. Safety glasses or goggles should be worn under face shields to provide primary eye protection.

It is not uncommon for workers to use the wrong type of eye protection for a particular work assignment. As a case in point, consider workers who must work with corrosive chemicals. These workers normally wear safety goggles, but they might be the wrong type of safety goggle for the work they are performing. Safety goggles are available in vented, nonvented, and shielded vent types. When working with liquid corrosive chemicals, the worker should wear goggles that are not vented or do not have shielded vents. When working with gaseous chemicals, the worker should wear nonvented goggles only. Vented goggles are to be used only for grinding operations or for assignments when chemicals are not used. In addition to requiring workers to wear the correct type of goggle, the plant safety person should also require workers to wear face shields for added safety.

Employees who wear prescription eyewear on the job must also wear approved eye protection. Workers who wear prescription glasses wrongly assume that they are automatically wearing eye protection. This is not the case, however, and employers are not required to provide workers with prescription protective eyewear. Workers who choose to purchase their own prescription protective eyewear must ensure that the protective eyewear meets the applicable American National Standards Institute (ANSI) standard. It is wise to issue oversized goggles that are designed to fit over the wearer's regular prescription glasses. This method seems to suit workers' needs and provides the required protection.

Head protection is required for workers who are or might be exposed to injury from falling objects or work near exposed electrical conductors that could contact the head area. A government study on disabilities suggests that over 65,000 head or face injuries occur each year. Another study of accidents and injuries conducted by the Bureau of Labor Statistics noted that most workers who suffered impact injuries to the head were not wearing head protection. Although it is true that head protection would not have prevented all of these injuries, it is also true that there are plenty of workers who have suffered head injuries who wish they had been better protected at the time of their injury.

The primary head protection recommended is the hard hat. Hard hats are designed to protect the worker from impact and penetration caused by objects hitting the head. They also provide limited protection against electrical shock. Hard hats are tested to withstand the impact of an 8-pound weight dropped 5 feet. They must meet other requirements, including those regarding weight, electrical insulating properties, and flammability. It is interesting to note that a Bureau of Labor Statistics survey found that 91% of injuries to persons wearing hard hats occurred when the person was struck other than on top of the head. Lateral head protection is available but it is larger, heavier, hotter, and more expensive than standard hard hats (Minter, 1990).

Hard hats come in three classes: A, B, and C. Class A hard hats are made from insulating material that is designed to protect the worker from falling objects and electric shock by voltages of up to 2200 volts. Class B hard hats are made from insulating material designed to protect the worker from falling objects and electric shock by voltages up to 20,000 volts. Class C hard hats are designed to protect workers from falling objects but are not designed for use around live electrical wires or where corrosive substances are present.

Most organizations require workers to wear the Class B hard hat. Because corrosives, overhead objects (cranes), and electrical circuitry are present in most wastewater treatment facilities, the Class B hard hat is best suited to protect workers in this environment. It is also important to label or post those areas in the plant site where hard hats are required. When major construction work is in progress on the plant site, hard hats should always be worn by plant operators who might have to make hourly rounds in, through, or near these areas. Hard hats should be routinely inspected and replaced at regular intervals.

Arm and hand on-the-job injuries are frequent in wastewater treatment facilities. The OSHA PPE standard requires employers to provide hand protection for workers for on-the-job use. The key to ensuring proper finger, hand, and arm protection is to ensure that workers wear protection when they are exposed to such hazards as skin absorption of harmful substances; severe abrasions, cuts, or lacerations; punctures; chemical burns; thermal burns; vibration; and harmful temperature extremes.

Gloves are the most common type of hand protection. Depending on the type of work involved the type of glove will vary. Whatever type of glove selected, it must fit the worker's hand. Other devices can be used to protect the worker's fingers. Finger cots are designed to protect individual fingers or fingertips. Thimbles protect the thumb. The palm of the hand can be protected from cuts, friction, and burns by using hand pads. Long sleeves and forearm cuffs protect arms and wrists from heat, splashing liquids, impact, and cuts. When hand lotions and creams are used for hand and finger protection, they are not to be used as a substitute for gloves. In the wastewater treatment plant laboratory or chemical handling area, special gloves should be used, including nitrile or synthetic rubber gloves for handling oils, some solvents, and grease. Neoprene gloves can be used for handling a broad range of chemicals, oils, acids, caustics, and solvents. Polyvinyl chloride (PVC) gloves can be used when handling acids, caustics, alkalis, bases, and alcohol.

When working with chemicals, the type of glove chosen should protect against the toxic properties of the chemical, not only local effects on the skin but also systemic effects. Generally, gloves that are rated "chemical resistant" can be used to work with dry powders. An important factor to remember whenever using gloves to protect against chemicals is that the gloves selected must be removable without contaminating the skin. When in doubt about whether or not gloves are required for chemical handling and what type of glove should be used, consult with the chemical material safety data sheet (MSDS) or ask the manufacturer.

Finally, it is important to provide workers with gloves that will protect them against severe temperature extremes and vibration. For example, when work is to be performed around or on plant incinerators a special heat-insulating glove should be issued to the worker. In the winter, workers assigned to an excavation in the field should be issued gloves that will protect against frostbite. Antivibration and impact gloves are available for purchase for use by workers who perform jack-hammering and other high-vibration types of jobs. The purpose of using impact and antivibration gloves is to dampen the shock before it reaches the worker's hands.

Note: Keep in mind that whatever type glove that is chosen to protect the worker's hands and fingers, the glove must remain functional in terms of dexterity, comfort, durability, and cost.

According to the Bureau of Labor Statistics, most of the workers in selected occupations who suffered foot injuries were not wearing protective footwear. In the wastewater industry, foot injuries usually occur for the same reason. Moreover, foot injuries usually occur when heavy or sharp objects fall (typically falling fewer than 4 feet) on the foot, when something rolls over the foot, or when the worker steps on an object that pierces the sole of the shoe. *Foot protection* is another requirement of the OSHA PPE standard.

Selecting the proper protective footwear for workers depends on the type of work they will be performing. For construction work (excavations) or work involving rolling objects (e.g., rolling chlorine cylinders), safety shoes with impact-resistant toes should be worn. For work in or around liquid corrosive chemicals, rubber or synthetic footwear should be worn. When a worker is involved in work around exposed electric wires, metal-free nonconductive shoes should be worn. Again, the type of safety shoe to be worn depends on the type of work that the worker is assigned to do. Safety shoes come in a variety of styles and materials, such as leather and rubber boots and oxfords.

An important factor about safety footwear that the plant safety person needs to keep in mind is that, although OSHA requires employers to ensure that workers are wearing proper safety shoes on the job, OSHA does not mandate that the employer *provide* the safety shoes. This can be a point of contention between the worker and management. Safety shoes are not inexpensive. Some workers may resist purchasing the expensive safety shoes required. This is where the plant safety person must use the power of persuasion to ensure that management supports and workers comply with this important safety requirement. As always, training on footwear protection is crucial.

1.13.7 Electrical Safety (29 CFR 1910.301–339)

Wastewater workers seem to have a healthy respect for electricity. This respect for the power of electricity is well warranted; however, it seems somewhat ironic that despite this deep respect for electricity most workers seem to ignore or abuse electrical safe work practices. Perhaps the answer lies in the fact that electricity, as a source of power, has become so readily accepted that not much thought is given to its potential hazards. Because it has become such a familiar part of our surroundings, it often is not treated with the level of respect or fear it deserves.

Wastewater treatment and collection workers are exposed to electrical equipment and hazards on a daily basis. For this reason, the wastewater safety person must pay particular attention to this important safety topic. When seeking information and guidance on electrical hazards and their control, several different sources of information are available, such as Subpart S of the OSHA standards, which governs electrical work. OSHA requires the employer to train all workers in safe work practices for working with electrical equipment. OSHA's training rules distinguish between workers who do not work on or near exposed energized components and those who do. Even workers who are not qualified to work on or around energized electrical equipment are required to know the specific safety practices that apply to their jobs.

The key to developing and maintaining a sound electrical safety program is to make worker awareness of electrical hazards an important part of the safety and health program. Worker awareness is brought about through worker training. Workers need to be aware of the primary hazards of electricity, including shock, burns, fires, explosions, and arc blast.

Workers must also have knowledge of the causes of electrical accidents. They must be trained and made to understand that accidents and injuries that occur when working with or around electricity are caused by a combination of factors, such as unsafe equipment, unsafe workplaces, unsafe work practices, and unsafe equipment installation.

Along with ensuring worker training on and awareness about electrical hazards, the plant safety person must make elimination or control of electrical hazards his or her goal. Preventing electrical accidents can be accomplished by utilizing protective methods to prevent electrical hazards. These protective methods include ensuring that electrical devices and circuitry are properly insulated and insisting that electrical-grade matting be installed in front of all high-voltage switchgears. Electrical protective devices such as fuses, circuit breakers, guardrails, and ground connections should also be utilized. The plant safety person should check the integrity of electrical wiring throughout the facility. Electrical shock can be prevented if hanging live electrical wires are discovered and properly removed. A safety auditor who finds hanging live electrical wires should address the source of the occurrence. In other words, how did such an unsafe condition get left "hanging around," so to speak? When such conditions are found, it is instantly obvious that safe electrical work practices are being ignored.

Wastewater treatment plant electricians must also be trained in safe work practices. Although electricians are usually highly trained and skilled technicians, these highly skilled and trained technicians can make mistakes, use poor judgment, or perform their work in a careless manner. Electrical safety must be stressed to *all* workers. Moreover, all plant workers must be reminded that the plant requires the use of a lockout/tagout procedure to de-energize electrical equipment and that it will be enforced. Additionally, workers must be reminded not to wear metal objects (e.g., watches, rings) when working with electricity.

In summary, an effective workplace electrical safety program can be instituted if the following steps are followed and enforced:

1. Identify and label all workplace electrical hazards.
2. Train all employees on electrical safety.

3. Use safe work practices:
    - De-energize electric equipment before inspecting or making repairs.
    - Use electrical tools that are in good repair.
    - Use good judgment when working near energized lines.
    - Use appropriate protective equipment.

1.13.8 Fire Safety (29 CFR 1910.38, 1910.106, and 1910.157)

Wastewater treatment plants are not immune to fire and its terrible consequences. Fortunately, plant safety officials are aided in their fire prevention and control efforts by the authoritative and professional guidance available from the National Fire Protection Association (NFPA), the National Safety Council (NSC), fire code agencies, local fire authorities, and OSHA regulations.

Along with providing fire prevention guidance, OSHA regulates several aspects of fire prevention and emergency response. Emergency response, evacuation, and fire prevention plans are required under 29 CFR 1910.38. Additionally the requirement for fire extinguishers and worker training are addressed in 29 CFR 1910.157. More specifically, OSHA, along with state and municipal authorities, has listed several fire safety requirements for general industry.

All of these advisory and regulatory authorities approach fire safety in much the same manner. For example, they all agree that fires in the workplace are usually started by electrical short circuits or malfunctions. Along with electrical causes, other leading causes of fire in the workplace are friction heat, welding and cutting of metals, improperly handled chemicals, improperly stored flammable/combustible materials, open flames, and cigarette smoking.

For fire to start, three ingredients are needed:

$$\text{Heat} + \text{Fuel} + \text{Oxygen}$$

It is the objective of fire prevention and firefighting to separate any one of these ingredients from the other two. For example, to prevent fires, keep fuel (i.e., combustible materials) away from heat; store such materials in airtight containers to isolate the fuel from the oxygen in the air and heat.

To help in gaining a better perspective of the chemical reaction known as fire it should be pointed out that the combustion reaction normally occurs in the gas phase, and, generally, the oxidizer is air. If a flammable gas is mixed with air, there is a minimum gas concentration below which ignition will not occur. That concentration is known as the lower flammable limit (LFL). When considering the LFL and its counterpart, the upper flammable limit (UFL), it helps to refer to the familiar example of the combustion process that occurs in the automobile engine. When an automobile engine has a gas/air mixture that is below the LFL, the engine will not start because the mixture is too lean. When the same engine has a gas/air mixture that is above the UFL, it will not start because the mixture is too rich (engine is flooded). When the gas/air mixture is between the LFL and UFL levels, the engine should start.

Fire experts advise that the best way to reduce the possibility of fire in the workplace is through prevention. The plant safety person has an important responsibility in fire prevention. In the first place, the plant safety person must ensure that workers are trained in fire prevention practices. Second, workplace housekeeping practices must be monitored and strongly enforced. If workers allow debris or flammable material to accumulate and supervisors do not correct this practice, the risk of fire increases. The plant safety person and work center supervisors must ensure that all workers understand that fire prevention is everyone's job. Because of the deadly nature of fire, it is to all workers' benefit to know how to size up a fire and how to respond in a fire emergency.

1.13.8.1 Fire Prevention and Control

Fire prevention and control measures are taken *before* fires start. Fire prevention and control are best accomplished by:

- Eliminating heat and ignition sources
- Separating incompatible materials
- Having available adequate means of fire fighting (e.g., sprinklers, extinguishers, hoses)
- Proper construction and choices of storage containers
- Proper ventilation systems for venting and reducing vapor buildup

In the event of a fire emergency, unobstructed means of egress for workers must be provided. Additionally, adequate aisle and fire-lane clearance for firefighters and equipment must be maintained.

All workers need to know what to do in the case of a fire emergency; they need a plan. The fire emergency plan normally is the protocol to follow for fire emergency response and evacuation. The plant safety person is usually charged with the responsibility for developing fire prevention and emergency response plans that spell out everyone's role. Make your fire plan as easy as possible. Along with an easily understood fire plan, the workers need to know what actions they are expected to take in the event of a fire.

Keep in mind that in addition to some type of fire emergency response action plan, each plant needs to have a well thought out fire emergency evacuation plan.

1.13.8.2 Fire Protection

OSHA requires employers to provide portable fire extinguishers that are mounted, located, and identified so they are readily accessible to workers without subjecting the worker to possible injury. In addition, OSHA requires that each workplace institute a portable fire extinguisher maintenance plan. Fire extinguisher maintenance service must be performed at least once a year and a written record kept to show the maintenance or recharge date.

Note: When the plant safety person provides portable fire extinguishers for worker use in the plant, the worker must be provided with an education program to learn the general principles of fire extinguisher use and the hazards involved with fire fighting.

Wastewater workers must be trained to know where and what type of fire extinguishers are available for the different classes of fire. The ABC type of fire extinguisher is probably best suited for the wastewater industry. These extinguishers can be used on Class A, B, and C fires. The only exception to this practice is fire extinguishers located in electrical substations or switchgear rooms. In areas like these, only Class C (carbon dioxide; CO_2) extinguishers should be used. Combination ABC fire extinguishers will extinguish most electrical fires, but the sticky chemical residue left behind can damage delicate electrical or electronic components; thus, CO_2 extinguishers are more suitable for extinguishing electrical fires. Each worker must know how to use the fire extinguisher. Most importantly, the workers must know when it is not safe to use fire extinguishers—that is, when the fire is beyond being extinguished with a portable fire extinguisher. Emergency telephone numbers should be strategically placed throughout the workplace. Workers need to know where these emergency numbers are posted. Moreover, workers should be trained on the information that they need to pass on to the 911 operator in case of fire.

1.13.8.3 Flammable and Combustible Liquids

In addition to basic fire prevention and emergency response training, workers must be trained on flammable and combustible liquids. 29 CFR 1910.106 addresses this area. Wastewater treatment and collection operations use all types of flammable and combustible liquids. These dangerous materials must be clearly labeled and safely stored when not in use. Additionally, the safe handling of flammable and combustible liquids is a topic that should be fully addressed by the plant's safety person and workplace supervisors. The importance of worker awareness of the potential hazards that flammable and combustible liquids pose must be stressed. Workers need to know that flammable and combustible liquid fires burn extremely hot and can produce copious amounts of dense black smoke. In addition, explosion hazards exist under certain conditions in enclosed, poorly ventilated spaces where vapors can accumulate. A flame or spark can cause vapors to ignite, creating a flash fire with the terrible force of an explosion.

One of the keys to reducing the potential spread of flammable and combustible fires is to provide adequate containment. All storage tanks should be surrounded by storage dikes or containment systems. Correctly built and installed dikes will contain spilled liquid. Spilled flammable and combustible liquids that are contained are easier to manage than those that have free run of the workplace. Additionally, properly installed dikes can prevent environmental contamination of soil and groundwater.

In summary, the plant's workers, supervisors, and safety person must be prepared for fire and its consequences. It is important for the plant to maintain a fire prevention strategy that will ensure that work areas are clean and clutter free. Workers must know how to handle and properly store chemicals. Workers must know what they are expected to do in case of a fire emergency. Workers must know how and whom to call when fire occurs, and they must be thoroughly trained in fire prevention and emergency response procedures.

1.13.9 Laboratory Safety (29 CFR 1910.1450)

Wastewater treatment plant laboratories function to perform process-control tests for permit compliance. The size of the laboratory generally depends on the size of the plant. For example, some plants are satellite treatment works within a larger sanitation district. In this case, each individual plant usually has a laboratory designed specifically to handle the work required to meet compliance and perform testing criteria for the plant. On a larger scale, the main laboratory of a sanitation district usually conducts testing for the entire organization; it augments and refines site testing.

No matter the size of your particular wastewater treatment laboratory, safety plays a key role in maintaining worker well-being and compliance with applicable health, safety, and environmental standards. Wastewater treatment laboratories are expected to comply with 29 CFR 1910.1450, which mandates development of a chemical hygiene plan (CHP). Additionally, wastewater treatment laboratories must comply with the requirements of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA); with Superfund Amendments and Reauthorization Act (SARA) rules and regulations; and with rules and procedures set by the state water control board or other local environmental agencies.

The wastewater treatment plant safety person should ensure that the laboratory has a safety program. The goal of the laboratory safety program is multifaceted, as it should protect laboratory workers, others who may be exposed to hazards from the laboratory, and the environment. The hazards associated with laboratories are not unlike other work areas. Common injuries that occur in these laboratories are cuts, burns, slips, and falls; however, because there is a constant exposure to potentially dangerous substances, all personnel that work in the laboratory must be instructed as to proper laboratory methods and safety precautions.

Laboratory personnel are required to perform analyses on a variety of wastewater and biosolids (sludge) samples. Although the risk of infection from wastewater samples is not as high in the laboratory environment as in the collection systems where direct exposure to raw wastewater is high (in sewers, pumping stations, and interceptor pipelines), infectious agents that are commonly found in laboratory samples are nonetheless a biological hazard.

1.13.10 Slips, Trips, Falls, and Safe Lifting Practice

Slips, trips, and falls are common mishaps in wastewater treatment facilities. Many workplace activities involve carrying loads and other material handling activities. These material handling activities are major contributors to slips, trips, falls, and back injuries in the workplace. Additionally, the use of ladders or scaffolds can put workers at risk for fall-related injuries. When chemicals are introduced into the work activity, the occurrence of slips, trips, and falls seems to escalate. As a case in point, consider chemical polymers. Polymers are used in wastewater treatment for varying purposes. One use of polymer is for biosolid (sludge) conditioning. When polymer becomes wet, it produces a severe walking surface hazard because of its slippery nature. Polymer is only one of several chemicals used in wastewater treatment facilities that can create slippery walkways and stairs. The point is that all spills must be cleaned up immediately. Workers must be trained to react whenever they spill chemicals or observe a spill. Even minor spills can be hazardous.

In practicing good housekeeping in the workplace, maintaining clean floors is step one. Providing well-lighted work areas is another step. Additionally, clutter in aisles or stairs is a major contributing factor to trips and falls in the workplace. Hazards due to loose footing on stairs, steps, and floors must be eliminated. The plant safety person plays a major role in the prevention of slips, trips, and falls in the workplace. The safety person's routine plant audit should focus on this vital area. Moreover, plant safety meetings should always stress the importance of keeping the work area clean.

Ranking right up there in frequency of occurrence of finger and hand injuries are injuries to the back. Back injuries present a constant dilemma to the plant safety person. How can they be prevented? What steps are necessary to prevent them? Back injury prevention begins with the safety plant official gaining insight into mishaps caused by material handling. This insight is gained through consideration of several factors. For example, a determination should be made as to whether or not it is practical to provide workers with material handling aids that will make lifting safer. Lifting aids would include insisting that workers lift the properly sized containers and that workers use lifting trucks when necessary, as well as by providing workers with lifting tools such as hooks. Another aid to safe lifting that should be looked at is whether or not it is practical to provide conveyers or other mechanical devices for moving packages. As a last resort, the safety person should decide if personal protective equipment such as gloves might help prevent injuries.

After making an assessment of the task and the workplace, having conducted a review of back injuries that have occurred at the plant site in the past, and after determining whether or not mechanical devices or personal protective equipment can help reduce back injuries, the safety person should decide on what type of worker back injury prevention training program to institute. Experience has shown that training can be an effective management aid in helping reduce back injuries. The back injury prevention program is an ongoing program. Back injury prevention and other types of safety training must be presented on a continuous basis. Moreover, follow-up training is the key to maintaining what was learned in the initial training sessions.

1.13.11 Excavation Safety (29 CFR 1926.650–652)

Wastewater collection systems are an integral part of wastewater treatment, a utility that commonly performs trenching and excavation work. Maintaining a leak-free, infiltration-free interceptor piping system is important to providing a constant wastewater stream to the treatment facility. Pipes fail. When they fail, they must be repaired or replaced. On occasion, before repairing or replacing the lines, they must be excavated.

Attempting repair work to aboveground interceptor lines is relatively easy as compared to making repairs to underground lines. When repairs are to be made to underground lines, either trenching or excavation is required. A trench is a narrow excavation that is less than 15 feet wide and is deeper than its width. An excavation, on the other hand, is a cavity or depression that is cut or dug into the earth's surface.

Whether trenching or excavating, either operation is inherently dangerous. As a matter of fact, working around and in excavations is one of the most dangerous jobs in the wastewater treatment and construction industries. It is estimated, for example, that in the construction industry alone, cave-ins claim about 100 lives every year. Thus, excavating interceptor lines is a very real hazard to wastewater workers. Having said the obvious, post-incident investigations of trenching and excavation mishaps have shown that little heed was paid by excavators to the hazards involved with excavating and trenching.

If your facility undertakes routine repairs to or replacement of underground interceptor lines, then you must ensure that the OSHA regulations pertaining to trenching and shoring are followed. These OSHA regulations can be found in 29 CFR 1926.650–652 (the Construction standard).

An effective trenching and shoring safety program begins with knowing the hazards. Workers must know what they face during these operations. Additionally, workers must know how to protect themselves from injury through the proper use of safe work practices—in trenching and excavation work there is no room for error. When a trench or excavation fails, injuries and fatalities occur fast, often in seconds.

There is also no room for poor judgment in performing excavation and trenching operations. Before beginning to trench or excavate, certain conditions must be checked, such as the location of utility installations (e.g., telephone, fuel, electric, water lines) or any other underground installations that reasonably may be expected to be encountered during excavation work prior to beginning an excavation.

Several other conditions must be checked before excavation is attempted, including soil, weather, and climate conditions. These factors will determine the amount and degree of sloping that should be used. Moreover, the strength of trenching support members (bracing and shoring) is based on soil type and weather conditions. Failure to properly support walls for a trench or excavation may cause disaster. Often, trenching and excavation jobs are driven by cost and time saving requirements. At other times, the supervisor in charge of the operation might determine that the trench or excavation will only be open for a short period and that proper shoring is not needed. What this supervisor is really doing is taking a chance on a shortcut … perhaps a shortcut to disaster.

When auditing various plant excavation programs it is not unusual to find a weak link in the program. This weak link can usually be attributed to a lack of supervisor and worker knowledge. The auditor often finds that workers are not aware of the hazards involved and the precautions necessary to minimize the hazard. A trenching and excavation training program should provide the information necessary to ensure that supervisors and workers know the hazards. They should know that the major hazard is cave-ins, which can crush or suffocate them. They should know that trenches and excavations can contain poisonous gases. There is also the very real possibility of uncovering a pocket of combustible vapors or gases. For example, when digging around interceptor lines, it is not unusual to run into a pocket of methane, leading to the danger of fire or explosion. Supervisors and workers also need to know that OSHA requires excavations to be protected from cave-ins by an adequate protective system that is designed to resist without failure all loads that are intended or could reasonably be expected to be applied or transmitted to the system.

Trenches and excavations can be full of additional obstacles; for example, carelessly placed tools and equipment or excavated material can cause injuries due to slips, trips, or falls. After explaining the general hazards that are present with any trenching or excavation job, the person performing the training needs to inform the workers about the causes of cave-ins—they need to know what to look for. Workers need to understand that cave-ins occur when an unsupported wall is weakened or undermined by too much weight or pressure or an unstable bottom.

One of the danger signs to look for in trenching or excavation work is surface cracking. These cracks usually occur near the edge of the trench or excavation. Overhangs and bulges are other signs of danger. An overhang at the top or a bulge in a wall can cause soil to slide into the trench or excavation. Whenever cracks or overhangs are discovered, work should be stopped and the problem reported immediately.

As mentioned earlier, weather and climate can have a serious impact on trenching and excavation activities. Rain, melting snow, groundwater, storm drains, nearby streams, or damaged water lines can loosen soil and increase pressure on walls. At the opposite extreme, extremely dry weather can also be dangerous because it tends to loosen soil. Frozen ground presents another problem. When the frozen ground thaws, walls of a trench or excavation can be weakened. When the excavation is a long-term job, there may be a need for extra weather and climate protection. Sides and faces of the dig should be covered with tarps to reduce danger.

Supervisors and workers also need to be trained in soil-type recognition procedures. Soils with high silt or sand content are very unstable unless properly shored or sloped. Wet or backfilled soil is also unstable and requires wall support. Even hard rock can present a problem unless it is properly supported. Hard rock that cracks or splits through a fault can break away and fall into the excavation.

One area of danger that is often overlooked in trenching and shoring operations is the presence of vibration. Vibrations can loosen soil and cause walls to collapse unless proper shoring or sloping is used. Sources of vibration at the worksite include vehicles, moving machinery, blasting operations, and machines that might be used nearby such as punch presses and forging hammers. Excavated material can also pose a hazard to the excavators. Excavated material (or spoil) should always be stored at least 2 feet from the edge of a trench or excavation. Never let excavated material accumulate near wall sides. Additionally, moving excavated soil can also pose a hazard to excavators. Heavy equipment operating near the trench or excavation can exert tremendous pressure on walls.

To protect excavators against accidents, proper techniques and equipment must be used in the trenching and shoring operations. Trench shoring material should consist of sheeting, bracing, and jacks. Never use shoring materials that have not been certified for use by a licensed professional engineer. After installation of the correct shoring materials, these materials should be inspected daily before anyone enters the trench or excavation.

When the decision is made to use ground sloping techniques to prevent cave-ins, the sides of a trench or excavation must be sloped correctly so the soil will not slide. Determining the *angle of repose* is critical in shaping the proper slope. The angle of repose is the steepest angle at which trench or excavation walls will lie without sliding. The more unstable the soil, the flatter the angle should be. For example, the angle of repose for solid rock should be set at 90°. For average soil, an angle of 45° is recommended. For loose sand, the proper angle of repose should be set at about 25°.

Several other safety considerations are necessary whenever a trenching or excavation project is undertaken. Workers must understand that it is important to provide site protection. Site protection protects workers from rocks or other objects kicked or thrown into the trench as well as pedestrians who might inadvertently fall into an open trench or excavation. Safety measures such as fences, barricades, covers for manholes, flags, security guards, and warning signs may be necessary. It is important to remember that lighting may be necessary so safety can be maintained at night.

Along with providing proper lighting so excavators can see well enough to work in an excavation, a stairway, ladder, ramp, or other safe means of egress must be located in trench excavations that are 4 feet or more in depth so as to require no more than 25 feet of lateral travel for workers.

As with any other dangerous operation, the plant safety person should ensure that a contingency plan for emergency response is used. This contingency plan must be made clear and understandable to all trenching and excavation personnel. Emergency procedures are worthless unless they are common knowledge. Someone should always be outside the trench or excavation to help, if necessary. Emergency telephone numbers should be readily available. As a final precaution, the trench or excavation should be backfilled as soon as possible when the work is completed.

As with many other work activities, OSHA requires that personnel involved with excavation activities be trained and that this training be documented. Moreover, OSHA also requires that the person in charge of the excavation be a *qualified* or *competent person*. When qualifying a qualified/competent person for excavation and trenching operations, it is wise to put together an excavation crew and a potential qualified/competent person as the person in charge and have the crew dig a hole 12 feet deep in a practice area. Experience gained through actually performing the work can never be replicated by listening to a classroom lecture on the topic.

While observing the dig and shoring procedures, note whether or not the potential qualified/competent person is conducting the dig as required. If the dig is done correctly, certify the person in charge as being qualified for excavation/trenching operations. The other excavation crew members should be given certificates of training verifying that they have been trained.

1.13.12 Hazardous Materials Emergency Response (29 CFR 1910.120)

CoVan (1995) defined emergency response “as a limited response to abnormal conditions expected to result in unacceptable risk requiring rapid corrective action to prevent harm to personnel, property, or systems function” (p. 54). OSHA and the EPA require that facilities handling or using hazardous materials (e.g., chlorine, sulfur dioxide, sodium hydroxide, methane) develop a site emergency response plan and provide worker training to give workers correct guidance on what to do in case of medical, fire, or chemical discharge emergencies. The OSHA/EPA joint standards on hazardous waste operations and emergency response are commonly referred to as *HAZWOPER*.

The HAZWOPER standard has an impact on wastewater treatment plants, which often surprises wastewater treatment plant management personnel. To determine whether or not HAZWOPER impacts them, plant managers should perform a site survey designed to account for and list all hazardous materials. For example, if a wastewater treatment plant uses more than 10 pounds of chlorine in its process, it must be prepared to manage or mitigate an accidental release of chlorine to comply with the HAZWOPER standard.

The site emergency response plan for wastewater treatment plants should include medical emergency instructions, fire emergency plans, and chemical release emergency plans. In addition, the plant emergency response plan should include an emergency evacuation plan, a chemical/safety equipment location diagram, and hazardous materials system line diagrams. Also, use of the DOT *Emergency Response Guidebook* as the primary reference manual is highly recommended.

The plant's emergency response plan should be user friendly. Emergency response plans that are written by technical personnel are usually slanted toward a technical point of view understood and readily utilized by technical personnel. This can defeat the intended purpose of developing quick, correct, safe mitigation procedures. Moreover, making emergency response highly technical or complicated defeats the purpose of making the plan user friendly. Workers must be fully aware of the plan's requirements and their own individual responsibilities.

The site emergency response plan should be written around two main objectives: (1) minimize the short-term or immediate hazards to the public, the responders, and the environment; and (2) ensure the recovery and long-term use of the affected plant site. Accomplishing the first objective may necessitate taking short-term actions that will delay or prolong accomplishment of the second objective; however, it is clear that these objectives must be accomplished in sequence.

Responding to a release of chlorine requires extensive training in chlorine repair kit use, chemical protective equipment, and respiratory protection. In addition, the plant emergency response team must coordinate its response efforts with other local emergency response teams. The plant must have a designated emergency response coordinator who is trained to coordinate the plant's response to chemical release.

1.13.12.1 Wastewater Treatment Plant Emergency Response Plan

The wastewater treatment plant's emergency response plan states the organization's policies and procedures for dealing with emergencies. All workers should be familiar with the plant's plan. Emergency response plans must be preapproved by local authorities when outside help, such as the local HazMat team or fire department, would normally be called to the scene to assist. The plan must list emergency phone numbers. These emergency numbers should be posted near all of the plant phones.

1.13.13 Machine Guarding (29 CFR 1910.212)

The wastewater treatment process would quickly come to a halt if it were not for the machines that provide the motive force to move the wastestream through the process. From sewage lines to interceptor lines through pumping stations and the pressurizing process, the influent is literally forced into the treatment plant by machines (gravity flow systems excepted). Additionally, the work of machines is not finished yet. Upon entering the plant, a variety of other machines and machine-operated devices screen the flow, remove grit from the flow, and then provide the force necessary to push the flow into primary and then secondary treatment. The need for additional machines continues as the wastestream enters and leaves the various treatment processes; for example, during the treatment process huge motor-driven blowers are used to aerate the flow. Later, when liquids and solids are separated, both wastestreams continue to move along, powered by machines.

It should be evident from the preceding discussion that the wastewater treatment process uses several different machines. When properly maintained and operated these machines make the operator's job easier, his or her performance more efficient, and his or her workplace safer.

As stated, worker safety is enhanced by machines, but only if the machine itself is safe. The basic purpose of machine guarding is to prevent contact of the human body with dangerous parts of machines. When body parts such as arms, fingers, or hair make contact with moving machinery, the result can be disastrous and sometimes fatal. Some of the most gruesome accident investigations involve body-part amputations caused by contact with unguarded moving machinery.

The plant safety person must quickly become familiar with the plant's moving machinery. Moreover, the plant safety person must be familiar with the methods of machine guarding. OSHA has published an excellent machine guarding reference source, *Concepts and Techniques of Machine Safeguarding* (Publ. No. 3067), that is highly recommended. It can be obtained from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

1.13.14 Chains, Slings, and Ropes

This section describes the various types of hoisting apparatus used in wastewater treatment. Specifically, the hoisting apparatus in the form of chains, slings, and ropes is addressed. Moreover, safety considerations and inspection of these devices are also discussed. OSHA has published two excellent references, *Sling Safety* (Publ. No. 3072) and *Materials Handling and Storage* (Publ. No. 2236), both of which can be obtained from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

During safety audits particular attention must be paid to hoisting apparatus. Considering the large number of different types of hoisting apparatus used in the wastewater industry, it is not surprising that these devices seem to be just about everywhere. Moreover, with their large numbers and frequent use, it is not surprising that hoisting devices play a large role in on-the-job injuries.

Wastewater personnel handle materials on a daily basis. Sometimes these materials need to be moved from one location to another. One-ton chlorine cylinders, for example, must be changed out and moved to keep the plant disinfection process in operation. Obviously, moving 1-ton cylinders of chlorine or other chemical would not be possible without using some type of hoisting apparatus.

The hoisting devices that seem to require the most attention are chains, slings, and ropes. Chains, slings, and ropes are commonly used between cranes and hoists and the load so the load may be lifted and moved to the desired location. When workers use chains, slings, and ropes in the hoisting process, they must ensure that they visually inspect each device before use and during operation. Damaged or defective chains, slings, and ropes must be removed from service.

1.13.15 Bloodborne Pathogens (29 CFR 1910.1030)

Although scientific research has determined (at present) that HIV and other bloodborne pathogens are not found in the wastewater stream (except in strictly controlled laboratory conditions), the Centers for Disease Control (CDC) does warn that persons who provide emergency first aid could become contaminated. Thus, if your facility requires employees trained in first aid to render medical assistance as part of their job activities, your facility is covered under this standard. The major point to get across to all workers is that, if they render any kind of first aid assistance whereby the rescuer could be exposed to another person's body fluids, then care and caution must be exercised. It is a good idea to equip all wastewater facilities with first aid kits that are designed to protect against bloodborne pathogens. These kits are equipped with the following:

1. Rescue barrier mask to prevent mouth-to-mouth contact
2. Alcohol cleansing wipes for cleanup
3. Latex gloves to prevent hand contact with body fluids
4. Safety goggles to prevent body fluids from entering eyes
5. Biohazard bag for disposal of cleanup materials

Training should be provided to each worker on the dangers of bloodborne pathogens. Careful attention to personal hygiene habits should be stressed. Workers should be informed that handwashing is one of their best defenses against spreading infection, including HIV. Ensuring worker awareness is the key to complying with this standard.

Note: This section has provided a review of many of the safety programs that are required by OSHA and other regulators to be used in industry and at wastewater treatment facilities. There are several other safety requirements, depending on the size and nature of your operation. Safety programs that deal with safe forklift driving, material handling, and first aid procedures, for example, are important. If you are not sure of your requirements in this area, then you should contact your local branch of OSHA for guidance.

1.14 RECORDKEEPING

Personnel employed in the wastewater industry quickly learn about recordkeeping requirements. For example, wastewater treatment facilities that discharge to state waters must have a discharge permit issued by the state water control board or other official agency. This permit is known as the National Pollutant Discharge Elimination System (NPDES) permit. The NPDES permit has very specific and detailed recordkeeping requirements, such as recording monitoring information, instrument calibration and maintenance, reports required by the permit, and data used to complete the permit application. All records must be kept at least three years (longer if requested).

Because of the NPDES permit recordkeeping requirements, wastewater treatment plant operators soon learn that recordkeeping is an important part of their job. How important is this recordkeeping? The best way to answer this question is to consider the average routine within a wastewater treatment plant. You might actually be able to measure the pulse of the treatment operation by observing the strict attention that is given to keeping the plant operating log current. Among managers, operators, and assistants, a normal daily (indeed, hourly) topic of discussion seems to relate to the plant's need to "make permit" for the month. In other words, plant personnel are geared to constantly controlling the plant process to stay within specific permit guidelines or limits. An integral and critical part of "making permit" is data recording in the plant's operating log.

The plant's ongoing effort to "make permit" and the never-ending recordkeeping requirement bring up another point—that is, if the plant does as good a job in maintaining its safety and health records as it does with its permit records, then the plant would be "making permit" on a big-time scale. Safety and health records? Yes, absolutely. The OSH Act mandates certain recordkeeping requirements; moreover, the DOT and EPA also have certain recordkeeping requirements.

Safety and health records are vital for several reasons. First, as previously stated, they are kept because they are required. Second, without records, plant management has no way of knowing how the plant is performing. Without safety and health records on accidents and injuries, management may be unable to remedy hazards and develop prevention methods. Moreover, without the legally required records on safety and health, management may find itself subject to civil penalties; for example, if plant management fails to maintain employee health records (e.g., audiometric test results), then the result may be a liability suit for a former employee's hearing problem, even years after the alleged exposure took place.

1.15 SAFETY TRAINING

Throughout this chapter, a major point has been emphasizing and re-emphasizing the importance of employee safety training. This emphasis has been for good reason, for without a doubt providing routine safety training for workers is probably one of the most important job duties of the safety person. Indeed, most managers know the importance of safety training, but not as well known is that specific training requirements are detailed in OSHA, DOT, and EPA regulations. Under OSHA regulations, for example, it is stated or implied that the responsibility of the employer is to provide training and knowledge to the worker. Moreover, employees are to be apprised of all hazards to which they are exposed, relevant symptoms and appropriate emergency treatment, and proper conditions and precautions of safe use or exposure.

Several different OSHA safety and health standards or programs have been featured in this chapter. Employers must comply with these standards and must also require workers to comply. More than 100 OSHA, DOT, and EPA safety and health regulations contain training requirements. It is interesting to note that, although OSHA requires training, it does not always specify exactly what is required of the employer or entity providing the training. Whether specific or not, providing information and instruction on safety and health issues in the workplace is the key to building a viable organizational safety program. Workers cannot be expected to perform their assigned tasks safely unless they are aware of the hazards or the potential hazards involved with each job assignment.

For years, safety professionals have spoken about the three E's of safety: engineering, enforcement, and education. The best solution to control any hazard is to engineer out the problem, but enforcement is critical to maintaining proper safe work practices, and safety education is equally important. Education in the form of providing information and training is one of the most vital elements of safety simply because workers cannot be expected to comply with safe work practices if they have not been informed of and trained in the proper procedures.

Experts in the safety field have differing points of view on this topic. Some point out that safety is not a behavioral issue but instead is a technical one, meaning that safety can be accomplished by engineering out the hazard. It should be remembered, however, that if there is a possibility for something to go wrong, workers will find the way to make it happen. Even those workplaces that have state-of-the-art engineering safety devices and strong enforcement programs will not always have effective hazard control programs unless the workers and supervisors understand the hazards and the potential for hazards that arise from not observing routine safe work practices. A worker's work routine cannot be engineered, as workers are not robots.

Worker safety training should begin right after the employee is hired. New employee safety orientation training programs can be effective if correctly structured and presented early in the worker's tenure.

Before sending new employees to safety orientation training it must be determined who needs what training. The plant safety person, in conjunction with the personnel manager, work center supervisors, and safety council, should determine specific safety training requirements for each job classification. This can be accomplished by conducting a *needs assessment* (sometimes called *needs analysis*). The idea behind the needs assessment is to ensure that job classifications requiring confined space training, for example, receive this critical training. The needs assessment also functions to ensure that the plant clerk who needs hazard communication training but does not ever enter confined spaces, for example, does not receive confined space training.

Depending on the organization's turnover rate, the frequency of conducting new employee safety orientation training can vary from presenting a session each week, every other week, once a month, or as required. As stated previously, it is important that good records of worker safety training are kept.

1.16 SAFETY EQUIPMENT

As pointed out earlier, PPE basically is to be used as a last resort in protecting workers. Worksites should be thoroughly evaluated for hazards, and these hazards should be removed or engineered out prior to workers being required to perform work in them. Obviously, not all hazards can be eliminated or engineered out of the workplace. Wastewater treatment and collection is one of those industries where hazards cannot be completely eliminated; for example, confined space entry and chemical handling activities are hazards inherent to the industry and cannot be easily removed or done away with. However, performing work in confined spaces and handling chemicals can be made safer if workers have the proper safety equipment available to them for their use. Moreover, safety equipment is only as good as the proficiency of the workers who use the equipment. Here, again, the importance of proper safety training cannot be overemphasized.

1.17 CHAPTER REVIEW QUESTIONS

1.1 What is the first item that should be incorporated into an organizational safety program?

1.2 List the three steps in hazard control in their correct sequence.

1.3 What is the most important feature of any maintenance department's safety program?

1.4 What is the primary reason for conducting an accident investigation?

1.5 Lockout/tagout programs only apply to electrical systems (True or False).

1.6 At the scene of an incident, which concern should be given the highest priority?

REFERENCES AND RECOMMENDED READING

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CHAPTER 2

WATER HYDRAULICS

Beginning students of water hydraulics and its principles often approach the subject matter with certain misgivings. For example, water/wastewater operators quickly learn on the job that their primary operational and maintenance responsibilities involve a daily routine of monitoring, sampling, laboratory testing, and operation and process maintenance. How does water hydraulics relate to daily operations? The hydraulic functions of the treatment process have already been designed into the plant. Why learn water hydraulics at all?

> Simply put, while having hydraulic control of the plant is obviously essential to the treatment process, maintaining and ensuring continued hydraulic control is also essential. No water/wastewater facility (and/or distribution collection system) can operate without proper hydraulic control. The operator must know what hydraulic control is and what it entails to know how to ensure proper hydraulic control. Moreover, in order to understand the basics of piping and pumping systems, water/wastewater maintenance operators must have a fundamental knowledge of basic water hydraulics.
>
> **Spellman and Drinan (2001, p. 5)**

Note: The practice and study of water hydraulics are not new. Even in medieval times, water hydraulics was not new, as "Medieval Europe had inherited a highly developed range of Roman hydraulic components" (Magnusson, 2001, p. xi). The basic conveyance technology, based on low-pressure systems of pipe and channels, had already been established. When studying "modern" water hydraulics, it is important to remember that the science of water hydraulics is the direct result of two immediate and enduring problems: "the acquisition of freshwater and access to a continuous strip of land with a suitable gradient between the source and the destination" (Magnusson, 2001, p. 36).

2.1 WHAT IS WATER HYDRAULICS?

The word “hydraulic” is derived from the Greek words *hydro* (“water”) and *aulis* (“pipe”). Originally, hydraulics referred only to the study of water at rest and in motion (the flow of water in pipes or channels). Today, it is taken to mean the flow of *any* liquid in a system. What is a liquid? In terms of hydraulics, a liquid can be either oil or water. In the fluid power systems used in modern industrial equipment, the hydraulic liquid of choice is oil.

Some common examples of hydraulic fluid power systems include automobile braking and power steering systems, hydraulic elevators, and hydraulic jacks or lifts. Probably the most familiar hydraulic fluid power systems in water/wastewater operations are those used on dump trucks, front-end loaders, graders, and earth-moving and excavation equipment. In this text, though, we are concerned with liquid water.

Many find the study of water hydraulics difficult and puzzling (especially the licensure examination questions), but it is not all that mysterious in that it involves practical applications of the basic principles of water physics. Because water/wastewater treatment is based on the principles of water hydraulics, concise, real-world training is necessary for operators who must operate the plant and for those sitting for state licensure/certification examinations.

2.2 BASIC CONCEPTS

Air Pressure (at sea level) = 14.7 pounds per square inch (psi)

The relationship shown above is important because our study of hydraulics begins with air. A blanket of air, many miles thick, surrounds the Earth. The weight of this blanket on a given square inch of the Earth’s surface will vary according to the thickness of the atmospheric blanket above that point. At sea level, the pressure exerted is 14.7 pounds per square inch (psi). On a mountaintop, air pressure decreases because the blanket is not as thick.

The relationship shown below is also important:

$$1\ \text{ft}^3 \text{ of water} = 62.4 \text{ lb}$$

Note that both cubic feet and pounds are used to describe a volume of water. A defined relationship exists between the two units of measurement. The specific weight of water is defined relative to a cubic foot. One cubic foot of water weighs 62.4 lb; however, this relationship is true only at a temperature of 4°C and at a pressure of one atmosphere, conditions referred to as *standard temperature and pressure* (STP). One atmosphere = 14.7 psi at sea level and 1 ft^3 of water contains 7.48 gallons. The weight varies so little that, for practical purposes, this weight is used for temperatures ranging from 0 to 100°C.

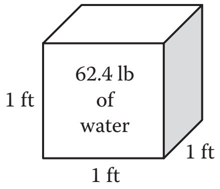

Figure 2.1 One cubic foot of water weighs 62.4 lb.

One cubic inch of water weighs 0.0362 lb. Water 1 ft deep will exert a pressure of 0.43 psi on the bottom area (12 in. × 0.0362 lb/in.^{3}). A column of water 2 ft high exerts 0.86 psi (2 ft × 0.43 psi/ft); one 10 ft high exerts 4.3 psi (10 ft × 0.43 psi/ft), and one 55 ft high exerts 23.65 psi (55 ft × 0.43 psi/ft). A column of water 2.31 ft high will exert 1.0 psi (2.31 ft × 0.43 psi/ft). To produce a pressure of 50 psi requires a 115.5-ft water column:

$$50 \text{ psi} \times 2.31 \text{ ft/psi} = 115.5 \text{ ft}$$

The important points being made here are:

1. 1 ft^3 of water = 62.4 lb (see Figure 2.1).
2. A column of water 2.31 ft high will exert 1.0 psi.

Another relationship is also important:

$$1 \text{ gal water} = 8.34 \text{ lb}$$

At standard temperature and pressure, 1 ft^3 of water contains 7.48 gal. With these two relationships, we can determine the weight of 1 gal of water:

$$\text{Weight of 1 gal of water} = 62.4 \text{ lb} \div 7.48 \text{ gal} = 8.34 \text{ lb/gal}$$

Thus,

$$1 \text{ gal water} = 8.34 \text{ lb}$$

Note: Further, this information allows cubic feet to be converted to gallons by simply multiplying the number of cubic feet by 7.48 gal/ft^3.

■ *Example 2.1*

Problem: Find the number of gallons in a reservoir that has a volume of 855.5 ft^3.

Solution:

$$855.5 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 = 6399 \text{ gallons (rounded)}$$

Note: As discussed later in this chapter, 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-foot column of water exerts 4.3 psi. This can be referred to as 4.3-psi pressure or 10 feet of head.

2.2.1 Stevin's Law

Stevin's law deals with water at rest. Specifically, it 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:

$$p = w \times h \tag{2.1}$$

where:

p = pressure in pounds per square foot (psf).

w = density in pounds per cubic foot (lb/ft^3).

h = vertical distance (ft).

■ ***Example 2.2***

Problem: What is the pressure at a point 18 ft below the surface of a reservoir?

Solution: To calculate this, we must know that the density of the water (w) is 62.4 lb/ft^3:

$$p = w \times h$$

$$p = 62.4\ \text{lb/ft}^3 \times 18\ \text{ft} = 1123\ \text{lb/ft}^2\ \text{(psf)}$$

Wastewater 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}):

$$p = \frac{1123\ \text{psf}}{144\ \text{in.}^2/\text{ft}^2} = 7.8\ \text{lb/in.}^2\ \text{or psi (rounded)}$$

2.3 PROPERTIES OF WATER

Table 2.1 shows the relationship between temperature, specific weight, and density of water.

2.3.1 Density and Specific Gravity

When we say that iron is heavier than aluminum, we say that iron has greater density than aluminum. In practice, what we are really saying is that a given volume of iron is heavier than the same volume of aluminum.

Note: What is density? Density is the *mass per unit volume* of a substance.

TABLE 2.1 WATER PROPERTIES

Temperature (°F)	Specific Weight (lb/ft³)	Density (slugs/ft³)	Temperature (°F)	Specific Weight (lb/ft³)	Density (slugs/ft³)
32	62.4	1.94	130	61.5	1.91
40	62.4	1.94	140	61.4	1.91
50	62.4	1.94	150	61.2	1.90
60	62.4	1.94	160	61.0	1.90
70	62.3	1.94	170	60.8	1.89
80	62.2	1.93	180	60.6	1.88
90	62.1	1.93	190	60.4	1.88
100	62.0	1.93	200	60.1	1.87
110	61.9	1.92	210	59.8	1.86
120	61.7	1.92			

Suppose you had a tub of lard and a large box of cold cereal, each having a mass of 600 g. The density of the cereal would be much less than the density of the lard because the cereal occupies a much larger volume than the lard occupies. The density of an object can be calculated by using the formula:

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} \tag{2.2}$$

In water/wastewater treatment, perhaps the most common measures of density are pounds per cubic foot (lb/ft^3) and pounds per gallon (lb/gal):

- 1 ft^3 of water weighs 62.4 lb; density = 62.4 lb/ft^3
- 1 gal of water weighs 8.34 lb; density = 8.34 lb/gal

The density of a dry material, such as cereal, lime, soda, or sand, is usually expressed in pounds per cubic foot. The density of a liquid, such as liquid alum, liquid chlorine, or water, can be expressed either as pounds per cubic foot or as pounds per gallon. The density of a gas, such as chlorine gas, methane, carbon dioxide, or air, is usually expressed in pounds per cubic foot.

As shown in Table 2.1, the density of a substance such as water changes slightly as the temperature of the substance changes. This occurs because substances usually increase in volume (size) by expanding as they become warmer. Because of this expansion with warming, the same weight is spread over a larger volume, so the density is lower when a substance is warm than when it is cold.

Note: What is specific gravity? Specific gravity is the weight (or density) of a substance compared to the weight (or density) of an equal volume of water. The specific gravity of water is 1.

This relationship is easily seen when a cubic foot of water, which weighs 62.4 lb, is compared to a cubic foot of aluminum, which weighs 178 lb. Aluminum is 2.8 times heavier than water.

It is not that difficult to find the specific gravity of a piece of metal. All you have to do is to weigh the metal in air, then weigh it under water. The loss of weight is the weight of an equal volume of water. To find the specific gravity, divide the weight of the metal by its loss of weight in water:

$$\text{Specific Gravity} = \frac{\text{Weight of Substance}}{\text{Weight of Equal Volume of Water}} \tag{2.3}$$

■ *Example 2.3*

Problem: Suppose a piece of metal weighs 150 lb in air and 85 lb under water. What is the specific gravity?

Solution:

$$150 \text{ lb} - 85 \text{ lb} = 65 \text{ lb loss of weight in water}$$

$$\text{Specific Gravity} = \frac{150}{65} = 2.3$$

Note: In a calculation of specific gravity, it is *essential* that the densities be expressed in the same units.

As stated earlier, the specific gravity of water is 1, which is the standard, or reference, against which all other liquid or solid substances are compared. Specifically, any object that has a specific gravity greater than 1 will sink in water (e.g., rocks, steel, iron, grit, floc, sludge). Substances with a specific gravity of less than 1 will float (wood, scum, gasoline). Considering the total weight and volume of a ship, its specific gravity is less than 1; therefore, it can float.

The most common use of specific gravity in water/wastewater treatment operations is in gallons-to-pounds conversions. In many cases, the liquids being handled have a specific gravity of 1 or very nearly 1 (between 0.98 and 1.02), so 1 may be used in the calculations without introducing significant error; however, in calculations involving a liquid with a specific gravity of less than 0.98 or greater than 1.02, the conversions from gallons to pounds must consider specific gravity. The technique is illustrated in the following example.

■ *Example 2.4*

Problem: A basin contains 1455 gal of a certain liquid. If the specific gravity of the liquid is 0.94, how many pounds of liquid are in the basin?

Solution: Normally, for a conversion from gallons to pounds, we would use the factor 8.34 lb/gal (the density of water) if the specific gravity of the substance is between 0.98 and 1.02. In this instance, however, the substance has a specific gravity outside this range, so the 8.34 factor must be adjusted. Multiply 8.34 lb/gal by the specific gravity to obtain the adjusted factor:

$$8.34 \text{ lb/gal} \times 0.94 = 7.84 \text{ lb/gal (rounded)}$$

Then convert 1455 gal to pounds using the adjusted factor:

$$1455 \text{ gal} \times 7.84 \text{ lb/gal} = 11{,}407 \text{ lb (rounded)}$$

2.4 FORCE AND PRESSURE

Water exerts force and pressure against the walls of its container, whether it is stored in a tank or flowing in a pipeline. There is a difference between force and pressure, although they are closely related. *Force* is the push or pull influence that causes motion. In the English system, force and weight are often used in the same way. The weight of 1 ft^3 of water is 62.4 lb. The force exerted on the bottom of a 1-ft cube is 62.4 lb (see Figure 2.1). If we stack two cubes on top of one another, the force on the bottom will be 124.8 lb. *Pressure* is a force per unit of area. In equation form, this can be expressed as:

$$P = \frac{F}{A} \tag{2.4}$$

where:

P = pressure.

F = force.

A = area over which the force is distributed.

Earlier we pointed out that pounds per square inch (lb/$in.^2$ or psi) or pounds per square foot (lb/ft^2) are common expressions of pressure. The pressure on the bottom of the cube is 62.4 lb/ft^2 (see Figure 2.1). It is normal to express pressure in pounds per square inch. This is easily accomplished by determining the weight of 1 $in.^2$ of a cube 1 ft high. If we have a cube that is 12 in. on each side, the number of square inches on the bottom surface of the cube is 12 × 12 = 144 $in.^2$; dividing the weight by the number of square inches determines the weight on each square inch:

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

This is the weight of a column of water 1-in. square and 1 ft tall. If the column of water were 2 ft tall, the pressure would be 2 ft × 0.433 psi/ft = 0.866.

Note: 1 foot of water = 0.433 psi.

With the above information, feet of head can be converted to psi by multiplying the feet of head times 0.433 psi/ft.

■ ***Example 2.5***

Problem: A tank is mounted at a height of 90 ft. Find the pressure at the bottom of the tank.

Solution:

$$90\text{ ft} \times 0.433\text{ psi/ft} = 39\text{ psi (rounded)}$$

Note: To convert psi to feet, divide the psi by 0.433 psi/ft.

■ ***Example 2.6***

Problem: Find the height of water in a tank if the pressure at the bottom of the tank is 22 psi.

Solution:

$$\text{Height in feet} = \frac{22\text{ psi}}{0.433\text{ psi/ft}} = 51\text{ ft (rounded)}$$

Note: One of the problems encountered in a hydraulic system is storing the liquid. Unlike air, which is readily compressible and is capable of being stored in large quantities in relatively small containers, a liquid such as water cannot be compressed. It is not possible to store a large amount of water in a small tank, as 62.4 lb of water occupies a volume of 1 ft^3, regardless of the pressure applied to it.

2.4.1 Hydrostatic Pressure

Figure 2.2 shows a number of differently shaped, connected, open containers of water. Note that the water level is the same in each container, regardless of the shape or size of the container. This occurs because pressure is developed within a liquid by the weight of the liquid above. If the water level in any one container is momentarily higher than that in any of the other containers, the higher pressure at the bottom of this container would cause some water to flow into the container with the lower liquid level. In addition, the pressure of the water at any level (such as line T) is the same in each of the containers. Pressure increases because of the weight of the water. The farther down from the

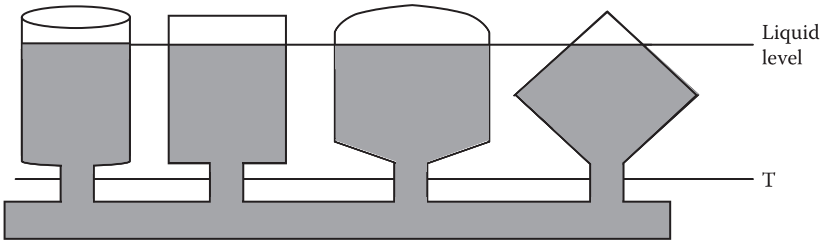

Figure 2.2 Hydrostatic pressure.

surface, the more pressure is created. This illustrates that the *weight*, not the volume, of water contained in a vessel determines the pressure at the bottom of the vessel.

Nathanson (1997, pp. 21–22) listed some very important principles that always apply for hydrostatic pressure:

1. The pressure depends only on the depth of water above the point in question (not on the water surface area).
2. The pressure increases in direct proportion to the depth.
3. The pressure in a continuous volume of water is the same at all points that are at the same depth.
4. The pressure at any point in the water acts in all directions at the same depth.

2.4.2 Effects of Water Under Pressure*

Water under pressure and in motion can exert tremendous forces inside a pipeline. One of these forces, called *hydraulic shock* or *water hammer*, is the momentary increase in pressure that occurs when there is a sudden change of direction or velocity of the water.

When a rapidly closing valve suddenly stops water flowing in a pipeline, pressure energy is transferred to the valve and pipe wall. Shock waves are set up within the system. Waves of pressure move in horizontal yo-yo fashion—back and forth—against any solid obstacles in the system. Neither the water nor the pipe will compress to absorb the shock, which may result in damage to pipes or valves and the shaking of loose fittings.

Another effect of water under pressure is called *thrust*, which is the force that water exerts on a pipeline as it rounds a bend. As shown in Figure 2.3, thrust usually acts perpendicular (at 90°) to the inside surface it pushes against. As stated, it affects bends but also reducers, dead ends, and tees. Uncontrolled, the thrust can cause movement in the fitting or pipeline which will lead to separation of the pipe coupling away from both sections of pipeline or at some other nearby coupling upstream or downstream of the fitting.

Two types of devices are commonly used to control thrust in larger pipelines: thrust blocks and thrust anchors. A *thrust block* is a mass of concrete cast in place onto the pipe and around the outside bend of the turn. An example is shown in Figure 2.4. These are used for pipes with tees or elbows that turn left or right or slant upward. The thrust is transferred to the soil through the larger bearing surface of the block. A *thrust anchor* is a massive block of concrete, often a cube, cast in

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* This section is adapted from information contained in Hauser, B.A., *Hydraulics for Operators*, Lewis Publishers, Boca Raton, FL, 1993, pp.16–18; AWWA, *Basic Science Concepts and Applications: Principles and Practices of Water Supply Operations*, 2nd ed., American Water Works Association, Denver, CO, 1995, pp. 351–353.

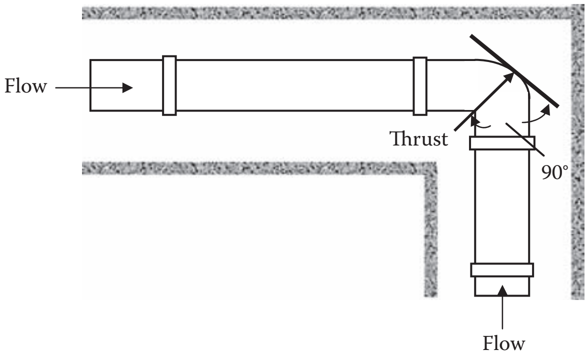

Figure 2.3 Direction of thrust in a pipe in a trench (viewed from above).

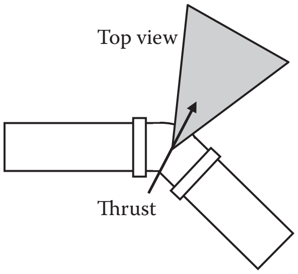

Figure 2.4 Thrust block.

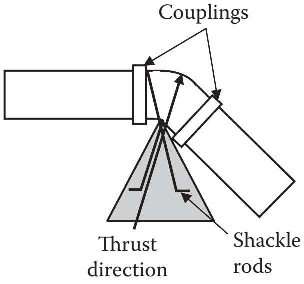

Figure 2.5 Thrust anchor.

place below the fitting to be anchored. As shown in Figure 2.5, imbedded steel shackle rods anchor the fitting to the concrete block, effectively resisting upward thrusts. The size and shape of a thrust control device depend on the pipe size, type of fitting, water pressure, water hammer, and soil type.

2.5 HEAD

Head is defined as the vertical distance the water/wastewater must be lifted from the supply tank to the discharge or as the height a column of water would rise due to the pressure at its base. A perfect vacuum plus atmospheric pressure of 14.7 psi would lift the water 34 ft. If the top of the sealed tube is opened to the atmosphere and the reservoir is enclosed, the pressure in the reservoir is increased and the water will rise in the tube. Because atmospheric pressure is essentially universal, we usually ignore the first 14.7 psi of actual pressure measurements and measure only the difference between the water pressure and the atmospheric pressure; we call this *gauge pressure*. Water in an open reservoir is subjected to 14.7 psi of atmospheric pressure, but subtracting this 14.7 psi leaves a gauge pressure of 0 psi, indicating that the water would rise 0 feet above the reservoir surface. If the gauge pressure in a water main were 120 psi, the water would rise in a tube connected to the main:

$$120 \text{ psi} \times 2.31 \text{ ft/psi} = 277 \text{ ft (rounded)}$$

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):

$$\text{Total Head} = \text{Static Head} + \text{Friction Head} + \text{Velocity Head} \qquad (2.5)$$

2.5.1 Static Head

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

$$\text{Static Head} = \text{Discharge Elevation} - \text{Supply Elevation} \qquad (2.6)$$

■ ***Example 2.7***

Problem: The supply tank is located at elevation 118 ft. The discharge point is at elevation 215 ft. What is the static head in feet?

Solution:

$$\text{Static Head} = 215 \text{ ft} - 118 \text{ ft} = 97 \text{ ft}$$

2.5.2 Friction Head

Friction head is the equivalent distance of the energy that must be supplied to overcome friction. Engineering references include tables providing 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:

$$\text{Friction Head} = \text{Energy Losses Due to Friction} \qquad (2.7)$$

2.5.3 Velocity Head

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

$$\text{Velocity Head} = \text{Energy Losses to Maintain Velocity} \qquad (2.8)$$

2.5.4 Total Dynamic Head (Total System Head)

$$\text{Total Head} = \text{Static Head} + \text{Friction Head} + \text{Velocity Head} \qquad (2.9)$$

2.5.5 Calculating Head if Pressure Is Known

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:

$$\text{Head (ft)} = \text{Pressure (psi)} \times 2.31\ \text{ft/psi} \qquad (2.10)$$

■ ***Example 2.8***

Problem: The pressure gauge on the discharge line from the influent pump reads 72.3 psi. What is the equivalent head in feet?

Solution:

$$\text{Head} = 72.3 \times 2.31\ \text{ft/psi} = 167\ \text{ft}$$

2.5.6 Calculating Pressure if Head Is Known

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

$$\text{Pressure (psi)} = \frac{\text{Head (ft)}}{2.31\ \text{ft/psi}} \qquad (2.11)$$

■ ***Example 2.9***

Problem: The tank is 22 ft deep. What is the pressure in psi at the bottom of the tank when it is filled with water?

Solution:

$$\text{Pressure (psi)} = \frac{22\ \text{ft}}{2.31\ \text{ft/psi}} = 9.52\ \text{psi (rounded)}$$

2.6 FLOW/DISCHARGE RATE: WATER IN MOTION

The study of fluid flow is much more complicated than that of fluids at rest, but it is important to have an understanding of these principles because the water in a waterworks and distribution system and in a wastewater treatment plant and collection system is nearly always in motion. *Discharge* (or flow) is the quantity of water passing a given point in a pipe or channel during a given period. Stated another way for open channels: The flow rate through an open channel is directly related to the velocity of the liquid and the cross-sectional area of the liquid in the channel:

$$Q = A \times V \tag{2.12}$$

where:

Q = Flow, or discharge, in cubic feet per second (cfs).

A = Cross-sectional area of the pipe or channel (ft^2).

V = water velocity in feet per second (fps).

■ *Example 2.10*

Problem: A channel is 6 ft wide and the water depth is 3 ft. The velocity in the channel is 4 fps. What is the discharge or flow rate in cubic feet per second?

Solution:

$$\text{Flow} = 6\text{ ft} \times 3\text{ ft} \times 4\text{ ft/s} = 72\text{ cfs}$$

Discharge or flow can be recorded as gal/day (gpd), gal/min (gpm), or cubic feet per second (cfs). Flows treated by many waterworks or wastewater treatment plants are large and are often referred to in million gallons per day (MGD). The discharge or flow rate can be converted from cubic feet per second (cfs) to other units such as gallons per minute (gpm) or million gallons per day (MGD) by using appropriate conversion factors.

■ *Example 2.11*

Problem: A 12-in.-diameter pipe has water flowing through it at 10 fps. What is the discharge in (a) cfs, (b) gpm, and (c) MGD?

Solution: Before we can use the basic formula (Equation 2.13), we must determine the area (A) of the pipe. The formula for the area of a circle is:

$$\text{Area } (A) = \pi \times \frac{D^2}{4} = \pi \times r^2 \tag{2.13}$$

where:

π = the constant value 3.14159 or simply 3.14.

D = diameter of the circle (ft).

r = radius of the circle (ft).

Therefore, the area of the pipe is:

$$A = \pi \times \frac{D^2}{4} = 3.14 \times \frac{(1\text{ ft})^2}{4} = 0.785\text{ ft}^2$$

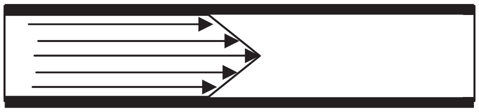

Figure 2.6 Laminar (streamline) flow.

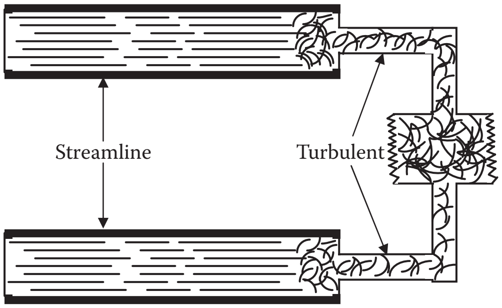

Figure 2.7 Turbulent flow.

(a) Now we can determine the discharge in cfs:

$$Q = V \times A = 10 \text{ ft/s} \times 0.785 \text{ ft}^2 = 7.85 \text{ ft}^3\text{/s (cfs)}$$

(b) We know that 1 cfs is 449 gpm, so 7.85 cfs × 449 gpm/cfs = 3525 gpm (rounded).

(c) 1 million gallons per day is 1.55 cfs, so:

$$\frac{7.85 \text{ cfs}}{1.55 \text{ cfs/MGD}} = 5.06 \text{ MGD}$$

Note: Flow may be *laminar* (i.e., streamline; see Figure 2.6) or *turbulent* (see Figure 2.7). Laminar flow occurs at extremely low velocities. The water moves in straight parallel lines, called *streamlines* or *laminae*, which slide upon each other as they travel, rather than mixing up. Normal pipe flow is turbulent flow, which occurs because of friction encountered on the inside of the pipe. The outside layers of flow are thrown into the inner layers. The result is that all of the layers mix and are moving in different directions and at different velocities; however, the direction of flow is forward.

Note: Flow may be steady or unsteady. For our purposes, we consider steady-state flow only; that is, most of the hydraulic calculations in this manual assume steady-state flow.

2.6.1 Area and Velocity

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 (if water does not leave or enter the pipe or channel). That is, under the assumption of steady-state flow, the flow that enters the pipe or channel is the same flow that exits the pipe or channel. In equation form, this becomes:

$$Q_1 = Q_2 \quad \text{or} \quad A_1V_1 = A_2V_2 \tag{2.14}$$

Note: With regard to the area/velocity relationship, Equation 2.14 also makes clear that, for a given flow rate, the velocity of the liquid varies indirectly with changes in cross-sectional area of the channel or pipe. This principle provides the basis for many of the flow measurement devices used in open channels (weirs, flumes, and nozzles).

■ *Example 2.12*

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 $A_1V_1 = A_2V_2$, we need to determine the area of each pipe:

$$A = \pi \times \frac{D^2}{4}$$

12-in. pipe

$$A = 3.14 \times \frac{(1\text{ ft})^2}{4} = 0.785\text{ ft}^2$$

6-in. pipe

$$A = 3.14 \times \frac{(0.5)^2}{4} = 0.196\text{ ft}^2$$

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:

$$V_2 = \frac{0.785\text{ ft}^2 \times 3\text{ ft/s}}{0.196\text{ ft}^2} = 12\text{ ft/s (fps)}$$

2.6.2 Pressure and Velocity

In a closed pipe flowing full (under pressure), the pressure is indirectly related to the velocity of the liquid. This principle, when combined with the principle discussed in the previous section, forms the basis for several flow measurement devices (e.g., Venturi meters and rotameters) as well as the injector used for dissolving chlorine into water and chlorine, sulfur dioxide, or other chemicals into wastewater:

$$\text{Velocity}_1 \times \text{Pressure}_1 = \text{Velocity}_2 \times \text{Pressure}_2 \tag{2.15}$$

or

$$V_1P_1 = V_2P_2$$

2.7 PIEZOMETRIC SURFACE AND BERNOULLI'S THEOREM

To keep the systems in your plant operating properly and efficiently, you must understand the basics of hydraulics—the laws of force, motion, and others. As stated previously, most applications of hydraulics in water/wastewater treatment systems involve water in motion—in pipes under pressure or in open channels under the force of gravity. The volume of water flowing past any given point in the pipe or channel per unit time is called the *flow rate* or *discharge*, or just *flow*. The *continuity of flow* and the *continuity equation* have already been discussed (see Equation 2.15). Along with the continuity of flow principle and continuity equation, the law of conservation of energy, piezometric surface, and Bernoulli's theorem (or principle) are also important to our study of water hydraulics.

2.7.1 Conservation of Energy

Many of the principles of physics are important to the study of hydraulics. When applied to problems involving the flow of water, few of the principles of physical science are more important and useful to us than the *law of conservation of energy*. Simply, the law of conservation of energy states that energy can neither be created nor destroyed, but it can be converted from one form to another. In a given closed system, the total energy is constant.

2.7.2 Energy Head

In addition to the kinetic and potential energy in hydraulic systems are three forms of mechanical energy: potential energy due to elevation, potential energy due to pressure, and kinetic energy due to velocity. Energy has the units of foot-pounds (ft-lb). It is convenient to express hydraulic energy in terms of *energy head* in feet of water. This is equivalent to foot-pounds per pound of water (ft-lb/lb = ft).

2.7.3 Piezometric Surface*

We have seen that when a vertical tube, open at the top, is inserted into a vessel of water, the water will rise in the tube to the water level in the tank. The water level to which the water rises in a tube is the *piezometric surface*. That is, the piezometric surface is an imaginary surface that coincides with the level of the water to which water in a system would rise in a *piezometer* (an instrument used to measure pressure).

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* This section is adapted from Spellman, F.R., *The Science of Water: Concepts & Applications*, Technomic, Lancaster, PA, 1998, pp. 92–93.

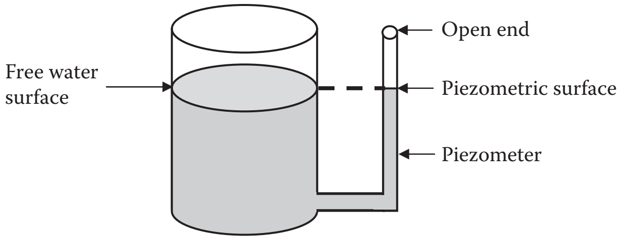

Figure 2.8 A container not under pressure where the piezometric surface is the same as the free water surface in the vessel.

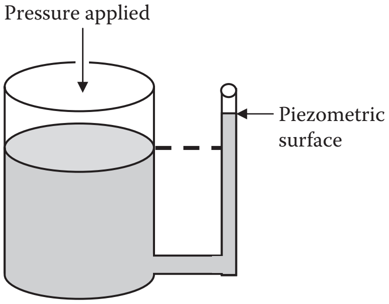

Figure 2.9 A container under pressure where the piezometric surface is above the level of the water in the tank.

The surface of water that is in contact with the atmosphere is known as *free water surface*. Many important hydraulic measurements are based on the difference in height between the free water surface and some point in the water system. The piezometric surface is used to locate this free water surface in a vessel, where it cannot be observed directly.

To understand how a piezometer actually measures pressure, consider the following example. If a clear, see-through pipe is connected to the side of a clear glass or plastic vessel, the water will rise in the pipe to indicate the level of the water in the vessel. Such a see-through pipe, the piezometer, allows you to see the level of the top of the water in the pipe; this is the piezometric surface. In practice, a piezometer is connected to the side of a tank or pipeline. If the water-containing vessel is not under pressure (as is the case in Figure 2.8), then the piezometric surface will be the same as the free water surface in the vessel, just as it would if a drinking straw (the piezometer) were left standing a glass of water.

In a pressurized tank and pipeline system, the pressure will cause the piezometric surface to rise above the level of the water in the tank. The greater the pressure, the higher the piezometric surface (see Figure 2.9). Increased pressure in a water pipeline system is usually obtained by elevating the water tank.

Note: In practice, piezometers are not installed on water towers because water towers are hundreds of feet high, or on pipelines. Instead, pressure gauges are used that record pressure in feet of water or in psi.

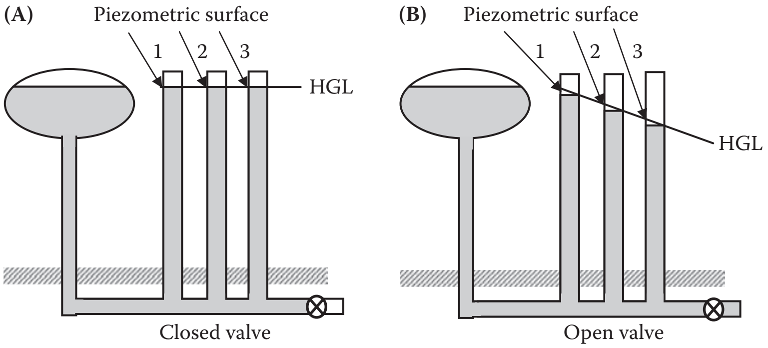

Figure 2.10 Changes in head loss and piezometric surface when water is flowing.

Water only rises to the water level of the main body of water when it is at rest (static or standing water). The situation is quite different when water is flowing. Consider, for example, an elevated storage tank feeding a distribution system pipeline. When the system is at rest, with all valves closed, all of the piezometric surfaces are the same height as the free water surface in storage. On the other hand, when the valves are opened and the water begins to flow, the piezometric surface changes. This is an important point because, as water continues to flow down a pipeline, less and less pressure is exerted. This happens because some pressure is lost (used up) to keep the water moving over the interior surface of the pipe (friction). The pressure that is lost is called *head loss*.

2.7.3.1 Head Loss

Head loss is best explained by example. Figure 2.10 shows an elevated storage tank feeding a distribution system pipeline. When the valve is closed (Figure 2.10A), all of the piezometric surfaces are the same height as the free water surface in storage. When the valve opens and water begins to flow (Figure 2.10B), the piezometric surfaces *drop*. The farther along the pipeline, the lower the piezometric surface, because some of the pressure is used up to keep the water moving over the rough interior surface of the pipe. Thus, pressure is lost and is no longer available to push water up in a piezometer; this is the head loss.

2.7.3.2 Hydraulic Grade Line

When the valve shown in Figure 2.10B is opened, flow begins with a corresponding energy loss due to friction. The pressures along the pipeline can measure this loss. In Figure 2.10B, the difference in pressure heads between sections 1, 2, and 3 can be seen in the piezometer tubes attached to the pipe. A line connecting the water surface in the tank with the water levels at sections 1, 2, and 3 shows the pattern of continuous pressure loss along the pipeline. This is called the *hydraulic grade line* (HGL) or *hydraulic gradient* of the system.

Key Point: It is important to point out that, in a static water system, the HGL is always horizontal. The HGL is a very useful graphical aid when analyzing pipe flow problems.

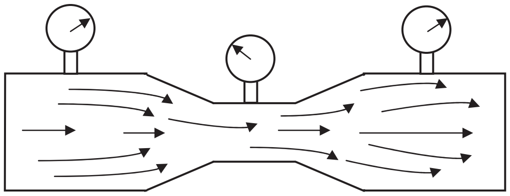

Figure 2.11 Bernoulli's principle.

Note: During the early design phase of a treatment plant, it is important to establish the hydraulic grade line across the plant because both the proper selection of the plant site elevation and the suitability of the site depend on this consideration.

Note: Changes in the piezometric surface occur when water is flowing.

2.7.4 Bernoulli's Theorem*

Swiss physicist and mathematician Samuel Bernoulli developed the calculation for the total energy relationship from point to point in a steady-state fluid system in the 1700s. Before discussing Bernoulli's energy equation, it is important to understand the basic principle behind Bernoulli's equation. Water (or any other hydraulic fluid) in a hydraulic system possesses kinetic energy and potential energy. *Kinetic energy* is present when the water is in motion; the faster the water moves, the more kinetic energy is used. *Potential energy* is a result of the water pressure. The *total energy* of the water is the sum of the kinetic energy and potential energy. Bernoulli's principle states that the total energy of the water (fluid) always remains constant; therefore, when the water flow in a system increases, the pressure must decrease. When water starts to flow in a hydraulic system, the pressure drops. When the flow stops, the pressure rises again. The pressure gauges shown in Figure 2.11 indicate this balance more clearly.

Note: The basic principle explained above ignores friction losses from point to point in a fluid system employing steady-state flow.

2.7.4.1 Bernoulli's Equation

In a hydraulic system, total energy head is equal to the sum of three individual energy heads. This can be expressed as:

Total Energy Head = Elevation Head + Pressure Head + Velocity Head

where the elevation head is the pressure due to the elevation of the water, the pressure head is the height of a column of water that a given hydrostatic pressure in a system could support, and the velocity head is the

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* This section is adapted from Nathanson, J.A., *Basic Environmental Technology: Water Supply, Waste Management, and Pollution Control*, 2nd ed., Prentice Hall, Upper Saddle River, NJ, 1997, pp. 29–30.

energy present due to the velocity of the water. This can be expressed mathematically as:

$$E = z + \frac{p}{w} + \frac{v^2}{2g} \tag{2.16}$$

where:

E = total energy head.

z = height of the water above a reference plane (ft).

p = pressure (psi)

w = unit weight of water (62.4 lb/ft^3).

v = flow velocity (ft/s).

g = acceleration due to gravity, (32.2 ft/s^2).

Consider the constriction in the section of pipe shown in Figure 2.12. We know, based on the law of energy conservation, that the total energy head at section A (E_1) must equal the total energy head at section B (E_2). Using Equation 2.16, we get Bernoulli's equation:

$$z_A + \frac{P_A}{w} + \frac{v_A^2}{2g} = z_B + \frac{P_B}{w} + \frac{V_B^2}{2g} \tag{2.17}$$

The pipeline system shown in Figure 2.12 is horizontal; therefore, we can simplify Bernoulli's equation because $z_A = z_B$. Because they are equal, the elevation heads cancel out from both sides, leaving:

$$\frac{P_A}{w} + \frac{v_A^2}{2g} = \frac{P_B}{w} + \frac{v_B^2}{2g} \tag{2.18}$$

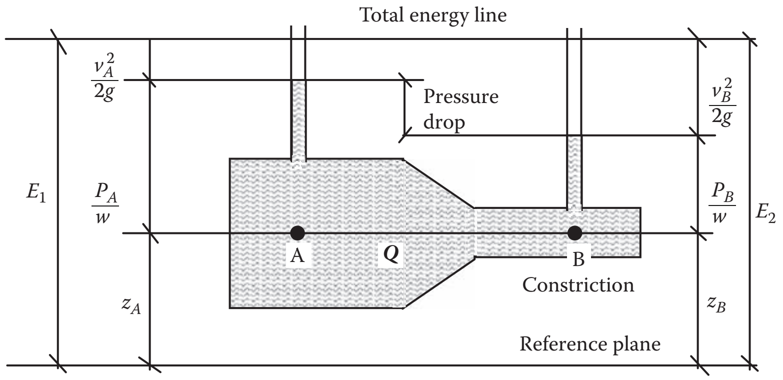

Figure 2.12 The law of conservation of energy: The velocity and kinetic energy of the water flowing in the constricted section must increase, so the potential energy may decrease. This is observed as a pressure drop in the constriction. (Adapted from Nathanson, J.A., *Basic Environmental Technology: Water Supply, Waste Management, and Pollution Control*, 2nd ed., Prentice Hall, Upper Saddle River, NJ, 1997, p. 29.)

As water passes through the constricted section of the pipe (section B), we know from continuity of flow that the velocity at section B must be greater than the velocity at section A because of the smaller flow area at section B. This means that the velocity head in the system increases as the water flows into the constricted section; however, the total energy must remain constant. For this to occur, the pressure head, and therefore the pressure, must drop. In effect, pressure energy is converted into kinetic energy in the constriction. The fact that the pressure in the narrower pipe section (constriction) is less than the pressure in the bigger section seems to defy common sense; however, it does follow logically from continuity of flow and conservation of energy. The fact that there is a pressure difference allows measurement of flow rate in the closed pipe.

■ *Example 2.13*

Problem: In Figure 2.12, the diameter at section A is 8 in., and at section B it is 4 in. The flow rate through the pipe is 3.0 cfs, and the pressure at section A is 100 psi. What is the pressure in the constriction at section B?

Solution: Compute the flow area at each section:

$$A_A = \frac{\pi \times (0.666\ \text{ft})^2}{4} = 0.349\ \text{ft}^2\ \ \text{(rounded)}$$

$$A_B = \frac{\pi \times (0.333\ \text{ft})^2}{4} = 0.087\ \text{ft}^2$$

From $Q = A \times V$ or $V = Q/A$, we get:

$$V_A = \frac{3.0\ \text{ft}^3/\text{s}}{0.349\ \text{ft}^2} = 8.6\ \text{ft/s (rounded)}$$

$$V_B = \frac{3.0\ \text{ft}^3/\text{s}}{0.087\ \text{ft}^2} = 34.5\ \text{ft/s (rounded)}$$

Applying Equation 2.18, we get:

$$\frac{(100 \times 144)}{62.4} + \frac{(8.6)^2}{(2 \times 32.2)} = \frac{(P_B \times 144)}{62.4} + \frac{(34.5)^2}{(2 \times 32.2)}$$

Note: The pressures are multiplied by 144 in.^{2}/ft^2 to convert from psi to lb/ft^2 to be consistent with the units for *w*; the energy head terms are in feet of head.

Continuing, we get:

$$231 + 1.15 = 2.3P_B + 18.5$$

and

$$P_B = \frac{(232.2 - 18.5)}{2.3} = \frac{213.7}{2.3} = 93\ \text{psi (rounded)}$$

2.8 HYDRAULIC MACHINES (PUMPS)

Chapter 3 presents a thorough treatment of pumps and pumping characteristics important to wastewater treatment. In this chapter, we briefly introduce pumping basics in order to provide a more complete treatment of water hydraulics. Conveying wastewater to and from process equipment is an integral part of the wastewater industry that requires energy consumption. The amount of energy required depends on the height to which the water/wastewater is raised, the length and diameter of the conveying conduits, the rate of flow, and the physical properties of the water/wastewater (in particular, viscosity and density). In some applications, external energy for transferring wastewater is not required; for example, when water/wastewater flows to a lower elevation under the influence of gravity, a partial transformation of the potential energy of the water/wastewater into kinetic energy occurs. However, when conveying water or wastewater through horizontal conduits, especially to higher elevations within a system, mechanical devices such as pumps are employed. Requirements vary from small units used to pump only a few gallons per minute to large units capable of handling several hundred cubic feet per second (Cheremisinoff and Cheremisinoff, 1989). Table 2.2 lists pump applications in wastewater treatment operations.

Note: When determining the amount of pressure or force a pump must provide to move the water or wastewater, the term *pump head* is used.

Several methods are available for transporting water, wastewater, and chemicals for treatment between process equipment:

- Centrifugal force inducing fluid motion
- Volumetric displacement of fluids, either mechanically or with other fluids
- Transfer of momentum from another fluid
- Mechanical impulse
- Gravity-induced transport

Depending on the facility and unit processes contained within, all of the methods above may be important to the maintenance operator.

2.8.1 Pumping Hydraulics*

During operation, water enters a pump on the suction side, where the pressure is lower. Because the function of the pump is to add pressure to the system, discharge pressure will always be higher. An important concept to keep in mind is that in pump systems measurements are taken from the point of reference to the centerline of the pump (horizontal line drawn through the center of the pump).

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* This section is adapted from Arasmith, S., *Introduction to Small Water Systems*, ACR Publications, Albany, OR, 1993, pp. 59–61.

TABLE 2.2 PUMP APPLICATIONS IN WATER/WASTEWATER SYSTEMS

Application	Function	Pump Type
Low service	To lift water from the source to treatment processes or from storage to the filter-backwashing system	Centrifugal
High service	To discharge water under pressure to the distribution system; to pump collected or intercepted wastewater to the treatment facility	Centrifugal
Booster	To increase pressure in the distribution/ collection system or to supply elevated storage tanks	Centrifugal
Well	To lift water from shallow or deep wells and discharge it to the treatment plant, storage facility, or distribution system	Centrifugal or jet
Chemical feed	To add chemical solutions at the desired dosages for treatment processes	Positive-displacement
Sampling	To pump water/wastewater from sampling points to the laboratory or automatic analyzers	Positive-displacement or centrifugal
Sludge/ biosolids	To pump sludge or biosolids from sedimentation facilities to further treatment or disposal	Positive-displacement or centrifugal

Source: Adapted from AWWA, *Water Transmission and Distribution*, 2nd ed., American Water Works Association, Denver, CO, 1996, p. 358.

To understand pump operation, or pumping hydraulics, we need to be familiar with certain basic terms and then relate these terms to how water is pumped from one point to another (see Figure 2.13):

Static head—The distance between the suction and discharge water levels when the pump is shut off. Static head conditions are represented by the letter Z (see Figure 2.13).

Suction lift—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; the pump must have the energy to provide this lift. A pump is said to be in a suction lift condition any time the center (eye) of the impeller is above the water being pumped (see Figure 2.13).

Suction head—A pump is said to be in a suction head condition any time the center (eye) of the impeller is below the water level being pumped. Specifically, 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 (see Figure 2.13).

Total dynamic head—The total energy needed to move water from the centerline of a pump (eye of the first impeller of a lineshaft turbine) to some given elevation or to develop some given pressure. This includes the static head, velocity head, and the head loss due to friction (see Figure 2.13).

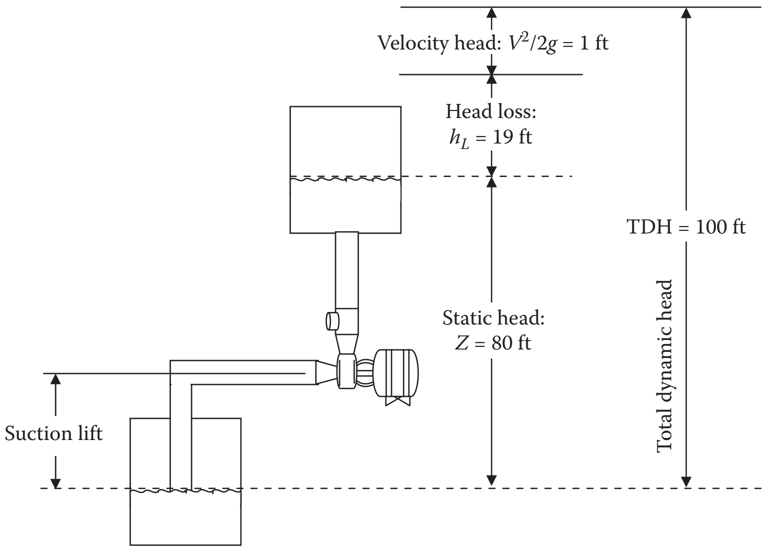

Figure 2.13 Components of total dynamic head.

Velocity head—The amount of energy required to bring water or wastewater from standstill to its velocity. For a given quantity of flow, the velocity head will vary indirectly with the pipe diameter. Velocity head is often represented mathematically as $V^2/2g$ (see Figure 2.13).

2.9 WELL AND WET-WELL HYDRAULICS

When the source of water for a water distribution system is from a groundwater supply, knowledge of well hydraulics is important to the operator. Basic well hydraulics terms are presented and defined in this section (see Figure 2.14). Also discussed are wet wells, which are important both in water and wastewater operations.

2.9.1 Well Hydraulics

Cone of depression—In unconfined aquifers, water flows in the aquifer from all directions toward the well during pumping. The free water surface in the aquifer then takes the shape of an inverted cone or curved funnel line. The curve of the line extends from the pumping water level to the static water level at the outside edge of the zone (or radius) of influence (see Figure 2.14).

Drawdown—The difference, or the drop, between the static water level and the pumping water level, measured in feet. Simply, it is the distance the water level drops once pumping begins (see Figure 2.14).

Pumping water level—The water level when the pump is off. When water is pumped out of a well, the water level usually drops below the level in the surrounding aquifer and eventually stabilizes at a lower level; this is the pumping level (see Figure 2.14).

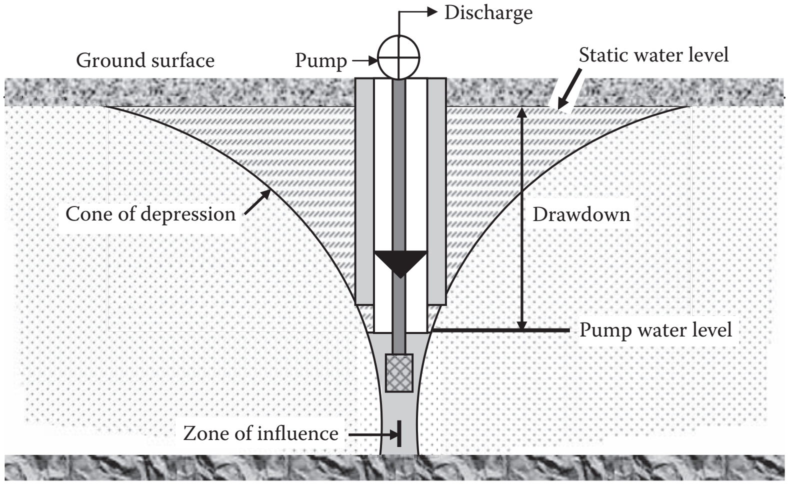

Figure 2.14 Hydraulic characteristics of a well.

Static water level—The water level in a well when no water is being taken from the groundwater source (i.e., the water level when the pump is off; see Figure 2.14). Static water level is normally measured as the distance from the ground surface to the water surface. This is an important parameter because it is used to measure changes in the water table.

Note: The shape and size of the cone of depression are dependent on the relationship between the pumping rate and the rate at which water can move toward the well. If the rate is high, the cone will be shallow and its growth will stabilize. If the rate is low, the cone will be sharp and continue to grow in size.

Zone (or radius) of influence—The distance between the pump shaft and the outermost area affected by drawdown (see Figure 2.14). The distance depends on the porosity of the soil and other factors. This parameter becomes important in well fields with many pumps. If wells are set too close together, the zones of influence will overlap, increasing the drawdown in all wells. Obviously, pumps should be spaced apart to prevent this from happening.

Two important parameters not shown in Figure 2.14 are well yield and specific capacity:

Well yield is the rate of water withdrawal that a well can supply over a long period. Alternatively, it is the maximum pumping rate that can be achieved without increasing the drawdown. The yield of small wells is usually measured in gallons per minute (liters per minute) or gallons per hour (liters per hour). For large wells, it may be measured in cubic feet per second (cubic meters per second).

Specific capacity is the pumping rate per foot of drawdown (gpm/ft), or

$$\text{Specific Capacity} = \text{Well Yield} \div \text{Drawdown} \tag{2.19}$$

■ ***Example 2.14***

Problem: If the well yield is 300 gpm and the drawdown is measured to be 20 ft, what is the specific capacity?

Solution:

Specific Capacity = 300 ÷ 20 = 15 gpm per foot of drawdown

Specific capacity is one of the most important concepts in well operation and testing. The calculation should be made frequently in the monitoring of well operation. A sudden drop in specific capacity indicates such problems as pump malfunction, screen plugging, or other situations that can be serious. Such problems should be identified and corrected as soon as possible.

2.9.2 Wet-Well Hydraulics

Water pumped from a wet well by a pump set above the water surface exhibits the same phenomena as the groundwater well. In operation, a slight depression of the water surface forms right at the intake line (drawdown), but in this case it is minimal because there is free water at the pump entrance at all times (at least there should be). The most important consideration in wet-well operations is to ensure that the suction line is submerged far enough below the surface so air entrained by the active movement of the water at this section is not able to enter the pump. Because water or wastewater flow is not always constant or at the same level, variable speed pumps are commonly used in wet-well operations, or several pumps are installed for single or combined operation. In many cases, pumping is accomplished in an on/off mode. Control of pump operation is in response to water level in the well. Level control devices such as mercury switches are used to sense a high and low level in the well and transmit the signal to pumps for action.

2.10 FRICTION HEAD LOSS

Materials or substances capable of flowing cannot flow freely. Nothing flows without encountering some type of resistance. Consider electricity, the flow of free electrons in a conductor. Whatever type of conductor used (e.g., copper, aluminum, silver), it offers some resistance. In hydraulics, the flow of water/wastewater is analogous to the flow of electricity. Within a pipe or open channel, for instance, flowing water (like electrons flowing in a conductor) encounters resistance. This resistance to the flow of water is generally termed *friction loss* (or more appropriately, *friction head loss*).

2.10.1 Flow in Pipelines

The topic of wastewater flow in pipelines (e.g., predicting flow rates through pipes of given characteristics, calculating energy conversions therein) is encountered in many applications of water/wastewater

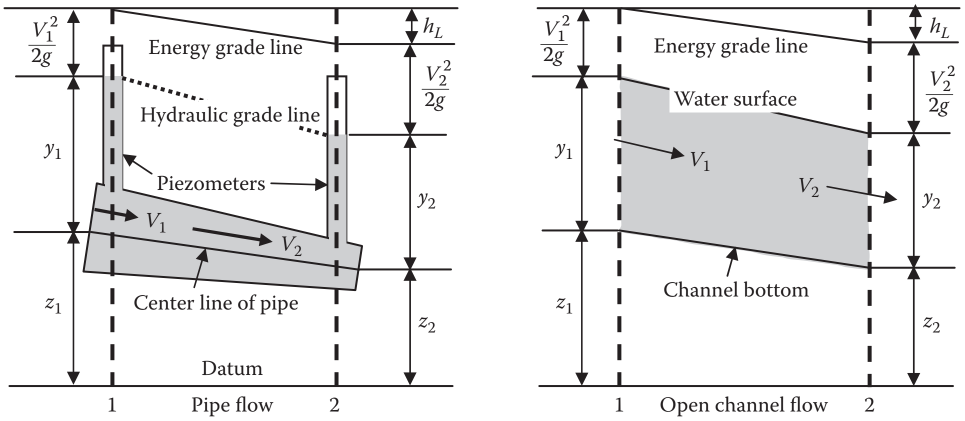

Figure 2.15 Comparison of pipe flow and open channel flow. (Adapted from Metcalf & Eddy, *Wastewater Engineering: Collection and Pumping of Wastewater*, McGraw-Hill, New York, 1981, p.11).

operations and practice. Although the subject of pipe flow embraces only those problems in which pipes flow completely full (as in water lines), we also address pipes that flow partially full (wastewater lines, normally treated as open channels) in this section. Also discussed is the solution of practical pipe flow problems resulting from application of the energy principle, the equation of continuity, and the principle and equation of water resistance. Resistance to flow in pipes is not only the result of long reaches of pipe but also affected by pipe fittings, such as bends and valves, which dissipate energy by producing relatively large-scale turbulence.

2.10.2 Pipe and Open Flow Basics

To gain an understanding of what friction head loss is all about, it is necessary to review a few terms presented earlier in the text and to introduce some new terms pertinent to the subject.*

Energy grade line—The total energy of flow in any section with reference to some datum (i.e., a reference line, surface, or point) is the sum of the elevation head (z), the pressure head (y), and the velocity head ($V^2/2g$). Figure 2.15 shows the energy grade line, or energy gradient, which represents the energy from section to section. In the absence of frictional losses, the energy grade line remains horizontal, although the relative distribution of energy may vary among the elevation, pressure, and velocity heads. In all real systems, however, losses of energy occur because of resistance to flow, and the resulting energy grade line is sloped (i.e., the energy grade line is the slope of the specific energy line).

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* A more complete listing of hydraulic terms can be found in Lindeburg, M.R., *Civil Engineering Reference Manual*, 4th ed., Professional Publications, San Carlos, CA, 1986, pp. 5-2–5-3.

Hydraulic grade line (HGL)—Recall that the hydraulic grade line (shown in Figure 2.15) is a line connecting two points to which the liquid would rise at various places along any pipe or open channel if piezometers were inserted in the liquid. It is a measure of the pressure head available at these various points.

Note: When water flows in an open channel, the HGL coincides with the profile of the water surface.

Laminar and turbulent flow—Laminar flow is ideal flow, or water particles moving along straight, parallel paths in layers or streamlines. Moreover, in laminar flow the water has no turbulence and there is no friction loss. This is not typical of normal pipe flow because the water velocity is too great, but it is typical of groundwater flow. Turbulent flow (characterized as normal for a typical water system) occurs when water particles move in a haphazard fashion and continually cross each other in all directions, resulting in pressure losses along a length of pipe.

Slope (gradient)—Slope is the head loss per foot of channel.

Specific energy (E)—Sometimes called *specific head*, specific energy is the sum of the pressure head (y) and the velocity head ($V^2/2g$). The specific energy concept is especially useful in analyzing flow in open channels.

Steady flow—Steady flow occurs when the discharge or rate of flow at any cross-section is constant.

Uniform and nonuniform flow—Uniform flow occurs when the depth, cross-sectional area, and other elements of flow are substantially constant from section to section. Nonuniform flow occurs when the slope, cross-sectional area, and velocity change from section to section. The flow through a Venturi section used for measuring flow is a good example.

Varied flow—Flow in a channel is considered varied if the depth of flow changes along the length of the channel. The flow may be gradually varied or rapidly varied (when the depth of flow changes abruptly) as shown in Figure 2.16.

2.10.3 Major Head Loss

Major head loss consists of pressure decreases along the length of pipe caused by friction created as water encounters the surfaces of the pipe. It typically accounts for most of the pressure drop in a pressurized or dynamic water system.

2.10.3.1 Components of Major Head Loss

The components that contribute to major head loss are roughness, length, diameter, and velocity.

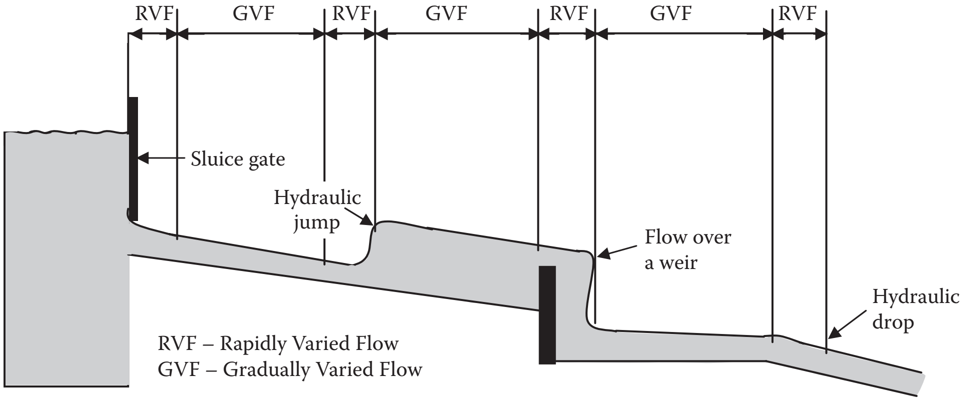

Figure 2.16 Varied flow.

2.10.3.1.1 Roughness

Even when new, the interior surfaces of pipes are rough. The roughness varies, of course, depending on the pipe material, corrosion (tuberculation and pitting), and age. Because normal flow in a water pipe is turbulent, the turbulence increases with pipe roughness, which in turn causes pressure to drop over the length of the pipe.

2.10.3.1.2 Pipe Length

With every foot of pipe length, friction losses occur. The longer the pipe, the more head loss. Friction loss because of pipe length must be factored into head loss calculations.

2.10.3.1.3 Pipe Diameter

Generally, small-diameter pipes have more head loss than large-diameter pipes because in a large-diameter pipe less of the water actually touches the interior surfaces of the pipe (encountering less friction) compared to a small-diameter pipe.

2.10.3.1.4 Water Velocity

Turbulence in a water pipe is directly proportional to the speed (or velocity) of the flow; thus, the velocity head also contributes to head loss.

Note: For a constant-diameter pipe, when flow increases, head loss increases.

2.10.3.2 Calculating Major Head Loss

Darcy, Weisbach, and others developed the first practical equation used to determine pipe friction in about 1850. The *Darcy–Weisbach* equation for circular pipes is:

$$h_f = f \frac{LV^2}{D^2 g} \tag{2.20}$$

In terms of the flow rate Q, the equation becomes:

$$h_f = \frac{8fLQ^2}{\pi^2 g D^5} \tag{2.21}$$

where:

h_f = head loss (ft).

f = coefficient of friction.

L = length of pipe (ft).

V = mean velocity (ft/s).

D = diameter of pipe (ft).

g = acceleration due to gravity (32.2 ft/s^2).

Q = flow rate (ft^3/s).

The Darcy–Weisbach formula was meant to apply to the flow of any fluid and into this friction factor was incorporated the degree of roughness and an element called *Reynold's number*, which was based on the viscosity of the fluid and the degree of turbulence of flow. The Darcy–Weisbach formula is used primarily for determining head loss calculations in pipes. For open channels, the *Manning* equation was developed during the latter part of the 19th century. Later, this equation was used for both open channels and closed conduits.

In the early 1900s, a more practical equation, the *Hazen–Williams* equation, was developed for use in making calculations related to water pipes and wastewater force mains:

$$Q = 0.435 \times CD^{2.63} \times S^{0.54} \tag{2.22}$$

where:

Q = flow rate (ft^3/s).

C = coefficient of roughness (C decreases with roughness).

D = hydraulic radius r (ft).

S = slope of energy grade line (ft/ft).

2.10.3.2.1 C Factor

The *C factor*, as used in the Hazen–Williams formula, designates the coefficient of roughness. *C* does not vary appreciably with velocity, and by comparing pipe types and ages it includes only the concept of roughness, ignoring fluid viscosity and Reynold's number. Based on experience (experimentation), accepted tables of *C* factors have been established for pipe (see

Key Point: A high C factor means a smooth pipe; a low C factor means a rough pipe.

TABLE 2.3 *C* FACTORS

Type of Pipe	*C* Factor
Asbestos cement	140
Brass	140
Brick sewer	100
Cast iron	
10 years old	110
20 years old	90
Ductile iron (cement lined)	140
Concrete or concrete lined	
Smooth, steel forms	140
Wooden forms	120
Rough	110
Copper	140
Fire hose (rubber-lined)	135
Galvanized iron	120
Glass	140
Lead	130
Masonry conduit	130
Plastic	150
Steel	
Coal-tar-enamel lined	150
New unlined	140
Riveted	110
Tin	130
Vitrified	120
Wood stave	120

Source: Adapted from Lindeburg, M.R., *Civil Engineering Reference Manual*, 4th ed., Professional Publications, San Carlos, CA, 1986, p. 3-20.

Table 2.3). Generally, the *C* factor decreases by one with each year of pipe age. Flow for a newly designed system is often calculated with a *C* factor of 100, based on averaging it over the life of the pipe system.

Note: An alternative to calculating the Hazen–Williams formula, called an *alignment chart*, has become quite popular for fieldwork. The alignment chart can be used with reasonable accuracy.

2.10.3.2.2 Slope

Slope is defined as the head loss per foot. In open channels, where the water flows by gravity, slope is the amount of incline of the pipe and is calculated as feet of drop per foot of pipe length (ft/ft). Slope is designed to be just enough to overcome frictional losses, so the velocity remains constant, the water keeps flowing, and solids will not settle in the conduit. In piped systems, where pressure loss for every foot of pipe is experienced, slope is not provided by slanting the pipe but instead by adding pressure to overcome friction.

2.10.4 Minor Head Loss

In addition to the head loss caused by friction between the fluid and the pipe wall, losses also are caused by turbulence created by obstructions (i.e., valves and fittings of all types) in the line, changes in direction, and changes in flow area.

Note: In practice, if minor head loss is less than 5% of the total head loss, it is usually ignored.

2.11 BASIC PIPING HYDRAULICS

Water, regardless of the source, is conveyed to the waterworks for treatment and distribution to the users. Conveyance from the source to the point of treatment occurs by aqueducts, pipelines, or open channels, but the treated water is normally distributed in pressurized closed conduits. After use, whatever the purpose, the water becomes wastewater, which must be disposed of somehow but almost always ends up being conveyed back to a treatment facility before being outfalled to some water body to begin the cycle again. We call this an *urban water cycle*, because it provides a human-generated imitation of the natural water cycle. Unlike the natural water cycle, however, without pipes, the cycle would be nonexistent or, at the very least, short circuited.

For use as water mains in a distribution system, pipes must be strong and durable in order to resist applied forces and corrosion. The pipe is subjected to internal pressure from the water and to external pressure from the weight of the backfill (soil) and vehicles above it. The pipe may also have to withstand water hammer. Damage due to corrosion or rusting may also occur internally because of the water quality or externally because of the nature of the soil conditions. Pipes used in a wastewater system must be able to resist the abrasive and corrosive properties of the wastewater. Like water pipes, wastewater pipes must also be able to withstand the stresses caused by the soil backfill material and the effect of vehicles passing above the pipeline. Joints between wastewater collection and interceptor pipe sections should be flexible but tight enough to prevent excessive leakage, either of sewage out of the pipe or groundwater into the pipe. Of course, pipes must be constructed to withstand the expected conditions of exposure, and pipe configuration systems for water distribution or wastewater collection and interceptor systems must be properly designed and installed in terms of water hydraulics. Because the water/wastewater operator should have a basic knowledge of water hydraulics related to commonly used standard piping configurations, piping basics are briefly discussed in this section.

2.11.1 Pipe Networks

It would be far less costly and much more efficient if municipal water and wastewater systems were built with individual, single-pipe networks extending from the treatment plant to each user's residence or from the user's sink or bathtub drain to the local wastewater treatment plant.

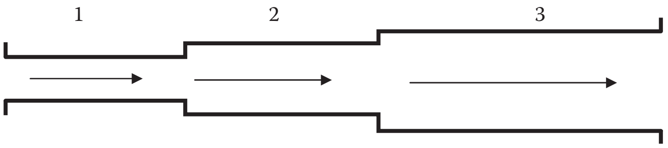

Figure 2.17 Pipes in series

Unfortunately, this ideal single-pipe scenario is not practical for real-world applications. Instead of a single piping system, a network of pipes is laid under the streets. Each of these piping networks is composed of different materials that vary (sometimes considerably) in diameter, length, and age. These networks range in complexity to varying degrees, and each of these joined-together pipes contributes energy losses to the system.

2.11.1.1 Energy Losses in Pipe Networks

Wastewater flow networks may consist of pipes arranged in series, parallel, or some complicated combination. In any case, an evaluation of friction losses for the flows is based on energy conservation principles applied to the flow junction points. Methods of computation depend on the particular piping configuration. In general, however, they involve establishing a sufficient number of simultaneous equations or employing a friction loss formula where the friction coefficient depends only on the roughness of the pipe (e.g., see Equation 2.22, the Hazen–Williams equation).

Note: Demonstrating the procedure for making these complex computations is beyond the scope of this text. We only present the operator “need to know” aspects of complex or compound piping systems in this text.

2.11.1.2 Pipes in Series

When two pipes of different sizes or roughnesses are connected in series (see Figure 2.17), head loss for a given discharge, or discharge for a given head loss, may be calculated by applying the appropriate equation between the bonding points, taking into account all losses in the interval. Thus, head losses are cumulative. Series pipes may be treated as a single pipe of constant diameter to simplify the calculation of friction losses. The approach involves determining an “equivalent length” of a constant-diameter pipe that has the same friction loss and discharge characteristics as the actual series pipe system. In addition, application of the continuity equation to the solution allows the head loss to be expressed in terms of only one pipe size.

Note: In addition to the head loss caused by friction between the water and the pipe wall, losses are also caused by obstructions in the line, changes in directions, and changes in flow area. In practice, the method of equivalent length is often used to determine these losses. The method of equivalent length uses a table to convert each valve or fitting into an equivalent length of straight pipe.

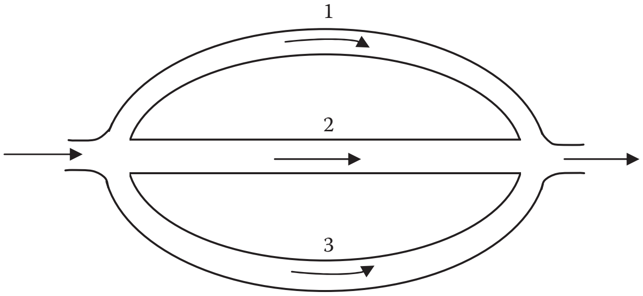

Figure 2.18 Pipe in parallel.

When making calculations involving pipes in series, remember these two important basic operational tenets:

1. The same flow passes through all pipes connected in series.
2. The total head loss is the sum of the head losses of all of the component pipes.

In some operations involving series networks where the flow is given and the total head loss is unknown, we can use the Hazen–Williams equation to solve for the slope and the head loss of each pipe as if they were separate pipes. Adding up the head losses to get the total head loss is then a simple matter.

Other series network calculations may not be as simple to solve using the Hazen–Williams equation. For example, one problem we may be faced with is what diameter to use with varying sized pipes connected together in a series combination. Moreover, head loss is applied to both pipes (or other multiples), and it is not known how much loss originates from each one; thus, determining slope would be difficult but not impossible.

In such cases the *equivalent pipe theory*, as mentioned earlier, can be used. Again, one single "equivalent pipe" is created that will carry the correct flow. This is practical because the head loss through it is the same as that in the actual system. The equivalent pipe can have any *C* factor and diameter, just as long as those same dimensions are maintained all the way through to the end. Keep in mind that the equivalent pipe must have the correct length so it will allow the correct flow and yield the correct head loss (the given head loss).[*]

2.11.1.3 Pipes in Parallel

Two or more pipes connected (as in Figure 2.18) so flow is first divided among the pipes and is then rejoined comprise a parallel pipe system. A parallel pipe system is a common method for increasing the

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[*] For more information on how to use the equivalent pipe theory in making computations involving series or parallel pipe combinations, refer to Lindeburg, M.R., *Civil Engineering Reference Manual*, 4th ed., Professional Publications, San Carlos, CA, 1986.

capacity of an existing line. Determining flows in pipes arranged in parallel is also accomplished by applying energy conservation principles; specifically, energy losses through all pipes connecting common junction points must be equal. Each leg of the parallel network is treated as a series piping system and converted to a single equivalent length pipe. The friction losses through the equivalent length parallel pipes are then considered equal and the respective flows determined by proportional distribution.

Note: Computations used to determine friction losses in parallel combinations may be accomplished using a simultaneous solution approach for a parallel system that has only two branches; however, if the parallel system has three or more branches, a modified procedure using the Hazen–Williams loss formula is easier (Lindeburg, 1986, p. 3-26).

2.12 OPEN CHANNEL FLOW

Water is transported over long distances through aqueducts to locations where it is to be used or treated. Selection of an aqueduct type rests on such factors as topography, head availability, climate, construction practices, economics, and water quality protection. Along with pipes and tunnels, aqueducts may also include or be solely composed of open channels (Viessman and Hammer, 1998, p. 119). In this section, we deal with water passage in open channels, which allow part of the water to be exposed to the atmosphere. This type of channel (an open flow channel) includes natural waterways, canals, culverts, flumes, and pipes flowing under the influence of gravity.

2.12.1 Characteristics of Open Channel Flow[*]

Basic hydraulic principles apply in open channel flow (with water depth constant), although there is no pressure to act as the driving force. Velocity head is the only natural energy this water possesses, and at normal water velocities this is a small value ($V^2/2g$). Several parameters can be (and often are) used to describe open channel flow; however, we begin our discussion by addressing a few characteristics of open channel flow, including laminar or turbulent, uniform or varied, and subcritical, critical, or supercritical.

2.12.1.1 Laminar and Turbulent Flow

Laminar and turbulent flow in open channels is analogous to that in closed pressurized conduits (e.g., pipes). It is important to point out, however, that flow in open channels is usually turbulent. In addition, laminar flow essentially never occurs in open channels in either water or wastewater unit processes or structures.

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[*] This section is adapted from McGhee, T.J., *Water Supply and Sewerage*, 2nd ed., McGraw-Hill, New York, 1991, p. 45.

2.12.1.2 Uniform and Varied Flow

Flow can be a function of time and location. If the flow quantity is invariant, it is said to be steady. Uniform flow is flow in which the depth, width, and velocity remain constant along a channel; that is, if the flow cross-section does not depend on the location along the channel, then the flow is said to be uniform. For varied or nonuniform flow, a change in one factor produces a change in the others. Most circumstances of open channel flow in water/wastewater systems involve varied flow. The concept of uniform flow is valuable, however, in that it defines a limit that the varied flow may be considered to be approaching in many cases.

Note: Uniform channel construction does not ensure uniform flow.

2.12.1.3 Critical Flow

Critical flow (i.e., flow at the critical depth and velocity) defines a state of flow between two flow regimes. Critical flow coincides with minimum specific energy for a given discharge and maximum discharge for a given specific energy. Critical flow occurs in flow measurement devices at or near free discharges and establishes controls in open channel flow. Critical flow occurs frequently in water/wastewater systems and is very important in their operation and design.

Note: Critical flow minimizes specific energy and maximizes discharge.

2.12.1.4 Parameters Used in Open Channel Flow

The three primary parameters used in open channel flow are hydraulic radius, hydraulic depth, and slope (S).

2.12.1.4.1 Hydraulic Radius

The *hydraulic radius* is the ratio of area in flow to the wetted perimeter:

$$r_H = \frac{A}{P} \tag{2.23}$$

where:

r_H = hydraulic radius.

A = the cross-sectional area of the water.

P = wetted perimeter.

Why is hydraulic radius important? Good question. Probably the best way to answer this question is by illustration. Consider, for example, that in open channels it is of primary importance to maintain the proper velocity. This is the case, of course, because if velocity is not maintained then flow stops (theoretically). In order to maintain velocity at a constant level, the channel slope must be adequate to overcome friction losses. As with other flows, calculation of head loss at a given flow

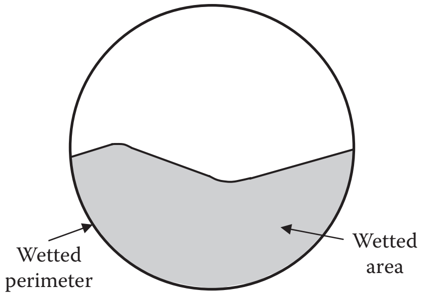

Figure 2.19 Hydraulic radius.

is necessary, and the Hazen–Williams equation is again useful ($Q = .435 \times C \times D^{2.63} \times S^{.54}$). Keep in mind that the concept of slope has not changed. The difference? We are now measuring, or calculating for, the physical slope of a channel (ft/ft), equivalent to head loss.

The preceding seems logical and makes sense, but there is a problem. The problem is with the diameter. In conduits that are not circular (grit chambers, contact basins, streams and rivers) or in pipes only partially full (e.g., drains, wastewater gravity mains, sewers) where the cross-sectional area of the water is not circular, there is no diameter. Without a diameter, what do we do? Another good question. Because we do not have a diameter in situations where the cross-sectional area of the water is not circular, we must use another parameter to designate the size of the cross-section and the amount of it that contacts the sides of the conduit. This is where the *hydraulic radius* (r_H) comes in. The hydraulic radius is a measure of the efficiency with which the conduit can transmit water. Its value depends on pipe size and amount of fullness. Simply, we use the hydraulic radius to measure how much of the water is in contact with the sides of the channel, or how much of the water is not in contact with the sides (see Figure 2.19).

Note: For a circular channel flowing either full or half-full, the hydraulic radius is $D/4$. Hydraulic radii of other channel shapes are easily calculated from the basic definition.

2.12.1.4.2 Hydraulic Depth

The hydraulic depth is the ratio of area in flow to the width of the channel at the fluid surface (note that other names for hydraulic depth are *hydraulic mean depth* and *hydraulic radius*):

$$d_H = \frac{A}{w} \tag{2.24}$$

where:

d_H = hydraulic depth.

A = area in flow.

w = width of the channel at the fluid surface.

2.12.1.4.3 Slope

The *slope* (S) in open channel equations is the slope of the energy line. If the flow is uniform, the slope of the energy line will be parallel to the water surface and channel bottom. In general, the slope can be calculated from the Bernoulli equation as the energy loss per unit length of channel:

$$S = \frac{D_h}{D_l} \tag{2.25}$$

2.12.2 Open Channel Flow Calculations

As mentioned, calculating the head loss at a given flow is typically accomplished by using the Hazen–Williams equation. In addition, in open channel flow problems, although the concept of slope has not changed, a problem again arises with the diameter. In pipes only partially full where the cross-sectional area of the water is not circular, we have no diameter. Thus, the hydraulic radius is used for these noncircular areas.

The original version of the Hazen–Williams equation incorporated the hydraulic radius. Moreover, similar versions developed by Chezy (pronounced "Shay-zee"), Manning, and others incorporated the hydraulic radius. *Manning's* formula is the most commonly used one for open channels:

$$Q = \frac{1.5}{n} \times A \times R^{.66} \times s^{.5} \tag{2.26}$$

where:

Q = channel discharge capacity (ft^3/s).

1.5 = constant.

n = channel roughness coefficient.

A = cross-sectional flow area (ft^2).

R = hydraulic radius of the channel (ft).

S = slope of the channel bottom (dimensionless).

The hydraulic radius of a channel is defined as the ratio of the flow area to the wetted perimeter P. In formula form, $R = A/P$. The new component is n (the roughness coefficient), which depends on the material and age of a pipe or lined channel and on topographic features for a natural streambed. It approximates roughness in open channels and can range from a value of 0.01 for a smooth clay pipe to 0.1 for a small natural stream. The value of n commonly assumed for concrete pipes or lined channels is 0.013. n values decrease as the channels get smoother (see Table 2.4). The following example illustrates the application of Manning's formula for a channel with a rectangular cross-section.

TABLE 2.4 MANNING ROUGHNESS COEFFICIENT, *n*

Type of Conduit	*n*	Type of Conduit	*n*
Pipe		Cast iron (uncoated)	0.013–0.015
Cast iron (coated)	0.012–0.014	Wrought iron (black)	0.012–0.015
Wrought iron (galvanized)	0.015–0.017	Corrugated	0.021–0.026
Steel (riveted and spiral)	0.015–0.017	Cement surface	0.010–0.013
Wood stave	0.012–0.013	Vitrified	0.013–0.015
Concrete	0.012–0.017	Metal (corrugated)	0.023–0.025
Clay, drainage tile	0.012–0.014	Wood (unplaned)	0.011–0.015
Lined channels		Concrete	0.014–0.016
Metal (smooth semicircular)	0.011–0.015	Grass	up to 0.020
Wood (planed)	0.010–0.015	Earth (dredged)	0.025–0.033
Cement (lined)	0.010–0.013	Earth (stony)	0.025–0.040
Cement rubble	0.017–0.030	Rock (jagged and irregular)	0.035–0.045
Unlined channels			
Earth (straight and uniform)	0.017–0.025		
Earth (winding)	0.023–0.030		
Rock (smooth and uniform)	0.025–0.035		

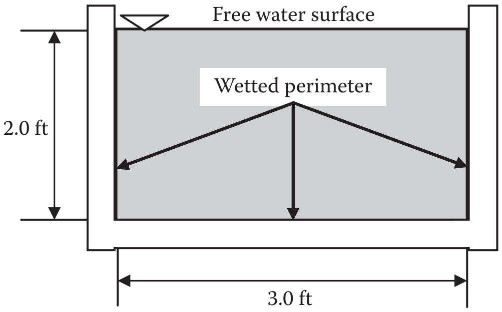

Figure 2.20 For Example 2.15.

■ ***Example 2.15***

Problem: A rectangular drainage channel is 3 ft wide and is lined with concrete, as illustrated in Figure 2.20. The bottom of the channel drops in elevation at a rate of 0.5 per 100 ft. What is the discharge in the channel when the depth of water is 2 ft?

Solution: Assume n = 0.013. Referring to Figure 2.20, we see that the cross-sectional flow area (A) = 3 ft × 2 ft = 6 ft^2, and the wetted perimeter (P) = 2 ft + 3 ft + 2 ft = 7 ft. The hydraulic radius (R) = A/P = 6 ft^2/7 ft = 0.86 ft. The slope (S) = 0.5/100 = 0.005. Applying Manning's formula, we get:

$$Q = \frac{2.0}{0.013} \times 6 \times 0.86.66 \times 0.005.5 = 59 \text{ cfs}$$

2.12.3 Open Channel Flow: The Bottom Line

To this point, we have set the stage for explaining (in the simplest possible way) what open channel flow is—what it is all about. Now that we have explained the necessary foundational material and important concepts, we are ready to explain open channel flow in a manner whereby it will be easily understood. We stated earlier that when water flows in a pipe or channel with a *free surface* exposed to the atmosphere it is referred to as *open channel flow*. We also know that gravity provides the motive force, the constant push, while friction resists the motion and causes energy expenditure. River and stream flow is open channel flow. Flows in sanitary sewers and stormwater drains are open channel flow, except in force mains, where the water is pumped under pressure.

The key to solving routine stormwater and sanitary sewer problems is a condition known as *steady uniform flow*; that is, we assume steady uniform flow. Steady flow, of course, means that the discharge is constant with time. Uniform flow means that the slope of the water surface and the cross-sectional flow area are also constant. It is common practice to call a length of channel, pipeline, or stream that has a relatively constant slope and cross-section a *reach* (Nathanson, 1997). The slope of the water surface, under steady uniform flow conditions, is the same as the slope of the channel bottom. The hydraulic grade line (HGL) lies along the water surface, and, as in pressure flow in pipes, the HGL slopes

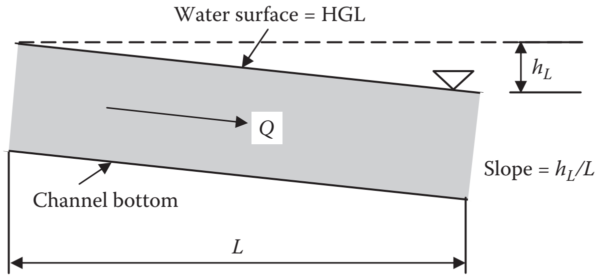

Figure 2.21 Steady uniform open channel flow, where the slope of the water surface (or HGL) is equal to the slope of the channel bottom.

downward in the direction of flow. Energy loss is evident as the water surface elevation drops. Figure 2.21 illustrates a typical profile view of uniform steady flow. The slope of the water surface represents the rate of energy loss. Figure 2.22 shows typical cross-sections of open channel flow. In Figure 2.22A, the pipe is only partially filled with water and there is a free surface at atmospheric pressure. This is still open channel flow, although the pipe is a closed underground conduit. Remember, the important point is that gravity and not a pump is moving the water.

Note: Rate of energy loss (see Figure 2.21) may be expressed as the ratio of the drop in elevation of the surface in the reach to the length of the reach.

2.13 FLOW MEASUREMENT

Although it is clear that maintaining water/wastewater flow is at the heart of any treatment process, clearly it is the measurement of flow that is essential to ensuring the proper operation of a water/wastewater treatment system. Few knowledgeable operators would argue with this statement. Hauser (1996, p. 91) asked: “Why measure flow?” Then she explained: “The most vital activities in the operation of water and wastewater treatment plants are dependent on a knowledge of how much water is being processed.”

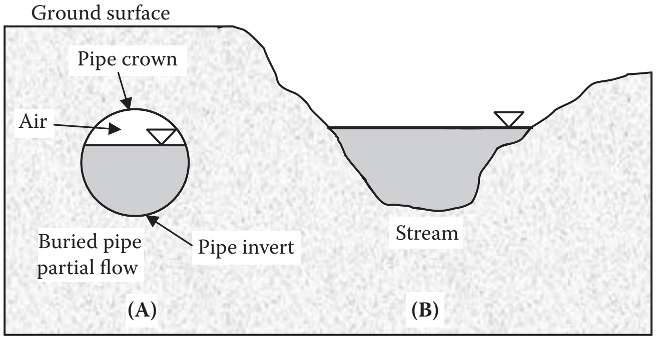

Figure 2.22 Open channel flow, whether in a surface stream or in an underground pipe. (Adapted from Nathanson, J.A., *Basic Environmental Technology: Water Supply, Waste Management, and Pollution Control*, Prentice Hall, Upper Saddle River, NJ, 1997, p. 35.)

In the statement above, Hauser made it clear that flow measurement is not only important but also routine in water/wastewater operations. Routine, yes, but also the most important variable measured in a treatment plant. Hauser provided several reasons to measure flow in a treatment plant, and the American Water Works Association (1995) listed several more reasons to measure flow:

- The flow rate through the treatment processes must be controlled so it matches distribution system use.
- It is important to determine the proper feed rate of chemicals added in the processes.
- The detention times through the treatment processes must be calculated. This is particularly applicable to surface water plants that must meet *CxT* values required by the Surface Water Treatment Rule.
- Flow measurement allows operators to maintain a record of water furnished to the distribution system for periodic comparison with the total water metered to customers. This provides a measure of "water accounted for," or conversely (as pointed out earlier by Hauser), the amount of water wasted, leaked, or otherwise not paid for—that is, lost water.
- Flow measurement allows operators to determine the efficiency of pumps (pumps are covered in detail in Chapter 3). Pumps that are not delivering their designed flow rate are probably not operating at maximum efficiency, so power is being wasted.
- For well systems, it is very important to maintain records of the volume of water pumped and the hours of operation for each well. The periodic computation of well pumping rates can identify problems such as worn pump impellers and blocked well screens.
- Reports that must be furnished to the state by most water systems must include records of raw and finished water pumpage.
- Wastewater generated by a treatment system must also be measured and recorded.
- Individual meters are often required for proper operation of individual pieces of equipment; for example, makeup water to a fluoride saturator is always metered to assist in tracking the fluoride feed rate.

Note: Simply put, measurement of flow is essential for operation, process control, and recordkeeping of water and wastewater treatment plants.

All of the uses just discussed create the need, obviously, for a number of flow measuring devices, often with different capabilities. In this section, we discuss many of the major flow measuring devices currently used in wastewater operations.

2.13.1 Flow Measurement: The Old-Fashioned Way

An approximate but very simple method to determine open channel flow has been used for many years. The procedure involves measuring the velocity of a floating object moving in a straight uniform reach of the channel or stream. If the cross-sectional dimensions of the channel are known and the depth of flow is measured, then flow area can be computed. From the relationship $Q = A \times V$, discharge Q can be estimated. In preliminary fieldwork, this simple procedure is useful in obtaining a ballpark estimate for the flow rate, but it is not suitable for routine measurements.

■ *Example 2.16*

Problem: A floating object is placed on the surface of water flowing in a drainage ditch and is observed to travel a distance of 20 m downstream in 30 seconds. The ditch is 2 m wide, and the average depth of flow is estimated to be 0.5 m. Estimate the discharge under these conditions.

Solution: The flow velocity is computed as distance over time, or:

$$V = D/T = 20 \text{ m}/30 \text{ s} = 0.67 \text{ m/s}$$

Channel area $A = 2 \text{ m} \times 0.5 \text{ m} = 1.0 \text{ m}^2$, and discharge $Q = A \times V = 1.0 \text{ m}^2 \times 0.66 \text{ m}^2 = 0.66 \text{ m}^3\text{/s}$.

2.13.2 Basis of Traditional Flow Measurement

Flow measurement can be based on flow rate or flow amount. *Flow rate* is measured in gallons per minute (gpm), million gallons per day (MGD), or cubic feet per second (cfs). Water/wastewater operations need flow rate meters to determine process variables within the treatment plant, in wastewater collection, and in potable water distribution. The flow rate meters normally used are pressure differential meters, magnetic meters, and ultrasonic meters. Flow rate meters are designed for metering flow in closed pipe or open channel flow.

Flow amount is measured in either gallons (gal) or cubic feet (ft^3). Typically, a totalizer, which sums up the gallons or cubic feet that pass through the meter, is used. Most service meters are of this type. They are used in private, commercial, and industrial activities where the total amount of flow measured is used to determine customer billing. In wastewater treatment, where sampling operations are important, automatic composite sampling units—flow proportioned to grab a sample every so many gallons—are used. Totalizer meters can be of the velocity (propeller or turbine), positive displacement, or compound type. In addition, weirs and flumes are used extensively for measuring flow in wastewater treatment plants because they are not affected (to a degree) by dirty water or floating solids.

2.13.3 Flow Measuring Devices

In recent decades, flow measurement technology has evolved rapidly from the old-fashioned way of measuring flow discussed earlier to the use of simple practical measuring devices to much more sophisticated devices. Physical phenomena discovered centuries ago have been the starting point for many of the viable flow meter designs used today. Moreover, the recent technology explosion has enabled flow meters to handle many more applications than could have been imagined centuries ago. Before selecting a particular type of flow measurement device, consider (Kawamura, 2000):

1. Is liquid or gas flow being measured?
2. Is the flow occurring in a pipe or in an open channel?
3. What is the magnitude of the flow rate?
4. What is the range of flow variation?
5. Is the liquid being measured clean, or does it contain suspended solids or air bubbles?
6. What is the accuracy requirement?
7. What is the allowable head loss by the flow meter?
8. Is the flow corrosive?
9. What types of flow meters are available to the region?
10. What type of post-installation service is available to the area?

2.13.4 Differential Pressure Flow Meters*

For many years *differential pressure* flow meters have been the most widely applied flow measuring device for water flow in pipes that require accurate measurement at reasonable cost. The differential pressure type of flow meter makes up the largest segment of the total flow measurement devices currently being used. Differential-pressure-producing meters currently on the market include the Venturi, Dall type, Hershel Venturi, universal Venturi, and Venturi inserts. The differential-pressure-producing device has a flow restriction in the line that causes a differential pressure, or head, to develop between the two measurement locations. Differential pressure flow meters are also known as *head meters*, and, of all the head meters, the orifice flow meter is the most widely applied device. The advantages of differential pressure flow meters include:

- Simple construction
- Relatively inexpensive
- No moving parts
- External transmitting instruments
- Low maintenance
- Wide application of flowing fluid, suitable for measuring both gas and liquid flow

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* This section is adapted from Husain, Z.D. and Sergesketter, M.J., in *Flow Measurement*, Spitzer, D.W., Ed., Instrument Society of America, Research Triangle Park, NC, 1991, pp. 119–160.

- Ease of instrument and range selection
- Extensive product experience and performance database

Disadvantages include:

- Flow rate being a nonlinear function of the differential pressure
- Low flow rate rangeability with normal instrumentation

2.13.4.1 Operating Principle

Differential pressure flow meters operate on the principle of measuring pressure at two points in the flow, which provides an indication of the rate of flow that is passing by. The difference in pressures between the two measurement locations of the flow meter is the result of the change in flow velocities. Simply, there is a set relationship between the flow rate and volume, so the meter instrumentation automatically translates the differential pressure into a volume of flow. The volume of flow rate through the cross-sectional area is given by:

$$Q = A \times v$$

where:

Q = the volumetric flow rate.

A = flow in the cross-sectional area.

v = the average fluid velocity.

2.13.4.2 Types of Differential Pressure Flow Meters

Differential pressure flow meters operate on the principle of developing a differential pressure across a restriction that can be related to the fluid flow rate.

Note: Optimum measurement accuracy is maintained when the flow meter is calibrated and installed in accordance with standards and codes of practice, and the transmitting instruments are periodically calibrated.

The most commonly used differential pressure flow meter types used in wastewater treatment are:

1. Orifice
2. Venturi
3. Nozzle
4. Pitot-static tube

2.13.4.2.1 Orifice

The most commonly applied type, the orifice flow meter is a thin, concentric, flat metal plate with an opening in the plate (see Figure 2.23) installed perpendicular to the flowing stream in a circular conduit or

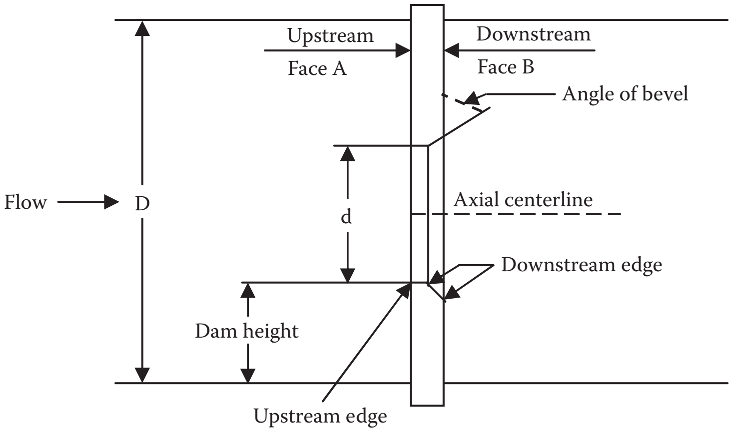

Figure 2.23 Orifice plate.

pipe. Typically, a sharp-edged hole is bored in the center of the orifice plate. As the flowing water passes through the orifice, the restriction causes an increase in velocity. A concurrent decrease in pressure occurs as potential energy (static pressure) is converted into kinetic energy (velocity). As the water leaves the orifice, its velocity decreases and its pressure increases as kinetic energy is converted back into potential energy according to the law of conservation of energy. However, there is always some permanent pressure loss due to friction, and the loss is a function of the ratio of the diameter of the orifice bore (*d*) to the pipe diameter (*D*). For dirty water applications (i.e., wastewater), a concentric orifice plate will eventually have impaired performance due to dirt buildup at the plate. *Eccentric* or *segmental* orifice plates (see Figure 2.24) can be used, but measurements are typically less accurate than those obtained from the concentric orifice plate, so they are rarely applied in current practice. The orifice differential pressure flow meter is the lowest cost differential flow meter, is easy to install, and has no moving parts; however, it also has high permanent head loss (ranging from 40 to 90%), higher pumping costs, and an accuracy of ±2% for a flow range of 4:1, and it is affected by wear or damage.

Note: Orifice meters are not recommended for permanent installation to measure wastewater flow; solids in the water easily catch on the orifice, throwing off accuracy. For installation, it is necessary to have ten diameters of straight pipe ahead of the orifice meter, to create a smooth flow pattern, and five diameters of straight pipe on the discharge side.

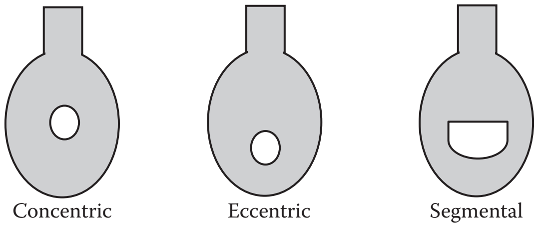

Figure 2.24 Orifice plates.

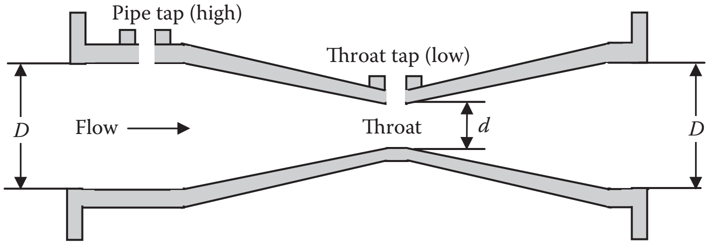

Figure 2.25 Venturi tube.

2.13.4.2.2 Venturi

A *Venturi* is a restriction with a relatively long passage with smooth entry and exit (see Figure 2.25). It has a long life expectancy, simplicity of construction, and relatively high pressure recovery (i.e., produces less permanent pressure loss than a similar sized orifice), but it is more expensive, is not linear with flow rate, and is the largest and heaviest differential pressure flow meter. It is often used in wastewater flows, as the smooth entry allows foreign material to be swept through instead of building up as it would in front of an orifice. The accuracy of this type flow meter is ±1% for a flow range of 10:1. The head loss across a Venturi flow meter is relatively small, ranging from 3 to 10% of the differential, depending on the ratio of the throat diameter to the inlet diameter (i.e., beta ratio).

2.13.4.2.3 Nozzle

Flow nozzles (flow tubes) have a smooth entry and sharp exit (see Figure 2.26). For the same differential pressure, the permanent pressure loss of a nozzle is of the same order as that of an orifice, but it can handle wastewater and abrasive fluids better than an orifice can. Note that for the same line size and flow rate, the differential pressure at the nozzle is lower (head loss ranges from 10 to 20% of the differential) than the differential pressure for an orifice; hence, the total pressure loss is lower than that of an orifice. Nozzles are primarily used in steam service because of their rigidity, which makes them dimensionally more stable at high temperatures and velocities than orifices.

Note: A useful characteristic of nozzles is that they reach a critical flow condition—that is, a point at which further reduction in downstream pressure does not produce a greater velocity through the nozzle. When operated in this mode, nozzles are very predictable and repeatable.

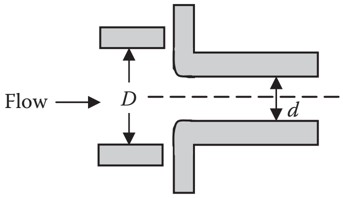

Figure 2.26 Long-radius flow nozzle.

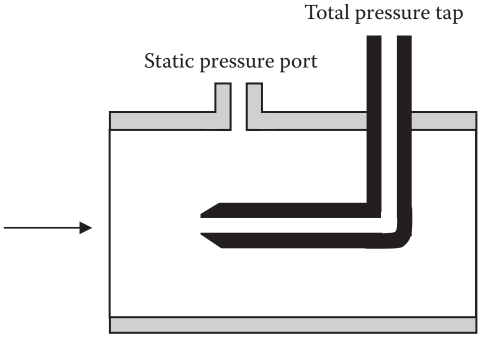

Figure 2.27 Pitot tube.

2.13.4.2.4 Pitot Tube

A *pitot tube* is a point velocity-measuring device (see Figure 2.27). It has an impact port; as fluid hits the port, its velocity is reduced to zero, and kinetic energy (velocity) is converted to potential energy (pressure head). The pressure at the impact port is the sum of the static pressure and the velocity head. The pressure at the impact port is also known as *stagnation pressure* or *total pressure*. The pressure difference between the impact pressure and the static pressure measured at the same point is the velocity head. The flow rate is the product of the measured velocity and the cross-sectional area at the point of measurement. Note that the pitot tube has negligible permanent pressure drop in the line, but the impact port must be located in the pipe where the measured velocity is equal to the average velocity of the flowing water through the cross-section.

2.13.5 Magnetic Flow Meters[*]

Magnetic flow meters are relatively new to the wastewater industry. They are volumetric flow devices designed to measure the flow of electrically conductive liquids in a closed pipe. They measure the flow rate based on the voltage created between two electrodes (in accordance with Faraday's law of electromagnetic induction) as the water passes through an electromagnetic field (see Figure 2.28). Induced voltage is proportional to flow rate. Voltage depends on magnetic field strength (constant), distance between electrodes (constant), and velocity of flowing water (variable). Properties of the magnetic flow meter include: (1) minimal head loss (no obstruction with line size meter); (2) no effect on flow profile; (3) suitable for sizes ranging from 0.1 to 120 in.; (4) accuracy rating of 0.5 to 2% of flow rate; and (5) measurement of forward or reverse flow.

The advantages of magnetic flow meters include:

- Obstructionless flow
- Minimal head loss

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[*] This section is adapted from Water and Wastewater ITA and USEPA, *Flow Instrumentation: A Practical Workshop on Making Them Work*, Water and Wastewater Instrumentation Testing Association and U.S. Environmental Protection Agency, Sacramento, CA, 1991.

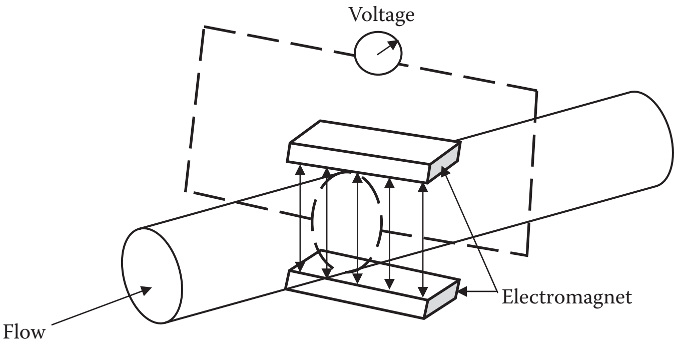

Figure 2.28 Magnetic flowmeter.

- Wide range of sizes
- Bidirectional flow measurement
- Negligible effect from variations in density, viscosity, pressure, and temperature
- Can be used for wastewater
- No moving parts

Disadvantages include:

- Metered liquid must be conductive (but you would not use this type of meter on clean fluids anyway).
- They are bulky and expensive in smaller sizes, and they may require periodic calibration to correct drifting of the signal.

The combination of a magnetic flow meter and transmitter is considered to be a system. A typical system, illustrated in Figure 2.29, includes a transmitter mounted remote from the magnetic flow meter, although some systems are available with transmitters mounted integral to the magnetic flow meter. Each device is individually calibrated during the manufacturing process, and the accuracy statement of the magnetic flow meter includes both pieces of equipment. One is not sold or used without the other. It is also interesting to note that, since 1983, almost every manufacturer has offered the microprocessor-based transmitter.

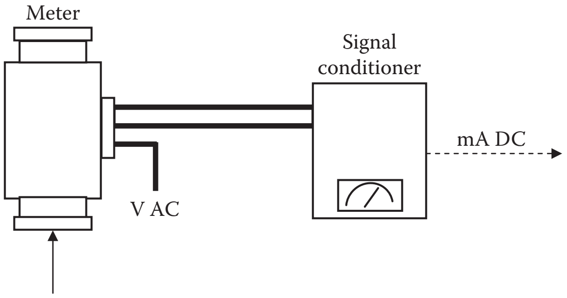

Figure 2.29 Magnetic flowmeter system.

With regard to minimum piping straight-run requirements, magnetic flow meters are quite forgiving of piping configuration. The downstream side of the magnetic flow meter is much less critical than the upstream side. Essentially, all that is required of the downstream side is that sufficient backpressure is provided to keep the magnetic flow meter full of liquid during flow measurement. Two diameters downstream should be acceptable (Mills, 1991).

Note: Magnetic flow meters are designed to measure conductive liquids only. If air or gas is mixed with the liquid, the output becomes unpredictable.

2.13.6 Ultrasonic Flow Meters

Ultrasonic flow meters use an electronic transducer to send a beam of ultrasonic sound waves through the water to another transducer on the opposite side of the unit. The velocity of the sound beam varies with the liquid flow rate, so the beam can be electronically translated to indicate flow volume. The accuracy is ±1% for a flow velocity ranging from 1 to 25 ft/s, but the meter reading is greatly affected by a change in the fluid composition. Two types of ultrasonic flow meters are in general use for closed pipe flow measurements. Time-of-flight or transit time flow meters usually use pulse transmission and are intended for use with clean liquids. The Doppler type usually uses continuous wave transmission and is intended for use with dirty liquids.

2.13.6.1 Time-of-Flight Ultrasonic Flow Meters[*]

Time-of-flight flow meters make use of the difference in the time required for a sonic pulse to travel a fixed distance, first in the direction of flow and then against the flow. This is accomplished by positioning opposing transceivers on a diagonal path across a meter spool, as shown in Figure 2.30. Each transmits and receives ultrasonic pulses with the flow and against the flow. The fluid velocity is directly proportional to the time difference in pulse travel. The time-of-flight ultrasonic flow meter operates with minimal head loss and has an accuracy range of 1 to 2.5% full scale. They can be mounted as integral spool piece transducers or as externally mountable clamp-ons. They can measure flow accurately when properly installed and applied.

The advantages of the time-of-flight ultrasonic flow meter include:

- No obstruction to flow
- Minimal head loss
- Can be clamped on
- Can be portable

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[*] This section is adapted from Brown, A.E., in *Flow Measurement*, Spitzer, D.W., Ed., Instrument Society of America, Research Triangle Park, NC, 1991, pp. 415–432.

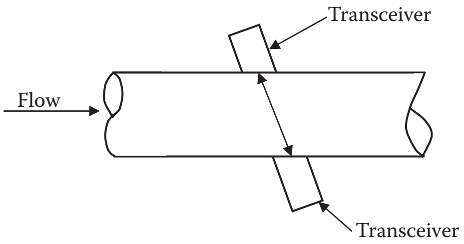

Figure 2.30 Time-of-flight ultrasonic flowmeter.

- No interruption of flow
- No moving parts
- Linear over a wide range
- Wide range of pipe sizes
- Bidirectional flow measurement

Disadvantages include:

- It is sensitive to solids or bubble content.
- It can interfere with sound pulses.
- It is sensitive to flow disturbances.
- Alignment of transducers is critical.
- Being clamped on requires pipe walls to freely pass ultrasonic pulses.

2.13.6.2 Doppler Ultrasonic Flow Meters

Doppler ultrasonic flow meters make use of the Doppler frequency shift caused by sound being scattered or reflected from moving particles in the flow path. Doppler meters are not considered to be as accurate as time-of-flight flow meters; however, they are very convenient to use and generally more popular and less expensive than time-of-flight flow meters. In operation, a propagated ultrasonic beam is interrupted by particles in moving fluid and reflected toward a receiver. The difference between the propagated and reflected frequencies is directly proportional to the fluid flow rate. Ultrasonic Doppler flow meters feature minimal head loss with an accuracy of 2 to 5% full scale. They are either the integral spool piece transducer type or externally mountable clamp-ons.

The advantages of the Doppler ultrasonic flow meter include:

- No obstruction to flow
- Minimal head loss
- Can be clamped on
- Portability

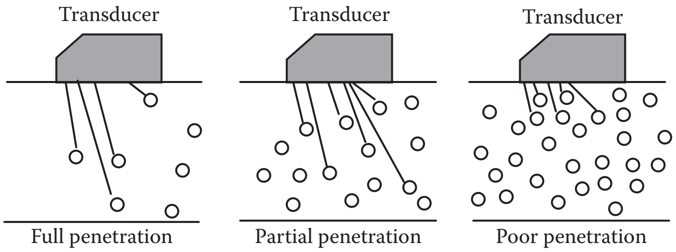

Figure 2.31 Particle concentration effect—the greater the number of particles, the greater the error.

- No interruption of flow
- No moving parts
- Linear over a wide range
- Wide range of pipe sizes
- Low installation and operating costs
- Bidirectional flow measurement

The disadvantages include:

- It requires a minimum concentration and size of solids or bubbles for reliable operation (see Figure 2.31).
- It requires a minimum speed to maintain suspension.
- Clamp-on type is limited to sonically conductive pipe.

2.13.7 Velocity Flow Meter*

Velocity or turbine flow meters use a propeller or turbine to measure the velocity of the flow passing the device (see Figure 2.32A). The velocity is then translated into a volumetric amount by the meter register. Sizes are available from a variety of manufacturers to cover a flow range from 0.001 gpm to over 25,000 gpm for liquid service. End connections are available to meet the needs of various piping systems. The flow meters are typically manufactured of stainless steel but are also available in a wide variety of materials, including plastic. Velocity meters are applicable to all clean fluids. Velocity meters are particularly well suited for measuring intermediate flow rates on clean water.

The advantages of the velocity meter include:

- Highly accurate
- Corrosion-resistant materials
- Long-term stability

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* This section is adapted from Oliver, P.D., in *Flow Measurement*, Spitzer, D.W., Ed., Instrument Society of America, Research Triangle Park, NC, 1991, pp. 373–414.

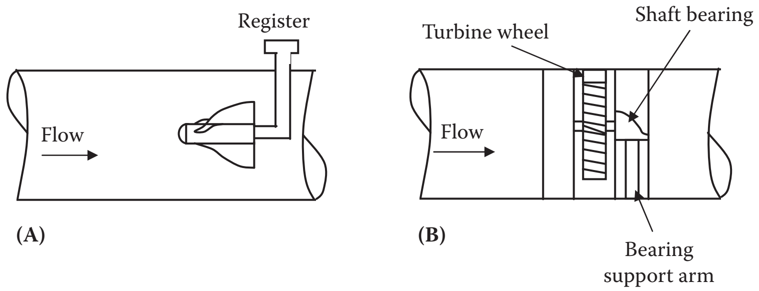

Figure 2.32 (A) Propeller meter and (B) turbine meter.

- Liquid or gas operation
- Wide operating range
- Low pressure drop
- Wide temperature and pressure limits
- High shock capability
- Wide variety of electronics available

As shown in Figure 2.32B, a turbine flow meter consists of a rotor mounted on a bearing and shaft in a housing. The fluid to be measured is passed through the housing, causing the rotor to spin with a rotational speed proportional to the velocity of the fluid flowing within the meter. The actual flow measurement is obtained by a device that measures the speed of the rotor. The sensor can be a mechanical, gear-driven shaft attached to a meter or an electronic sensor that detects the passage of each rotor blade generating a pulse. The rotational speed of the sensor shaft and the frequency of the pulse are proportional to the volumetric flow rate through the meter.

2.13.8 Positive-Displacement Flow Meters[*]

Positive-displacement flow meters are most commonly used for customer metering; they have long been used to measure liquid products. These meters are very reliable and accurate for low flow rates because they measure the exact quantity of water passing through them. Positive-displacement flow meters are frequently used to measure small flows in a treatment plant because of their accuracy. Repair or replacement is easy, as they are so common in the distribution system. In essence, a positive-displacement flow meter is a hydraulic motor with high volumetric efficiency that absorbs a small amount of energy from the flowing stream. This energy is used to overcome internal friction in driving the flow meter and its accessories and is reflected as a pressure drop across the flow meter. Pressure drop is considered to be unavoidable but must be minimized. It is the pressure drop across the internals of a positive-displacement flow meter that actually creates a hydraulically unbalanced rotor and subsequent rotation.

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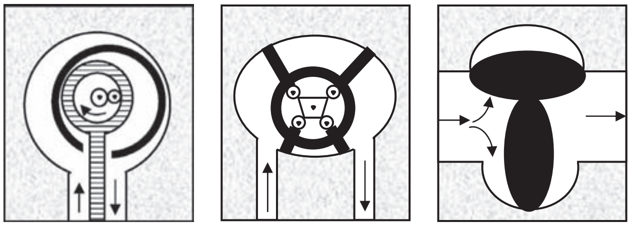
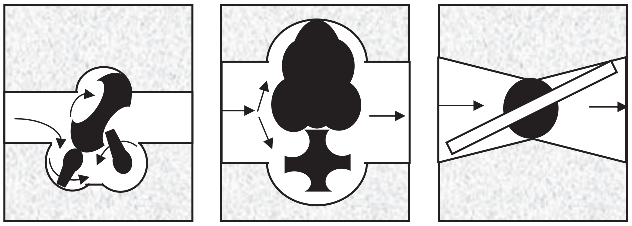
[*] This section is adapted from Barnes, R.G., in *Flow Measurement*, Spitzer, D.W., Ed., Instrument Society of America, Research Triangle Park, NC, 1991, pp. 315–322.



Piston Sliding vane Oval gear



Trirotor Birotor Disc

Figure 2.33 Six common positive-displacement meter principles.

Simply, a positive-displacement flow meter is one that continuously divides the flowing stream into known volumetric segments, isolates the segments momentarily, and returns them to the flowing stream while counting the number of displacements. A positive-displacement flow meter can be broken down into three basic components: the external housing, the measuring unit, and the counter drive train. The external housing is the pressure vessel that contains the product being measured. The measuring unit is a precision metering element made up of the measuring chamber and the displacement mechanism. The most common displacement mechanisms include the oscillating piston, sliding vane, oval gear, trirotor, birotor, and nutating disc types (see Figure 2.33). The counter drive train is used to transmit the internal motion of the measuring unit into a usable output signal. Many positive-displacement flow meters use a mechanical gear train that requires a rotary shaft seal or packing gland that penetrates the external housing.

The positive-displacement flow meter can offer excellent accuracy, repeatability, and reliability in many applications. It has satisfied many needs in the past and should play a vital role in serving future needs.

2.13.9 Open Channel Flow Measurement[*]

The majority of industrial liquid flows are carried in closed conduits that flow completely full and under pressure; however, this is not the case for high-volume flows of liquids in waterworks, sanitary, and stormwater systems that are commonly carried in open channels. Low system heads and high volumetric flow rates characterize flow in open channels. The most commonly used method of measuring the rate of flow in an open channel flow configuration is that of *hydraulic structures*. In this

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[*] This section is adapted from Grant, D.M., in *Flow Measurement*, D.W. Spitzer, Ed., Instrument Society of America, Research Triangle Park, NC, 1991, pp. 252–290.

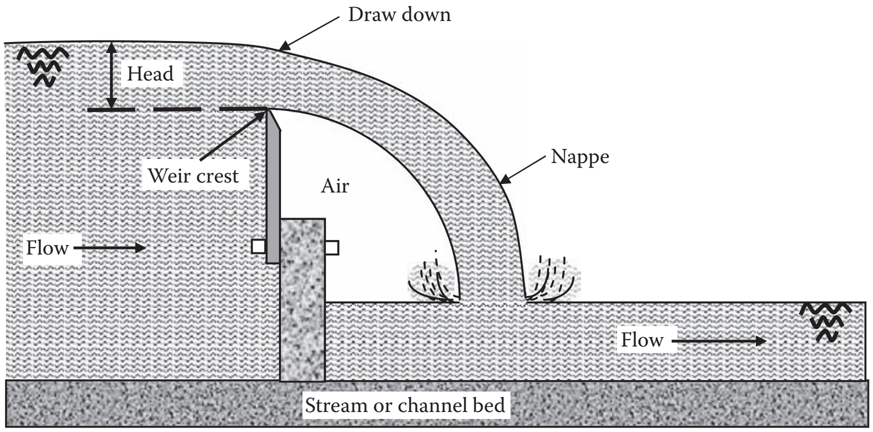

Figure 2.34 Side view of a weir.

method, flow in an open channel is measured by inserting a hydraulic structure into the channel which changes the level of liquid in or near the structure. By selecting the shape and dimensions of the hydraulic structure, the rate of flow through or over the restriction will be related to the liquid level in a known manner. Thus, the flow rate through the open channel can be derived from a single measurement of the liquid level in or near the structure. The hydraulic structures used in measuring flow in open channels are known as primary measuring devices and may be divided into two broad categories: *weirs* and *flumes*.

2.13.9.1 Weirs

The weir is a widely used device to measure open channel flow. As can be seen in Figure 2.34, a weir is simply a dam or obstruction placed in the channel so water backs up behind it and then flows over it. The sharp crest or edge allows the water to spring clear of the weir plate and to fall freely in the form of a *nappe*. When the nappe discharges freely into the air, there is a hydraulic relationship between the height or depth of water flowing over the weir crest and the flow rate (Nathanson, 1997). This height, the vertical distance between the crest and the water surface, is called the *head on the weir*; it can be measured directly with a meter or yardstick or automatically by float-operated recording devices.

Two common weirs, rectangular and triangular, are shown in Figure 2.35. *Rectangular weirs* are commonly used for large flows (see Figure 2.34A). The formula for rectangular weir computations is:

$$Q = 3.33 \times L \times h^{1.5} \tag{2.27}$$

where:

Q = flow.

L = width of weir.

h = head on weir (measured from the edge of the weir in contact with the water up to the water surface).

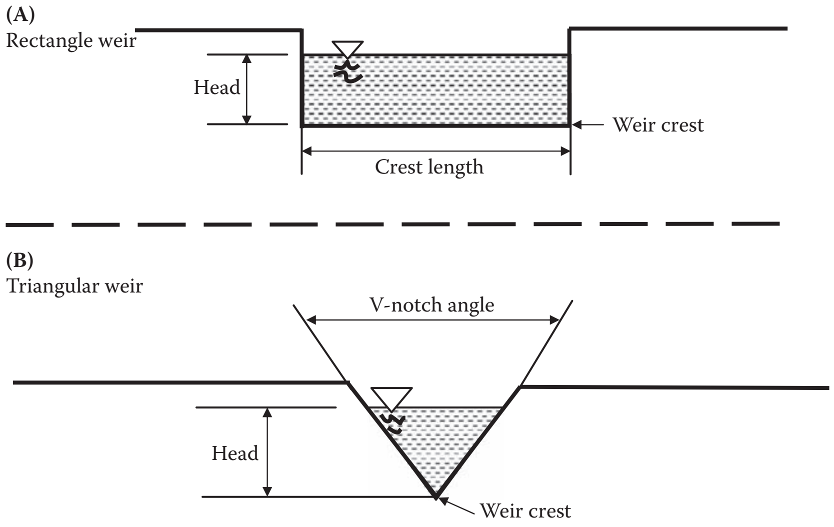

Figure 2.35 (A) Rectangular weir and (B) triangular V-notch weir.

■ ***Example 2.17***

Problem: A weir 4-ft high extends 15 ft across a rectangular channel in which the water is flowing at 80 cfs. What is the depth just upstream from the weir?

Solution:

$Q = 3.33 \times L \times h^{1.5}$

$80 = 3.33 \times 15 \times h^{1.5}$

$h = 1.4$ ft (with calculator, 1.6 INV $y^{x1.5} = 1.36$, or 1.4)

4 ft (height of weir) + 1.4 ft (head of water) = 5.4 ft (depth)

Triangular weirs, also called *V-notch weirs*, can have notch angles ranging from 22.5° to 90°, but right-angle notches are the most common (see Figure 2.34B). The formula used for V-notch (90°) weir calculations is:

$$Q = 2.5 \times h^{2.5} \tag{2.28}$$

where:

Q = flow.

h = head on weir (measured from bottom of notch to water surface).

■ ***Example 2.18***

Problem: What should be the minimum weir height to measure a flow of 1200 gpm with a 90° V-notch weir if the flow is moving at 4 ft/s in a 2.5-ft wide rectangular channel?

Solution:

$$\frac{1200 \text{ gpm}}{60 \text{ s/min} \times 7.48 \text{ gal/ft}^3} = 2.67 \text{ cfs}$$

$$Q = A \times V$$

$$2.67 = 2.5 \times d \times 4$$

$$d = 0.27 \text{ ft}$$

$$Q = 2.5 \times h^{2.5}$$

$$2.67 = 2.5 \times h^{2.5}$$

$$h = 1.03 \text{ (with calculator, 1.06 INV } y^{x2.5} = 1.026\text{, or 1.03)}$$

$$0.27 \text{ ft (original depth)} + 1.03 \text{ (head on weir)} = 1.3 \text{ ft}$$

It is important to point out that weirs, aside from being operated within their flow limits, must also be operated within the available system head. In addition, the operation of the weir is sensitive to the approach velocity of the water, often necessitating a stilling basin or pound upstream of the weir. Weirs are not suitable for water that carries excessive solid materials or silt, which can deposit in the approach channel behind the weir and destroy the conditions required for accurate discharge measurements.

Note: Accurate flow rate measurements with a weir cannot be expected unless the proper conditions and dimensions are maintained.

2.13.9.2 Flumes

A *flume* is a specially shaped constricted section in an open channel (similar to the Venturi tube in a pressure conduit). The special shape of the flume (see Figure 2.36) restricts the channel area or changes the channel slope, resulting in an increased velocity and a change in the level of the liquid flowing through the flume. The flume restricts the flow and then expands it in a definite fashion. The flow rate through the flume may be determined by measuring the head on the flume at a single point, usually at some distance downstream from the inlet.

Flumes can be categorized as belonging to one of three general families, depending upon the state of flow induced: subcritical, critical, or supercritical. Typically, flumes that induce a critical or supercritical state of flow are most commonly used because, when critical or supercritical flow occurs in a channel, one head measurement can indicate the discharge rate if it is made far enough upstream so the flow depth is not affected by the drawdown of the water surface as it achieves or passes through a critical state of flow. For critical or supercritical states of flow, a definitive head–discharge relationship can be established and measured, based on a single head reading. Thus, most commonly encountered flumes are designed to pass the flow from subcritical through critical or near the point of measurement.

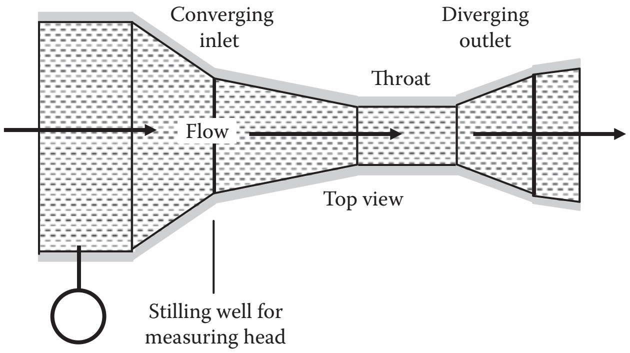

Figure 2.36 Parshall flume.

The most common flume used for a permanent wastewater flow-metering installation is called the *Parshall flume*, shown in Figure 2.36. Formulas for flow through Parshall flumes differ, depending on throat width. The formula below can be used for widths of 1 to 8 ft and applies to a medium range of flows:

$$Q = 4 \times W \times H_a^{1.52} \times W^{.026} \tag{2.29}$$

where:

Q = flow.

W = width of throat.

H_a = depth in stilling well upstream.

Note: Parshall flumes are low-maintenance items.

2.14 CHAPTER REVIEW QUESTIONS

2.1 What should be the minimum weir height for measuring a flow of 900 gpm with a 90° V-notch weir, if the flow is now moving at 3 ft/s in a 2-ft-wide rectangular channel?

2.2 A 90° V-notch weir is to be installed in a 30-in.-diameter sewer to measure 600 gpm. What head should be expected?

2.3 For dirty water operations, a ____________ or ____________ orifice plate should be used.

2.4 A ____________ has a smooth entry and sharp exit.

2.5 ____________ send a beam of ultrasonic sound waves through the water to another transducer on the opposite side of the unit.

2.6 Find the number of gallons in a storage tank that has a volume of 660 ft^3.

2.7 Suppose a rock weighs 160 lb in air and 125 lb under water. What is the specific gravity?

2.8 A 110-ft-diameter cylindrical tank contains 1.6 MG water. What is the water depth?

2.9 The pressure in a pipeline is 6400 psf. What is the head on the pipe?

2.10 The pressure on a surface is 35 psig. If the surface area is 1.6 ft^2, what is the force (lb) exerted on the surface?

2.11 Bernoulli's principle states that the total energy of a hydraulic fluid is ____________.

2.12 What is *pressure head*?

2.13 What is a *hydraulic grade line*?

2.14 A flow of 1500 gpm takes place in a 12-in. pipe. Calculate the velocity head.

2.15 Water flows at 5.00 mL/s in a 4-in. line under a pressure of 110 psi. What is the pressure head (ft of water)?

2.16 In Question 2.15, what is the velocity head in the line?

2.17 What is the velocity head in a 6-in. pipe connected to a 1-ft pipe if the flow in the larger pipe is 1.46 cfs?

2.18 What is *velocity head?*

2.19 What is *suction lift*?

2.20 Explain *energy grade line*.

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CHAPTER 3

HYDRAULIC MACHINES: PUMPS

A hydraulic machine, or pump, is a device that raises, compresses, or transfers fluids.

3.1 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 moving 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 is needed in higher areas, the energy needed to move that water must be created. Simply, some type of pump is needed. In 287 B.C., Archimedes, a Greek mathematician, physicist, and mathematician, invented the screw pump (see Figure 3.1). 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

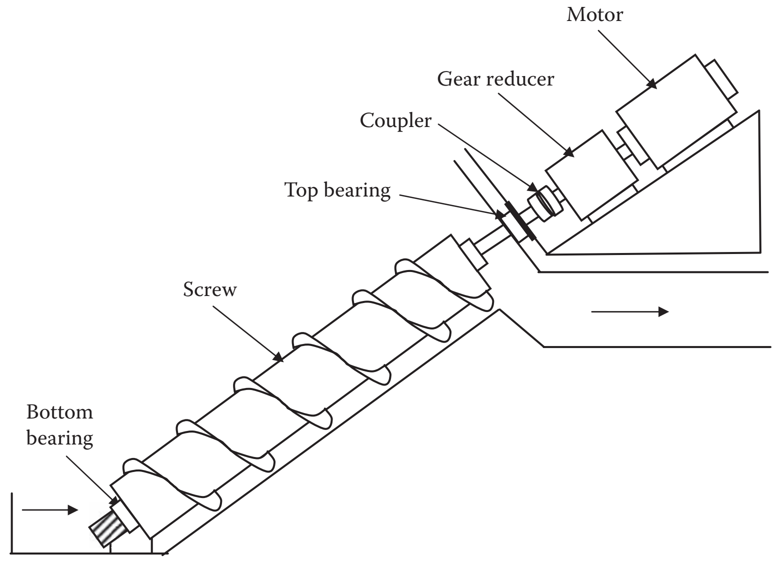

Figure 3.1 Archimedes's screw pump.

beginnings. The 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 moved from groundwater or a surface water body, from one unit treatment process to another, or to the 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. Water/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 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

3.2 BASIC PUMPING CALCULATIONS

Calculations, calculations, calculations, and more calculations! Yes, calculations; indeed, we cannot get away from them—not in wastewater treatment and collection 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 hydraulic 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 this section, although at a higher technical level.

3.2.1 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:

$$\text{Velocity } (V) \text{ (fps)} = \frac{\text{Flow } (Q) \text{ (cfs)}}{\text{Cross-Sectional Area } (A) \text{ (ft}^2\text{)}} \tag{3.1}$$

■ ***Example 3.1***

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 3.2***

Problem: If the same 9-MGD flow used in Example 3.1 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.

$$\text{Area}_1 \times \text{Velocity}_1 = \text{Area}_2 \times \text{Velocity}_2 \tag{3.2}$$

Note: The concept just explained is extremely important in the operation of a centrifugal pump and will be discussed further later.

3.2.2 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:

$$\text{Pressure}_1 \times \text{Velocity}_1 = \text{Pressure}_2 \times \text{Velocity}_2 \tag{3.3}$$

■ *Example 3.3*

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:

$$P_1 \times V_1 = P_2 \times V_2$$

$$4 \text{ psi} \times 3 \text{ fps} = P_2 \times 4 \text{ fps}$$

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 hydraulics principle that is very important to the operation of a centrifugal pump.

3.2.3 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:

$$\text{Static Head (ft)} = \text{Discharge Level (ft)} - \text{Supply Level (ft)} \tag{3.4}$$

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.

3.2.3.1 Static Suction Head

Static suction head refers to when the supply is located above the pump datum:

$$\text{Static Suction Head (ft)} = \text{Supply Level (ft)} - \text{Pump Level (ft)} \tag{3.5}$$

3.2.3.2 Static Suction Lift

Static suction lift refers to when the supply is located below the pump datum.

$$\text{Static Suction Lift (ft)} = \text{Pump Level (ft)} - \text{Supply Level (ft)} \tag{3.6}$$

3.2.3.3 Static Discharge Head

$$\text{Static Discharge Head (ft)} = \text{Discharge Level (ft)} - \text{Pump Datum (ft)} \tag{3.7}$$

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 suction head or suction lift.

For suction head:

$$\text{Total Static Head (ft)} = \text{Static Discharge Head (ft)} - \text{Static Suction Lift (ft)} \tag{3.8}$$

For suction lift:

$$\text{Total Static Head (ft)} = \text{Static Discharge Head (ft)} + \text{Static Suction Lift (ft)} \tag{3.9}$$

■ ***Example 3.4***

Problem: Refer to Figure 3.2 to determine total static head.

Solution:

$$\text{Static Suction Lift (ft)} = \text{Pump Level (ft)} - \text{Supply Level (ft)}$$

$$\text{Static Suction Lift} = 128\text{ ft} - 121\text{ ft} = 7\text{ ft}$$

Figure 3.2 For Example 3.4.

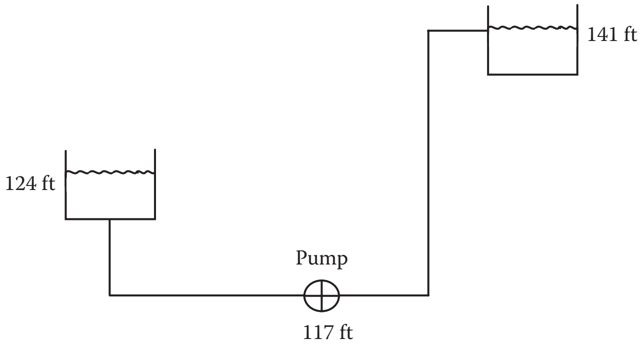

Figure 3.3 For Example 3.5.

$$\text{Static Discharge Head (ft)} = \text{Discharge Level (ft)} + \text{Static Suction Lift (ft)}$$

$$\text{Static Discharge Head} = 145\text{ ft} - 128\text{ ft} = 17\text{ ft}$$

$$\text{Total Static Head (ft)} = \text{Static Discharge Head (ft)} + \text{Static Suction Lift (ft)}$$

$$\text{Total Static Head} = 17\text{ ft} + 7\text{ ft} = 24\text{ ft}$$

or

$$\text{Total Static Head (ft)} = \text{Discharge Level (ft)} - \text{Supply Level (ft)}$$

$$\text{Total Static Head} = 145\text{ ft} - 119\text{ ft} = 24\text{ ft}$$

■ ***Example 3.5***

Problem: See Figure 3.3 to determine total static head.

Solution:

$$\text{Static Suction Head (ft)} = \text{Supply Level (ft)} - \text{Pump Level (ft)}$$

$$\text{Static Suction Head} = 124\text{ ft} - 117\text{ ft} = 7\text{ ft}$$

$$\text{Static Discharge Head (ft)} = \text{Discharge Level (ft)} - \text{Pump Level (ft)}$$

$$\text{Static Discharge Head} = 141\text{ ft} - 117\text{ ft} = 24\text{ ft}$$

$$\text{Total Static Head (ft)} = \text{Static Discharge Head (ft)} - \text{Static Suction Head (ft)}$$

$$\text{Total Static Head} = 24\text{ ft} - 7\text{ ft} = 17\text{ ft}$$

or

$$\text{Total Static Head (ft)} = \text{Discharge Level (ft)} - \text{Supply Level (ft)}$$

$$\text{Total Static Head} = 141\text{ ft} - 124\text{ ft} = 17\text{ ft}$$

3.2.4 Friction Head

Various formulae calculate friction losses. Hazen–Williams wrote 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.

$$\text{Friction Head (ft)} = \text{Roughness Factor } (f) \times \frac{\text{Length}}{\text{Diameter}} \times \frac{\text{Velocity}^2}{2g} \tag{3.10}$$

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 is normally in the range of .01 to .04.

■ *Example 3.6*

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:

$$\text{Friction Head} = \text{Roughness Factor (f)} \times \frac{\text{Length}}{\text{Diameter}} \times \frac{\text{Velocity}^2}{2g}$$

$$= 0.025 \times \frac{(150\text{ ft} + 75\text{ ft})}{0.5\text{ ft}} \times \frac{(3\text{ fps})^2}{2 \times 32\text{ ft/s}}$$

$$= 0.025 \times \frac{225\text{ ft}}{0.5\text{ ft}} \times \frac{9\text{ ft}^2/\text{s}^2}{64\text{ ft/s}^2} = 0.025 \times 450 \times 0.140\text{ ft} = 1.58\text{ ft}$$

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. The length of pipe
2. The diameter of the pipe
3. Velocity
4. Pipe equivalent of valves, elbows, T's, etc.

3.2.5 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:

$$\text{Velocity Head (ft)} = \frac{\text{Velocity}^2}{2g} \tag{3.11}$$

$$\begin{aligned}\text{Total Velocity Head (ft)} = {} & \text{Velocity Head Discharge (ft)} \\ & -\text{Velocity Head Suction (ft)}\end{aligned} \tag{3.12}$$

■ ***Example 3.7***

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.

3.2.6 Total Head

Total head is the sum of the static, friction, and velocity heads:

$$\begin{aligned}\text{Total Head (ft)} = {} & \text{Static Head (ft)} + \text{Friction Head (ft)} \\ & + \text{Velocity Head (ft)}\end{aligned} \tag{3.13}$$

3.2.7 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:

$$\text{Head (ft)} = \text{Pressure (psi)} \times 2.31\text{ ft/psi} \tag{3.14}$$

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 3.8*

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:

Head = Pressure (psi) × 2.31 ft/psi = 20 psi × 2.31 ft/psi = 46 ft (rounded)

Note: The pump must supply an additional head of 46 ft to overcome the internal pressure of the line.

3.2.8 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 ft-lb/s = 1 horsepower (hp)

or

33,000 ft-lb/min = 1 horsepower (hp)

A pump performs work when 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*.

3.2.8.1 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:

$$\text{WHP} = \frac{\text{Flow (gpm)} \times \text{Head (ft)} \times \text{Specific Gravity}}{3960} \tag{3.15}$$

Note: 3960 is derived by dividing 33,000 ft-lb by 8.34 lb/gal = 3960.

3.2.8.2 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 the 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; 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:

$$\text{Brake Horsepower (BHP)} = \frac{\text{Flow (gpm)} \times \text{Head (ft)} \times \text{Specific Gravity}}{3960 \times \text{Efficiency}} \tag{3.16}$$

3.2.9 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 called 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):

$$N_s = \frac{\text{rpm} \times Q^{0.5}}{H^{0.75}} \tag{3.17}$$

where:

rpm = revolutions per minute.

Q = flow (in gpm).

H = head (in ft).

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

3.2.9.1 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}:

$$N_{ss} = \frac{\text{rpm} \times Q^{0.5}}{\text{NPSHR}^{0.75}} \tag{3.18}$$

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 3.18 should be halved for double-suction pumps).

3.2.10 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):

$$Q_2/Q_1 = D_2/D_1 \tag{3.19}$$

$$H_2/H_1 = (D_2/D_1)^2 \tag{3.20}$$

$$BHP_2/BHP_1 = (D_2/D_1)^3 \tag{3.21}$$

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:

$$Q_2/Q_1 = N_2/N_1 \tag{3.22}$$

$$H_2/H_1 = (N_2/N_1)^2 \tag{3.23}$$

$$BHP_2/BHP_1 = (N_2/N_1)^3 \tag{3.24}$$

where:

N_1 = initial rpm.

N_2 = changed rpm.

■ *Example 3.9*

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) when the 8-in.-diameter data are:

Q_1 = 340 rpm

H_1 = 110 ft

BHP_1 = 10

Solution: Data for the 9-in. impeller diameter would be as follows:

$Q_2 = 340 \times 9/8 = 383$ gpm

$H_2 = 110 \times (9/8)^2 = 139$ ft

$BHP_2 = 10 \times (9/8)^3 = 14$

3.2.11 Net Positive Suction Head

In Volume I of this handbook, 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 for 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) defined 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.

3.2.11.1 Calculating NPSHA

In the following two examples, we demonstrate how to calculate NPSH 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.

3.2.11.1.1 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 3.4 and Figure 3.5. The formula for calculating NPSHA is:

$$\text{NPSHA} = P_a + h - P_v - h_e - h_f \tag{3.25}$$

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.

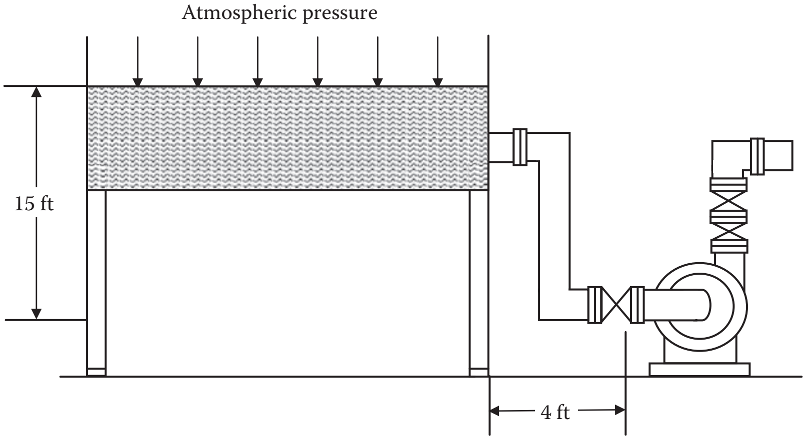

Figure 3.4 Open atmospheric tank.

■ ***Example 3.10***

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

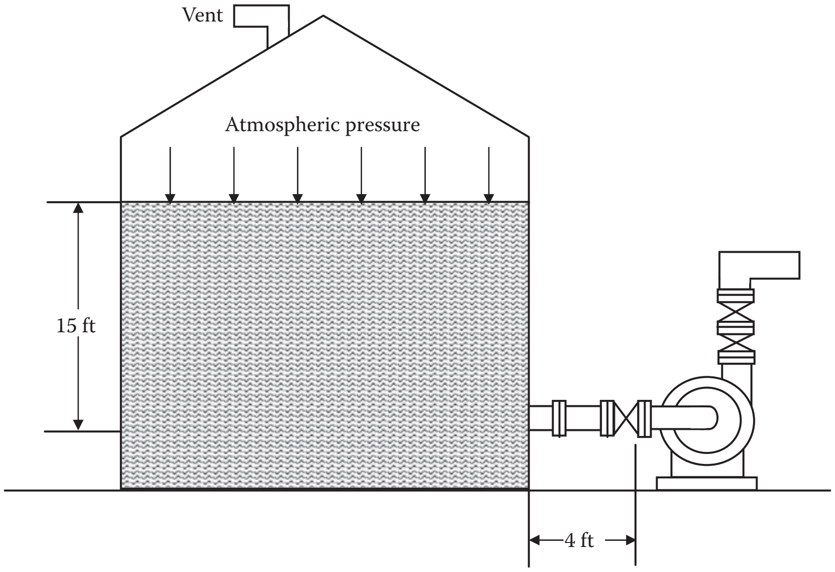

Figure 3.5 Roofed water storage tank.

Solution:

$$\text{NPSHA} = 34\text{ ft} + 15\text{ ft} - 0.6\text{ ft} - 0.4\text{ ft} - 2\text{ ft} = 46\text{ ft}$$

3.2.11.1.2 NPSHA: Suction Lift from Open Reservoir

■ ***Example 3.11***

Problem: Find the NPSHA in Figure 3.6, 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)

h_e = 0.4 ft

h_f = 2 ft

Q = 120 gpm

Solution:

$$\text{NPSHA} = 34\text{ ft} + (-20\text{ ft}) - 0.6\text{ ft} - 0.4\text{ ft} - 2\text{ ft} = 11\text{ ft}$$

3.2.12 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

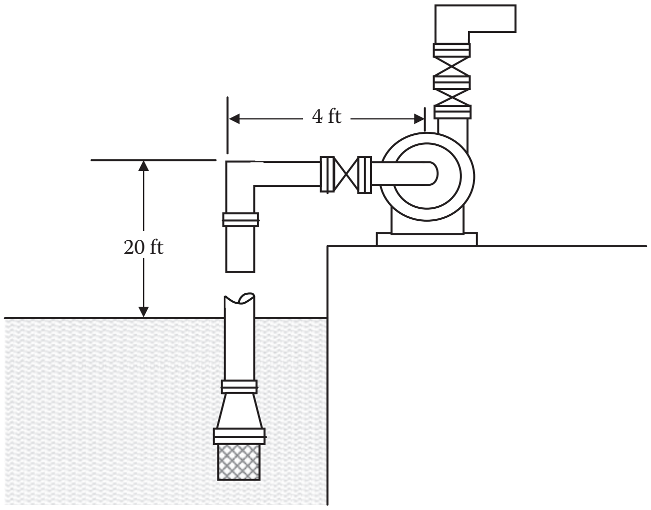

Figure 3.6 Suction lift from open reservoir.

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.

3.3 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 (or 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.

3.3.1 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 3.7.

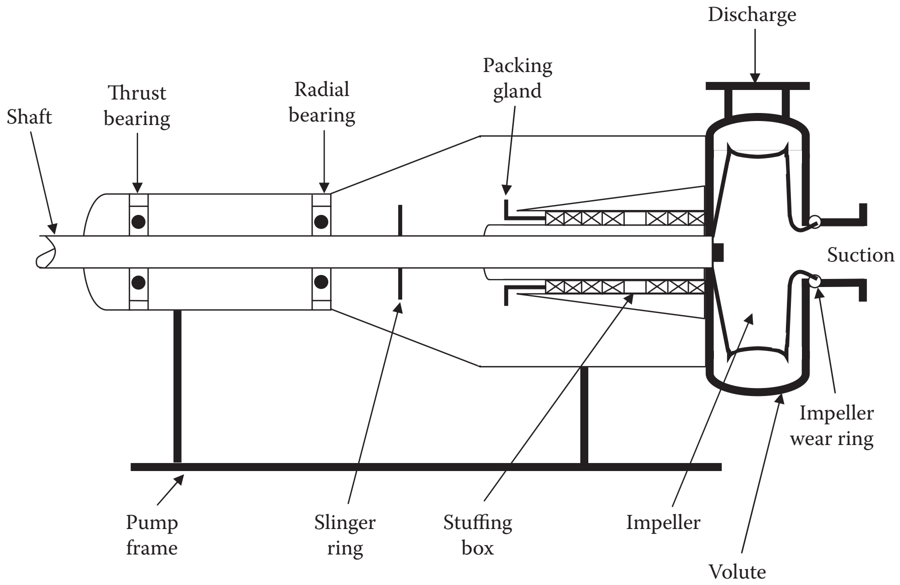

Figure 3.7 Major components of a centrifugal pump.

3.3.2 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 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 closet to the pump. It rides free in its own section and takes up and down stresses.
- *Thrust bearing*—In a single-suction pump, this 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. Mechanical seals 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).

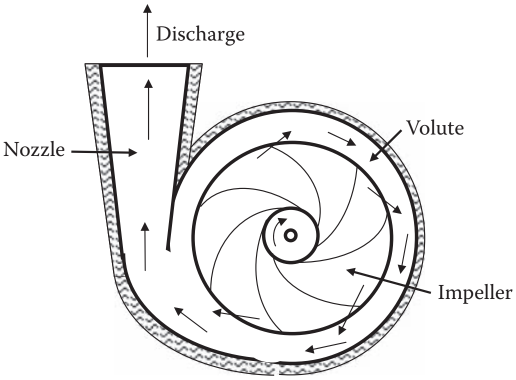

Figure 3.8 Cross-sectional diagram showing the features of a centrifugal pump.

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 ring—Device that is 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 a *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.

3.3.3 Pump Theory

The *volute-cased centrifugal pump* (see Figure 3.8) 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 it 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 3.8). 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.

3.3.4 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.

3.3.4.1 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 will decrease 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 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.

3.3.4.2 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.

3.3.4.3 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.

3.3.5 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 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 that 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 backwards 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.

3.3.6 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 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 is used.

3.3.7 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

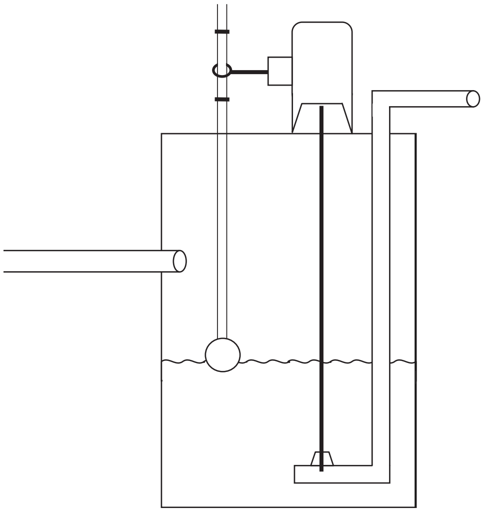

Figure 3.9 Float system for pump motor control.

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. In the following sections, we briefly describe the operation of various types of control devices used with centrifugal pumps.

3.3.7.1 Float Control

Currently, the *float control system* is the simplest of the centrifugal pump controls (see Figure 3.9). 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.

3.3.7.2 Pneumatic Controls

Pneumatic control systems (also known as *bubbler tube control systems*) are relatively simple systems 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 or basin; and pressure-sensitive switches with varying on/off set points and a pressure-relief valve (see Figure 3.10). The system works on the basic principle of measuring the depth of the water in the well or tank by determining the

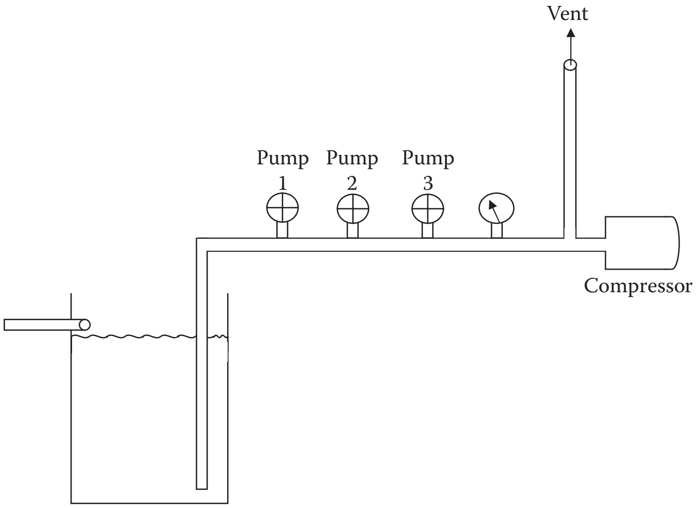

Figure 3.10 Pneumatic system for pump motor control.

air pressure necessary to just release a bubble from the bottom of the tube (see Figure 3.10)—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 airline 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 that will activate at a third preset well or tank depth (e.g., 4.6 ft/1.99 psi) and cut off a preset depth (e.g., 3.0 ft/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.

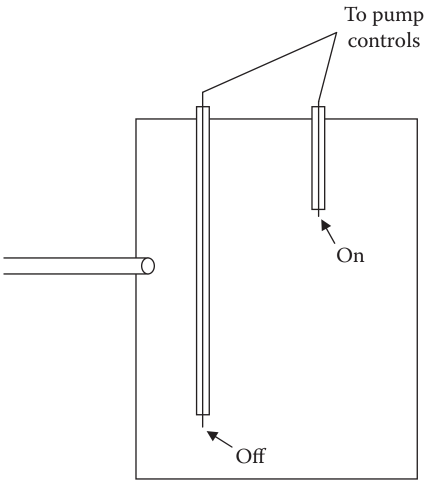

Figure 3.11 Electrode system for pump motor control.

3.3.7.3 Electrode Control Systems

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 3.11). 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.

3.3.7.4 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 3.12). 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 installing 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.

3.3.8 Electronic 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.

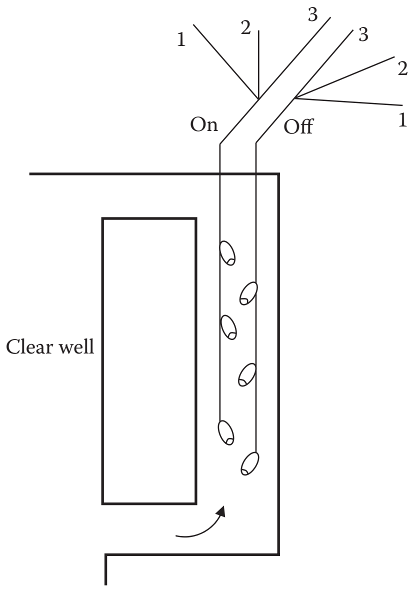

Figure 3.12 Electrical contacts for pump motor control.

3.3.8.1 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.

3.3.8.2 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.

3.3.8.3 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

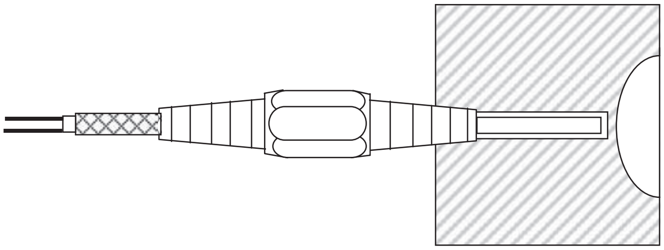

Figure 3.13 Thermocouple installation in journal bearing.

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.

3.3.8.4 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.

3.3.8.5 Temperature Detectors

Resistance temperature devices (RTDs) and *thermocouples* (see Figure 3.13) (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.

3.3.8.6 Vibration Monitors

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):

- 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

3.3.8.7 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.

3.3.9 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

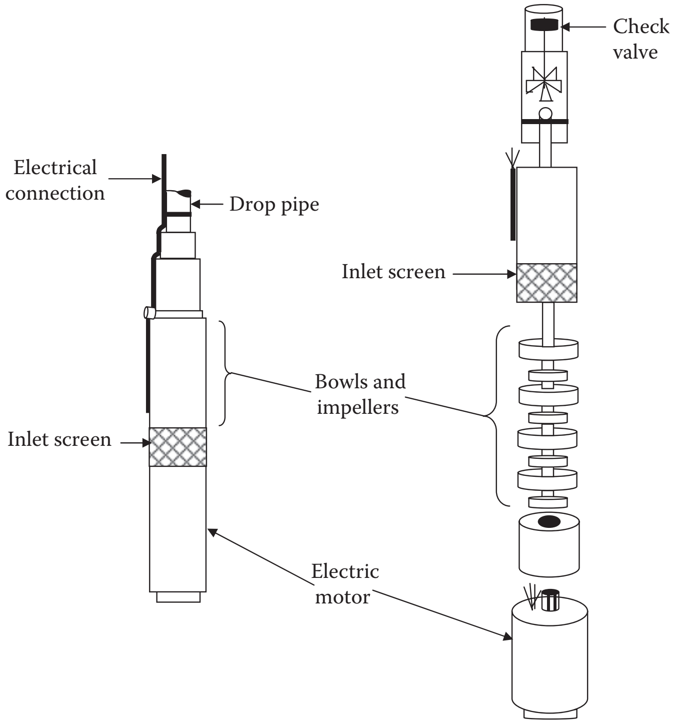

Figure 3.14 Submersible pump.

3.3.9.1 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 3.14 illustrates this system.

3.3.9.1.1 Description

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.

3.3.9.1.2 Applications

The submersible pump has wide applications in the 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.

3.3.9.1.3 Advantages

In addition to the advantages discussed earlier for a conventional centrifugal pump, the submersible pump has additional advantages:

- 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.

3.3.9.1.4 Disadvantages

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.

3.3.9.2 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 3.15). 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.

3.3.9.2.1 Applications

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.

3.3.9.2.2 Advantages

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.

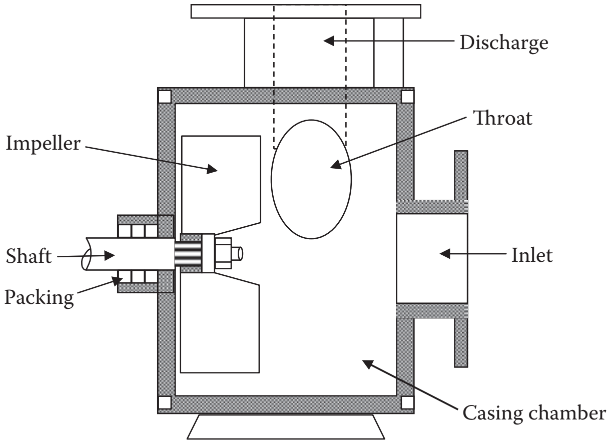

Figure 3.15 Schematic of a recessed impeller or vortex pump.

3.3.9.2.3 Disadvantages

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 the application of this 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 be passed into a less accessible location where it becomes 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.

3.3.9.3 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 3.16). 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.

3.3.9.3.1 Application

Due to the construction of the turbine pump, the major applications have traditionally been for pumping relatively clean water. The line shaft turbine pump has been used extensively for pumping drinking water, 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.

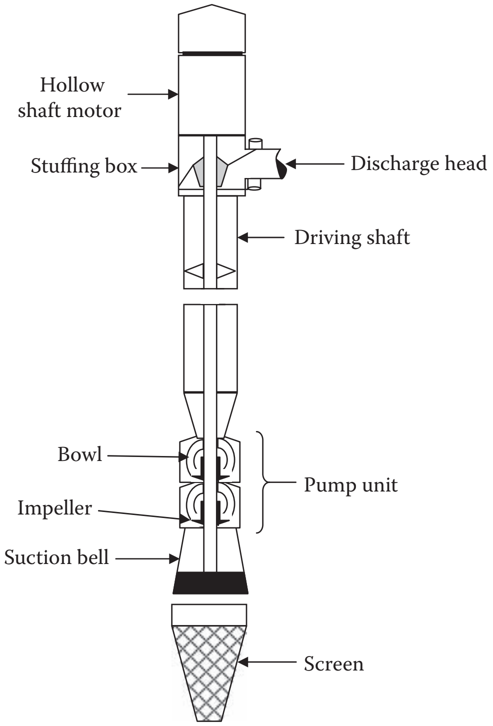

Figure 3.16 Vertical turbine pump.

3.3.9.3.2 Advantages

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.

3.3.9.3.3 Disadvantages

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.

3.4 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. Other positive-displacement pumps include piston pumps, diaphragm pumps, and peristaltic pumps, which are the focus of our discussion. 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.

3.4.1 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. 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.

3.4.2 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 assembly and a discharge valve assembly (see Figure 3.17). 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 they do not work well if

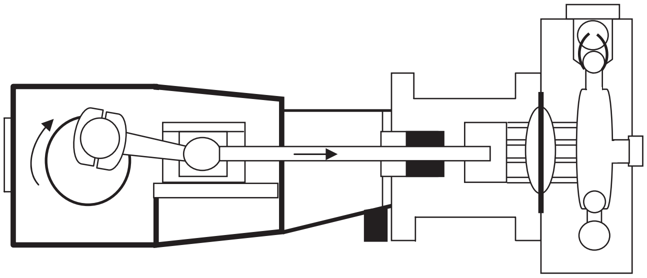

Figure 3.17 Diaphragm pump.

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.

3.4.3 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 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 the periodic replacement of the tubing in the pump head. This type of pump has no check valves or diaphragms.

3.5 CHAPTER REVIEW QUESTIONS

3.1 Applications in which chemicals must be metered under high pressure require high-powered ____________ pumps.

3.2 ____________ materials are materials that resist any flow-producing force.

3.3 What type of pump is usually used for pumping high-viscosity materials?

3.4 High-powered positive-displacement pumps are used to pump chemicals that are under ____________ pressure.

3.5 ____________ viscosity materials are thick.

3.6 When the ____________ of a pump impeller is above the level of the pumped fluid, the condition is called *suction lift*.

3.7 When a pump is not running, the conditions are referred to as ____________; when a pump is running, the conditions are ____________.

3.8 With the ____________, the difference in elevation between the suction and discharge liquid levels is called *static head*.

3.9 Velocity head is expressed mathematically as ____________.

3.10 The sum of total static head, head loss, and dynamic head is called ____________.

3.11 What are the three basic types of curves used for centrifugal pumps?

3.12 What liquid is used to rate pump capacity?

3.13 Because of the reduced amount of air pressure at high altitudes, less __________ is available for the pump.

3.14 With the pump shut off, the difference between the suction and discharge liquid levels is called __________.

3.15 __________ and __________ are the largest contributing factors to the reduction of pressure at a pump impeller.

3.16 The operation of a centrifugal pump is based on __________.

3.17 The casing of a pump encloses the pump impeller, the shaft, and the __________.

3.18 What part of the pump supplies energy to the fluid?

3.19 If wearing rings are used only on the volute case, we must replace the __________ and __________ at the same time.

3.20 Which part of the end suction pump directs water flow into and out of the pump?

3.21 What is the function of the pump's impeller?

3.22 What type of pump has no bearings?

3.23 __________ split casings split perpendicular to the pump shaft.

3.24 Name three types of impellers.

3.25 What type of casing adds a guiding vane to the fluid passage?

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CHAPTER 4

WASTEWATER CONVEYANCE

> The design considerations for the piping system are the function of the specifics of the system. However, all piping systems have a few common issues: The pipe strength must be able to resist internal pressure, handling, and earth and traffic loads; the pipe characteristics must enable the pipe to withstand corrosion and abrasion and expansion and contraction of the pipeline (if the line is exposed to atmospheric conditions); engineers must select the appropriate pipe support, bedding, and backfill conditions; the design must account for the potential for pipe failure at the connection point to the basins due to subsidence of a massive structure; and the composition of the pipe must not give rise to any adverse effects on the health of consumers.
>
> **Kawamura (1999)**

4.1 INTRODUCTION

Wastewater conveyance or piping systems resemble veins, arteries, and capillaries. According to Nayyar (2000), "They convey waste from residential and commercial buildings and other civic facilities to the treatment facility or the point of discharge." Wastewater operators must be familiar with piping, piping systems, and the many components that make piping systems function. Operators are directly concerned with various forms of piping, tubing, hose, and the fittings that connect these components to create workable systems. This chapter covers important, practical information about the piping systems that are a vital part of plant operation and essential to the success of the total activity. To prevent major system trouble, skilled operators are called upon to perform the important function of preventive maintenance to avoid major breakdowns, and they must be able to make needed repairs when breakdowns do occur. A comprehensive knowledge of piping systems and accoutrements is essential to maintaining plant operations.

4.2 CONVEYANCE SYSTEMS

With regard to early conveyance systems, the prevailing practice in medieval England was the use of closed pipes. This practice was contrary to the Romans, who generally employed open channels in their long-distance aqueducts and used pipes mainly to distribute water within cities. The English preferred to lay long runs of pipes from the water source to the final destination. The Italians, on the other hand, whose antique aqueduct arches are still visible, seem to have had more of a tendency to follow the Roman tradition of long-distance channel conduits. At least some of the channel aqueducts seem to have fed local distribution systems of lead or earthenware pipes (Magnusson, 2001).

With today's water and wastewater conveyance, not that much has changed from the past. Our goals today remain the same: (1) Convey water from source to treatment facility to user, and (2) convey wastewater from user to treatment to the environment. In wastewater operations, the term *conveyance* or *piping system* refers to a complete network of pipes, valves, and other components. For wastewater operations in particular, the piping system is all inclusive; it includes both the network of pipes, valves, and other components that bring the flow (influent) to the treatment facility, as well as the piping, valves, and other components that convey treated wastewater to outfall. In short, all piping systems are designed to perform a specific function.

Probably the best way to illustrate the importance of piping systems is to describe many of their applications in wastewater operations. In the modern wastewater treatment plant, piping systems are critical to successful operation. In wastewater operations, fluids and gases (chemicals and air) are used extensively in processing operations; they usually are conveyed through pipes. Piping carries wastewater into the plant for treatment, fuel oil to heating units, steam to steam services, lubricants to machinery, compressed air to pneumatic service outlets for air-powered tools, and chemicals to unit processes. In addition to wastewater influent and treated wastewater effluent, the materials conveyed through piping systems can include oils, chemicals, liquefied gases, acids, paints, and sludge, among many others. Thus, a wastewater treatment plant has many piping systems, not just the systems that convey wastewater. Along with those mentioned here, keep in mind that plant piping systems also include those that provide hot and cold water for plant personnel use. Another system heats the plant, while still another may be used for air conditioning.

Wastewater operators have many responsibilities and requisite basic skills. The typical plant operator is skilled in heating, ventilating, and air conditioning (HVAC) systems; chemical feed systems; mechanical equipment operation and repair; and piping system maintenance; however, only the fluid transfer systems themselves are important to us in this text.

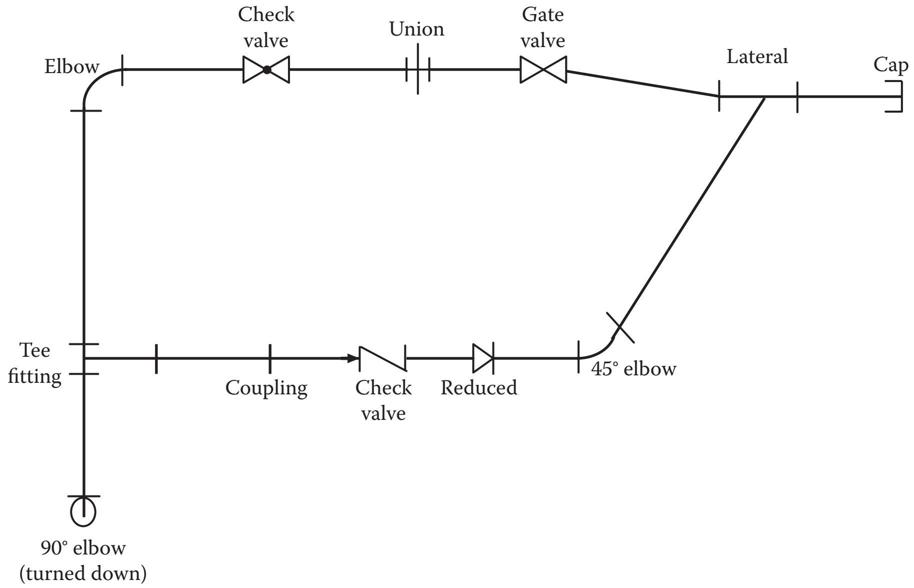


Figure 4.1 Various components in a single-line piping diagram.

For wastewater operators, a familiar example of a piping system is the network of sodium hypochlorite pipes in treatment plants that use this chemical for disinfection and other purposes. The whole group of components—pipes, fittings, and valves—working together for one purpose makes up a *system*. This particular system has a definite purpose—to carry sodium hypochlorite and distribute it, conveying it to point of application.

Note: This chapter is concerned only with the piping system used to circulate the chemical, not with the hypochlorination equipment itself. Our concern begins where the chemical outlet is connected to the storage tank and continues to the point where the pipe is connected to the point of application. The piping, fittings, and valves of the hypochlorination pipeline (and others) are important to us. Gate, needle, pressure-relief, air-and-vacuum relief, diaphragm, pinch butterfly, check, rotary, and globe valves; traps; expansion joints; plugs; elbows; tee fittings; couplings; reducers; laterals; caps; and other fittings help ensure the effective flow of fluids through the lines. Tracing a piping system through a plant site will reveal many of them (see Figure 4.1). They are important because they are directly related to the operation of the system. Piping system maintenance is concerned with keeping the system functioning properly, and to function properly piping systems must be kept closed and leakproof.

Note: Figure 4.1 shows a single-line diagram that is similar to an electrical schematic. It uses symbols for all the diagram components. A double-line diagram (not shown here) is a pictorial view of the pipe, joints, valves, and other major components similar to an electrical wiring diagram, instead of an electrical schematic.

4.3 DEFINITIONS

Key terms related to wastewater conveyance are listed and defined in this section.

Absolute pressure—Gauge pressure plus atmospheric pressure.

Alloy—A substance composed of two or more metals.

Annealing—Heating and then cooling a metal to make it softer and less brittle.

Asbestos—Fibrous mineral form of magnesium silicate.

Backsiphonage—A condition in which the pressure in the distribution system is less than atmospheric pressure, which allows contamination to enter a water system through a cross-connection.

Bellows—A device that uses a bellows for measuring pressure.

Bimetallic—Made of two different types of metal.

Bourdon tube—A semicircular tube of elliptical cross-section, used to sense pressure changes.

Brazing—Soldering with a nonferrous alloy that melts at a lower temperature than that of the metals being joined; also known as *hard soldering*.

Butterfly valve—A valve in which a disk rotates on a shaft as the valve opens and closes. In the full open position, the disk is parallel to the axis of the pipe.

Carcass—The reinforcement layers of a hose, between the inner tube and the outer cover.

Cast iron—A generic term for the family of high carbon–silicon–iron casting alloys including gray, white, malleable, and ductile iron.

Check valve—A valve that is designed to open in the direction of normal flow and to close with a reversal of flow. An approved check valve has substantial construction and suitable materials, is positive in closing, and permits no leakage in a direction opposite to normal flow.

Condensate—Steam that condenses into water in a piping system.

Diaphragm valve—A valve in which the closing element is a thin, flexible disk; often used in low-pressure systems.

Differential pressure—The difference between the inlet and outlet pressures in a piping system.

Double-line diagram—Pictorial view of the pipes, joints, valves, and other major components similar to an electrical wiring diagram.

Ductile—A term applied to a metal that can be fashioned into a new form without breaking.

Expansion joint—Absorbs thermal expansion and contraction in piping systems.

Extruding—Process of shaping a metal or plastic by forcing it through a die.

Ferrous—A term applied to a metal that contains iron.

Ferrule—A short bushing used to make a tight connection.

Filter—An accessory fitting used to remove solids from a fluid stream.

Fluid—Any substance that flows.

Flux—Used in soldering to prevent the formation of oxides during the soldering operation and to increase the wetting action so solder can flow more freely.

Friable—Readily crumbled by hand.

Gate valve—A valve in which the closing element consists of a disk that slides across an opening to stop the flow of water.

Gauge pressure—The amount by which the total absolute pressure exceeds the ambient atmospheric pressure.

Globe valve—A valve having a round, ball-like shell and horizontal disk.

Joint—A connection between two lengths of pipe or between a length of pipe and a fitting.

Laminar—Flow arranged in or consisting of thin layers.

Mandrel—A central core or spindle around which material may be shaped.

Metallurgy—The science and study of metals.

Neoprene—A synthetic material that is highly resistant to oil, flame, various chemicals, and weathering.

Nominal pipe size—The thickness given in the product material specifications or standard to which manufacturing tolerances are applied.

Nonferrous—A term applied to a material that does not contain iron.

Piping systems—A complete network of pipes, valves, and other components.

Ply—One of several thin sheets or layers of material.

Pressure-regulating valve—A valve with a horizontal disk for automatically reducing water pressures in a main to a preset value.

Prestressed concrete—Concrete that has been compressed with wires or rods to reduce or eliminate cracking and tensile forces.

PVC—Polyvinyl chloride plastic pipe.

Schedule—Approximate value of the expression $1000P/S$, where P is the service pressure and S is the allowable stress, both expressed in pounds per square inch.

Single-line diagram—Uses symbols for all the diagram components.

Soldering—A form of brazing that utilizes nonferrous filler metals having melting temperatures below 800°F (427°C). The filler material is called *solder* and is distributed between surfaces by *capillary action.*

Solenoid—An electrically energized coil of wire surrounding a movable iron case.

Stainless steel—An alloy steel having unusual corrosion-resisting properties, usually imparted by nickel and chromium.

Strainer—An accessory fitting used to remove large particles of foreign matter from a fluid.

Throttle—Controlling flow through a valve by means of intermediate steps between fully open and fully closed.

Tinning—Covering metal to be soldered with a thin coat of solder to work properly. Overheating or failure to keep the metal clean causes the point to become covered with oxide. The process of replacing this coat of oxide is tinning.

Trap—An accessory fitting used to remove condensate from steam lines.

Vacuum breaker—A mechanical device that allows air into the piping system, thereby preventing backflow that could otherwise be caused by the siphoning action created by a partial vacuum.

Viscosity—The thickness or resistance to flow of a liquid.

Vitrified clay—Clay that has been treated in a kiln to produce a glazed, watertight surface.

Water hammer—The concussion of moving water against the sides of a pipe, caused by a sudden change in the rate of flow or stoppage of flow in the line.

4.4 FLUIDS VS. LIQUIDS

We use the term *fluids* throughout this text to describe the substances being conveyed through various piping systems from one part of the plant to another. We normally think of pipes conveying some type of liquid substance, which most of us take to have the same meaning as fluid; however, a subtle difference exists between the two terms. The dictionary's definition of *fluid* is any substance that flows—which can mean a liquid or gas (e.g., air, oxygen, nitrogen). Some fluids carried by piping systems include thick viscous mixtures such as sludge in a semifluid state. Although sludge and other such materials might seem more solid (at times) than liquid, they do flow and are considered fluids. In addition to carrying liquids such as oil, hydraulic fluids, and chemicals, piping systems carry compressed air and steam, which also are considered fluids because they flow.

Key Point: Fluids travel through a piping system at various pressures, temperature, and speeds.

4.5 MAINTAINING FLUID FLOW IN PIPING SYSTEMS

The primary purpose of any piping system is to maintain free and smooth flow of fluids through the system. Another purpose is to ensure that the fluids being conveyed are kept in good condition (i.e., free of contamination). Piping systems are purposely designed to ensure free and smooth flow of fluids throughout the system, but additional system components are often included to ensure that fluid quality is maintained. Piping system filters are one example, and strainers and traps are two others.

It is extremely important to maintain free and smooth flow and fluid quality in piping systems, especially those that feed vital pieces of equipment or machinery. Consider the internal combustion engine, for example. Impurities such as dirt and metal particles can damage internal components and cause excessive wear and eventual breakdown. To help prevent such wear, the oil is run continuously through a filter designed to trap and filter out the impurities.

Other piping systems require the same type of protection that the internal combustion engine does, which is why most piping systems include filters, strainers, and traps. These filtering components may prevent damage to valves, fittings, the pipe itself, and downstream equipment or machinery. Chemicals, various types of waste products, paint, and pressurized steam are good examples of potentially damaging fluids. Filters and strainers play an important role in piping systems—protecting both the piping system and the equipment that the piping system serves.

4.5.1 Scaling

Because sodium and calcium hypochlorite are widely used in wastewater treatment operations, problems common in piping systems feeding this chemical are of special concern. In this section, we discuss *scaling* problems that can occur in piping systems that convey hypochlorite solution. To maintain the chlorine in solution (used primarily as a disinfectant), sodium hydroxide (caustic) is used to raise the pH of the hypochlorite; the excess caustic raises the shelf life. A high pH caustic solution raises the pH of the dilution water to over pH 9.0 after it is diluted. The calcium in the dilution water reacts with dissolved CO_2 and forms calcium carbonate. Experience has shown that 2-inch pipes can turn into 3/4-inch pipes due to scale buildup. The scale deposition is greatest in areas of turbulence such as pumps, valves, rotameters, and backpressure devices.

If lime (calcium oxide) is added for alkalinity, plant water used as dilution water will have higher calcium levels and generate more scale. Although it is true that softened water will not generate scale, it is also true that it is expensive in large quantities. Many facilities use softened water on hypochlorite mist odor scrubbers only.

Scaling also often occurs in solution rotameters, making flow readings impossible and freezing the flow indicator in place. Various valves can freeze up, and pressure-sustaining valves can freeze and become plugged. Various small diffuser holes fill with scale. To slow the rate of scaling, many facilities purchase water from local suppliers to dilute hypochlorite for the return activated sludge and miscellaneous uses. Some facilities have experimented with the system by not adding lime to it. When they did this, manganese dioxide (black deposits) developed on the rotameter glass, making viewing the float impossible. In many instances, moving the point of hypochlorite addition downstream of the rotameter seems to solve the problem.

If remedial steps are not taken, scaling from hypochlorite solutions can cause problems; for example, scale buildup can reduce the inside diameter of a pipe so much that the actual supply of hypochlorite solution required to properly disinfect water or wastewater is reduced. As a result, the water sent to the customer or outfalled to the receiving body may not be properly disinfected. Because of the scale buildup, the treatment system itself will not function as designed and could result in a hazardous situation in which the reduced pipe size increases the pressure level to the point of catastrophic failure. Scaling, corrosion, or other clogging problems in certain piping systems are far from an ideal situation.

■ *Example 4.1*

The scale problem can be illustrated by the use of an example. Assume that we have a piping system that is designed to provide chemical feed to a critical plant unit process. The motive force for conveying the chemical is provided by a positive-displacement pump at a given volume of solution at 70 psi through clean pipe. After clogging takes place, the pump continues trying to force the same volume of chemical through the system at 70 psi, but the pressure drops to 25 psi because of friction. The reduction of the inside diameter of the pipe increases the friction between the chemical solution and the inside wall of the pipe.

Key Point: A basic principle in fluid mechanics states that fluid flowing through a pipe is affected by friction—the greater the friction, the greater the loss of pressure. Another principle or rule states that the amount of friction increases as the square of the velocity. (Note that speed and velocity are not the same, but common practice refers to the "velocity" of a fluid.) In short, if the velocity of the fluid doubles, the friction is increased four times what it was before. If the velocity is multiplied by 5, the friction is multiplied by 25, and so on.

In Example 4.1, the pressure dropped from 70 psi to 25 psi because the solution had to run faster to move through the pipe. Because the velocity of the solution pushed by the pump had to increase to levels above those when the pipe was clean, the friction increased at a higher rate than before. The friction loss was the reason why a pressure of 25 psi arrived at the far end of the piping system. The equipment designed to operate at a pressure of 70 psi could not work on the 25 psi of pressure being supplied.

What is the solution to our pressure loss problem in Example 4.1? Actually, we can solve this problem in two possible ways—we can either replace the piping or clean it. Replacing the piping or cleaning sounds simple and straightforward, but it can be complicated. If the pipe is relatively short, no more than 20 to a few hundred feet in length, then we may decide to replace the pipe. But, what would we do if the pipe were 3 to 5 miles or more in length? In this case, cleaning such a length of pipe probably makes more sense than replacing its entire length. Each situation is different, requiring remedial choices based on practicality and expense.

Key Point: After reading the previous example, you might ask: "Why couldn't the pump be slowed down so the chemical solution could pass more slowly through the system, thus avoiding the effect of increased friction?" The lower pressure that results as pump speed is reduced causes other problems as well. Pumps that run at a speed other than that for which they are designed do so with a reduction in efficiency.

4.5.2 Piping System Maintenance

Maintaining a piping system can be an involved process; however, good maintenance practices can extend the life of piping system components, and rehabilitation can further prolong their life. The performance of a piping system depends on the ability of the pipe to resist unfavorable conditions and to operate at or near the capacity and efficiency that it was designed for. This performance can be checked in several ways: flow measurement, fire flow tests, loss-of-head tests, pressure tests, simultaneous flow and pressure tests, tests for leakage, and chemical and bacteriological water tests. These tests are an important part of system maintenance. They should be scheduled as part of the regular operation of the system (AWWA, 1996).

Most piping systems are designed with various protective features included to minimize wear and catastrophic failure, as well as the amount of maintenance required. Such protective features include pressure-relief valves, blow-off valves, and clean-out plugs:

Pressure-relief valve—A valve that opens automatically when the fluid pressure reaches a preset limit to relieve the stress on a piping system.

Blow-off valve—A valve that can be opened to blow out any foreign material in a pipe.

Clean-out plug—A threaded plug that can be removed to allow access to the inside of the pipe for cleaning.

Note: Use caution when removing a clean-out plug from a piping system. Before removing the plug, pressure must be cut off and the system bled of residual pressure. Many piping systems (including wastewater lines and interceptors) can be cleaned either by running chemical solvents through the lines or by using mechanical clean-out devices.

4.6 PIPING SYSTEM ACCESSORIES

Depending on the complexity of the piping system, the number of valves included in a system can range from no more than one in a small, simple system to a large number in very complex systems such as water distributions systems. Valves are necessary for both the operation of a piping system and control of the system and system components. In wastewater treatment, this control function is used to control various unit processes, pumps, and other equipment. Valves also function as protective devices; for example, valves used to protect a piping system may be designed to open automatically to vent fluid out of the pipe when the pressure in the lines becomes too high. In lines that carry liquids, relief valves preset to open at a given pressure are commonly used. The size and type of valve are selected depending on its intended use. Most valves require periodic inspection to ensure that they are operating properly.

Key Point: Not all valves function as safety valves; for example, hand-operated gate and globe valves function primarily as control valves.

Along with valves, piping systems typically include accessories such as pressure and temperature gauges, filters, strainers, pipe hangers, and supports:

Pressure gauges indicate the pressure in the piping system.

Temperature gauges indicate the temperature in the piping system.

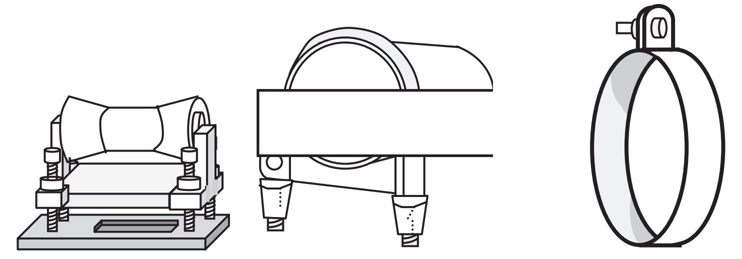
Filters and *strainers* are installed in piping systems to help keep fluids clean and free from impurities.

Pipe hangers and supports support piping to keep the lines straight and prevent sagging, especially in long runs. Various types of pipe hangers and supports are shown in Figure 4.2.

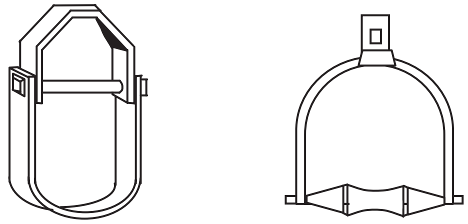
4.7 PIPING SYSTEMS: TEMPERATURE EFFECTS AND INSULATION

Most materials, especially metals, expand as the temperature increases and contract as the temperature decreases. This can be a significant problem in piping systems. To combat this problem and to allow for expansion and contraction in piping systems, *expansion joints* must be installed in the line between sections of rigid pipe. An expansion joint absorbs thermal expansion and terminal movement; as the pipe sections expand or contract with changing temperatures, the expansion joint expands or compresses accordingly, eliminating stress on the pipes.

Piping system temperature requirements also have an impact on how pipes are insulated; for example, we do not have to wander too far in most plant sites to find pipes covered with layers of piping insulation. Piping insulation amounts to wrapping the pipe in an envelope of insulating material. The thickness of the insulation depends on the application. Under normal circumstances, heat passes from a hot or warm surface to a cold or cooler one. Insulation helps prevent hot fluid from cooling as it passes through the system. For systems conveying cold fluid, insulation helps keep the fluid cold. Materials used for insulation vary, and they are selected according to the requirements of the application. Various types of insulating materials are also used to protect underground piping against rusting and corrosion caused by exposure to water and chemicals in the soil.



Adjustable pipe roll stand Anchor chair Standard ring and bolt hanger



Adjustable clevis and band hanger Adjustable swivel pipe roll

Figure 4.2 Pipe hangers and supports.

4.8 METALLIC PIPING

Pipe materials that are used to transport water may also be used to collect wastewater. It is more usual, however, to employ less expensive materials because wastewater lines rarely are required to withstand any internal pressure. Iron and steel pipe are used to convey wastewater only under unusual loading conditions or for force mains (interceptor lines) in which the wastewater flow is pressurized (McGhee, 1991).

4.8.1 Piping Materials

Materials selected for piping applications must be chosen keeping in mind the physical characteristics necessary for the intended service; for example, the piping material selected must be suitable for the flow medium and the given operating conditions of temperature and pressure during the intended design life of the product. For long-term service capability, the mechanical strength of the material must be appropriate; the piping material must be able to resist operational variables such as thermal or mechanical cycling. Extremes in application temperature must also be taken into account with respect to material capabilities.

Environmental factors must also be considered. The operating environment surrounding the pipe or piping components affects pipe durability and life span. Corrosion, erosion, or a combination of the two can result in degradation of material properties or loss of effective load-carrying cross-section. The nature of the substance contained by the piping is an important factor, as well.

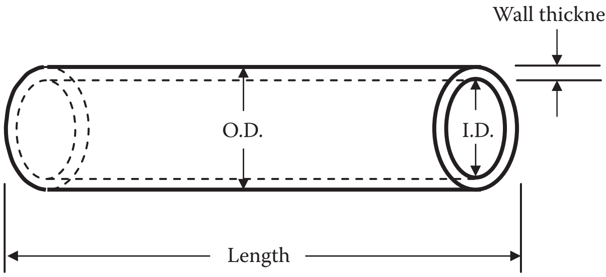


Figure 4.3 Pipe terminology.

Knowledge of the basic characteristics of the metals and nonmetals used for piping provides clues to the uses of the piping materials with which we work in water/wastewater treatment operations. Such knowledge is especially helpful to operators, making their job much easier and more interesting. In this section, metallic piping is discussed. Piping joints, how to join or connect sections of metallic piping, and how to maintain metallic pipe are also discussed.

4.8.2 Piping: The Basics

Earlier, we pointed out that piping includes pipe, flanges, fittings, bolting, gaskets, valves, and the pressure-containing portions of other piping components. Piping also includes pipe hangers and supports and other accessories necessary to prevent overpressurization and overstressing of the pressure-containing components. From a system viewpoint, a pipe is one element or a part of piping. Accordingly, when joined with fittings, valves, and other mechanical devices or equipment, pipe sections are called *piping*.

Note: A *pipe* is a tube with round cross-section conforming to the dimensional requirements of ASME B36.10M (Welded and Seamless Wrought Steel Pipe) and ASME B36.19M (Stainless Steel Pipe) (Nayyar, 2000).

4.8.3 Pipe Sizes

With time and technological advancements (development of stronger and corrosion-resistant piping materials), pipe sizes have become standardized and are usually expressed in inches or fractions of inches. As a rule, the size of a pipe is given in terms of its outside or inside diameter. Figure 4.3 shows the terminology that applies to a section of pipe. Pipes are designated by diameter. The principal dimensions are as follows:

- *Wall thickness*
- *Length*
- *Outside diameter* (O.D.), which is used to designate pipe greater than 12 inches in diameter
- *Inside diameter* (I.D.), which is used to designate pipe less than 12 inches in diameter

Note: Another important pipe consideration not listed above or shown in Figure 4.3 is *weight per foot*, which varies according to the pipe material and wall thickness.

In the continuing effort to standardize pipe size and wall thickness of pipe, the designation *nominal pipe size* (NPS) replaced the iron pipe size designation, and the term *schedule* (SCH) is used to specify the nominal wall thickness of pipe. The NPS (approximate dimensionless designator of pipe size) is generally somewhat different from its actual diameter; for example, the pipe we refer to as a "3-in.-diameter pipe" has an actual O.D. of 3.5 in., while the actual O.D. of a "12-in. pipe" may be .075 in. greater (i.e., 12.750 in.) than the nominal diameter. On the other hand, a pipe 14 in. or greater in diameter has an actual O.D. equal to the nominal size. The inside diameter will depend upon the pipe wall thickness specified by the schedule number.

Key Point: Keep in mind that whether the O.D. is small or large, the dimensions must be within certain tolerances in order to accommodate various fittings.

4.8.3.1 Pipe Wall Thickness

Original pipe wall thickness designations of STD (standard), XS (extra-strong), and XXS (double extra-strong) are still in use today; however, because this system allows no variation in wall thickness and because pipe requirements became more numerous, greater variation was needed. As a result, today the pipe wall thickness, or *schedule*, is expressed in numbers (e.g., 5, 5S, 10, 10S, 20, 20S, 30, 40, 40S, 60, 80, 80S, 100, 120, 140, 160). (Note that you will often hear piping referred to either in terms of its diameter or schedule number.) The most common schedule numbers are 40, 80, 120, and 160. The outside diameter of each pipe size is standardized; therefore, a particular nominal pipe size will have a different inside diameter depending on the schedule number specified. For example, a schedule 40 pipe with a 3-in. nominal diameter (actual O.D. of 3.500 in.) has a wall thickness of 0.216 in. The same pipe in a schedule 80 (XS) would have a wall thickness of 0.300 in.

Key Point: A schedule number indicates the approximate value of the expression 1000*P*/*S*, where *P* is the service pressure and *S* is the allowable stress, both expressed in pounds per square inch (psi). The higher the schedule number, the thicker the pipe is. The schedule numbers followed by the letter S are per ASME B36.19M, and they are primarily intended for use with stainless steel pipe.

4.8.4 Piping Classification

The usual practice is to classify pipe in accordance with the pressure–temperature rating system used for classifying flanges; however, because of the increasing variety and complexity of requirements for piping, a number of engineering societies and standards groups have devised codes, standards, and specifications that meet most applications. By consulting such codes, (e.g., ASTM, manufacturer's specifications, NFPA, AWWA) a designer can determine exactly what piping specification should be used for any application.

Key Point: Because pipelines often carry hazardous materials and fluids under high pressures, following a code helps ensure the safety of personnel, equipment, and the piping system itself.

1. *ASTM ratings.* The American Society for Testing and Materials (ASTM) publishes standards (codes) and specifications that are used to determine the minimum pipe size and wall thickness for a given application.
2. *Manufacturer's ratings.* Pipe manufacturers, because of the propriety design of pipe, fittings, or joints, often assign a pressure–temperature rating that may form the design basis for the piping system. (In addition, the manufacturer may impose limitations that must be adhered to.)

Caution: Under no circumstances shall the manufacturer's rating be exceeded.

3. *NFPA ratings.* Certain piping systems fall within the jurisdiction of the National Fire Protection Association (NFPA). These pipes are required to be designed and tested to certain required pressures (usually rated for 175 psi, 200 psi, or as specified).
4. *AWWA ratings.* The American Water Works Association (AWWA) publishes standards and specifications that are used to design and install water pipelines and distribution system piping. The ratings used may be in accordance with the flange ratings of AWWA, or the rating could be based on the rating of the joints used in the piping.
5. *Other ratings.* Sometimes a piping system may not fall within any of these rating systems. In this case, the designer may assign a specific rating to the piping system. This is a common practice in classifying or rating piping for main steam or hot reheat piping of power plants, whose design pressure and design temperature may exceed the pressure–temperature rating of ASME B16.5. In assigning a specific rating to such piping, the rating must be equal to or higher than the design conditions.

Key Point: Ratings of every pressure-containing components in a piping system must meet or exceed specific ratings assigned by the designer (Nayyar, 2000).

When piping systems are subjected to full-vacuum conditions or submerged in water, they experience both the internal pressure of the flow medium and external pressure. In such instances, piping must be rated for both internal and external pressures at the given temperature. Moreover, if a piping system is designed to handle more than one flow medium during its different modes of operation, it must be assigned a dual rating for two different flow media.

4.8.4.1 Code for Identification of Pipelines

Key Point: Not all plants follow the same code recommendations, which can be confusing for those not familiar with the system used. Standard piping color codes are often used in water and wastewater treatment operations. Plant maintenance operators must be familiar with the pipe codes used in their plants.

Under guidelines provided by the American National Standards Institute (ANSI A13.1), a code has been established for the identification of pipelines. This code involves the use of nameplates (tags), legends, and colors. The code states that the contents of a piping system must be identified by lettered legend giving the name of the contents. In addition, the code requires that information relating to temperature and pressure be included. Stencils, tape, or markers can be used to accomplish the marking. To identify the characteristic hazards of the contents, color should be used, but its use must be in combination with legends.

4.8.4.2 Types of Piping Systems

Piping systems consist of two main categories: *process lines* and *service lines*. Process lines convey the flow medium used in a manufacturing process or a treatment process such as fluid flow in wastewater treatment plants; for example, a major unit process operation in wastewater treatment is sludge digestion. The sludge is converted from bulky, odorous, raw sludge to a relatively inert material that can be rapidly dewatered with the absence of obnoxious odors. Because sludge digestion is a unit process operation, the pipes used in the system are process lines. Service lines (or utility lines) carry water, steam, compressed air, air conditioning fluids, and gas. Normally, all or part of the general service system of a plant is composed of service lines. Service lines cool and heat the plant, provide water where it is needed, and carry the air that drives air equipment and tools.

4.8.5 Metallic Piping Materials

In the not too distant past, it was not that difficult (relatively speaking) to design certain pipe delivery systems; for example, several hundred years ago (and even more recently in some cases), when it was desirable to convey water from a source to point of use, the designer was faced with only two issues. First, a source of fresh water had to be found. Next, if the source was found and it was determined suitable for whatever the need, a means of conveying the water to the point of use was necessary.

When designing early water conveyance systems, gravity was the key player. This point is clear when we consider that, before the advent of the pump, a motive force to power the pump and the energy required to provide power to the motive force were developed, gravity was the means by which water was conveyed from one location to another (with the exception of humans or animals physically carrying the water). Early gravity conveyance systems employed the use of clay pipe, wood pipe, natural gullies or troughs, aqueducts fashioned from stone, or any other means available to convey the water. Some of these earlier pipe or conveyance materials are still in use today. With the advent of modern technology (electricity, the electric motor, the pump, and various machines and processes) and the need to convey fluids other than water came the need to develop piping materials that could carry a wide variety of fluids.

Modern wastewater plants have a number of piping systems made up of different materials. One of the principal materials used in piping systems is metal. Metal pipes may be made of cast iron, stainless steel, brass, copper, and various alloys. Wastewater maintenance operators who work with metal piping must be knowledgeable about the characteristics of individual metals, as well as the kinds of considerations common to all piping systems. These considerations include the effect of temperature changes, impurities in the line, shifting of pipe supports, corrosion, and water hammer.

In this section, we present information about pipes made of cast iron, steel, copper, and other metals. We also discuss the behavior of fluids in a piping system, and the methods of connecting sections of pipe.

4.8.5.1 Characteristics of Metallic Materials

Metallurgy (the science and study of metals) deals with the extraction of metals from ores and with the combining, treating, and processing of metals into useful materials. Different metals have different characteristics, making them usable in a wide variety of applications. Metals are divided into two types: *ferrous*, which includes iron and iron-based alloys (a metal made up of two or ore metals that dissolve into each other when melted together), and *nonferrous*, covering other metals and alloys.

Key Point: Mixing a metal and a nonmetal, such as steel, which is a mixture of iron (a metal) and carbon (a nonmetal), can also form an alloy.

A *ferrous* metal is one that contains iron (Fe). Iron is one of the most common of metals but is rarely found in nature in its pure form. Comprising about 6% of the Earth's crust, iron ore is actually in the form of iron oxides (Fe_2O_3 or Fe_3O_4). Coke and limestone are used in the reduction of iron ore in a blast furnace, where oxygen is removed from the ore, leaving a mixture of iron and carbon and small amounts of other impurities. The end product removed from the furnace is called *pig iron*—an impure form of iron. Sometimes the liquid pig iron is cast from the blast furnace and used directly for metal castings; however, the iron is more often remelted in a furnace to further refine it and adjust its composition (Babcock & Wilcox, 1972).

Note: Piping is commonly made of wrought iron, cast iron, or steel. The difference among them is largely the amount of carbon that each contains.

Remelted pig iron is known as *cast iron* (meaning the iron possesses carbon in excess of 2% weight). Cast iron is inferior to steel in malleability, strength, toughness, and ductility (i.e., it is hard and brittle); however, cast iron has better fluidity in the molten state and can be cast satisfactorily into complicated shapes.

Steel is an alloy of iron with not more than 2.0% by weight carbon. The most common method of producing steel is to refine pig iron by oxidation of impurities and excess carbon—both of which have a higher affinity for oxygen than iron. *Stainless steel* is an alloy of steel and chromium.

Note: When piping is made of stainless steel, an "S" after the schedule number identifies it as such.

Various heat treatments can be used to manipulate specific properties of steel, such as hardness and ductility (meaning it can be fashioned into a new form without breaking). One of the most common heat treatments employed in steel processing is annealing. *Annealing* (sometimes referred to as *stress relieving*) consists of heating the metal and permitting it to cool gradually to make it softer and less brittle.

Note: Steel is one of the most important basic production materials of modern industry.

Nonferrous metals, unlike ferrous metals, do not contain iron. A common example of a nonferrous metal used in piping is brass. Other examples of nonferrous materials used in pipe include polyethylene, polybutylene, polyurethane, and polyvinyl chloride (PVC). Pipes of these materials are commonly used in low-pressure applications for transporting coarse solids (Snoek and Camey, 1981).

Key Point: Although aluminum is relatively strong, it is important to note that its strength *decreases* as temperature *increases*.

In addition to the more commonly used ferrous and nonferrous metals, special pipe materials for special applications are also gaining wider use in industry—even though they are more expensive. Probably one of the most commonly used materials that falls into this category is aluminum pipe. Aluminum pipe has the advantage of being lightweight and corrosion resistant with relatively good strength characteristics. Lead is another special pipe material used for certain applications, especially where a high degree of resistance to corrosive materials is desired. Tantalum, titanium, and zirconium piping materials are also highly resistant to corrosives.

Note: Piping materials selection for use in water treatment and distribution operations should be based on commonly accepted piping standards such as those provided by the American Society for Testing and Materials (ASTM), American Water Works Association (AWWA), American National Standards Institute (ANSI), American Society of Mechanical Engineers (ASME), and American Petroleum Industry (API).

Piping systems convey many types of water including service water, city water, treated or processed water, and distilled water. Service water, used for flushing and cooling purposes, is untreated water that is usually strained but is otherwise raw water taken directly from a source (e.g., lake, river, or deep well). City water is treated potable water. Treated water has been processed to remove various minerals that could cause deterioration or sludge in piping. Distilled water is specially purified.

4.8.5.1.1 Cast Iron Pipe

"There are more miles of [cast iron pipe] in use today than of any other type. There are many water systems having cast-iron mains that are over 100 years old and still function well in daily use" (AWWA, 1996). Cast iron pipe has the advantages of strength, long service life, and being reasonably maintenance free. Its disadvantages include its being subject to electrolysis and attack from acid and alkali soil and its heaviness (Gagliardi and Liberatore, 2000).

4.8.5.1.2 Ductile Iron Pipe

Ductile iron pipe resembles cast iron pipe in appearance and has many of the same characteristics. It differs from cast iron pipe in that the graphite in the metal is of a spheroidal or nodular form; that is, it is in a ball-shape form rather than a flake form. Ductile iron pipe is strong and durable; has high flexural strength and good corrosion resistance; is lighter weight than cast iron; has greater carrying capacity for the same external diameter; and is easily tapped. Ductile iron pipe, however, is subject to general corrosion if installed unprotected in a corrosive environment (Gigliarda and Liberatore, 2000).

4.8.5.1.3 Steel Pipe

Steel pipe is sometimes used as large feeder mains in water distribution systems. It is frequently used where there is particularly high pressure or where very large diameter pipe is required. Steel pipe has high tensile strength and offers lower costs; it is relatively easy to install, is good hydraulically when lined, and can be adapted to locations where some movement may occur. Steel pipe, however, is subject to electrolysis and external corrosion in acid or alkali soil and has poor corrosion resistance unless properly lined, coated, and wrapped.

Note: The materials of which street wastewater (sewer) pipes are most commonly constructed are vitrified clay pipe, plastic, concrete, and ductile iron pipe; however, ductile iron pipe is most commonly used in wastewater collection, primarily for force mains (e.g., interceptor lines) and for piping in and around buildings. Ductile iron pipe is generally not used for gravity sewer applications, however.

4.8.5.2 Maintenance Characteristics of Metallic Piping

Maintenance of metallic piping is determined in part by characteristics of the metal (i.e., expansion, flexibility, and support) but also includes the kind of maintenance common to nonmetallic piping systems, as well. The major considerations include:

- Expansion and flexibility
- Pipe support systems
- Valve selection
- Isolation
- Preventing backflow
- Water hammer
- Air binding
- Corrosion effects

4.8.5.2.1 Expansion and Flexibility

Key Point: Metals expand or contract according to temperature variations. Over a long run (length of pipe), the effects can cause considerable strain on the lines—damage or failure may result.

Because of thermal expansion, water/wastewater systems (which are rigid and laid out in specified lengths) must have adequate flexibility. In water/wastewater systems without adequate flexibility, thermal expansion may lead to failure of piping or anchors. Moreover, it may also lead to joint leakage and excessive loads on appurtences. The thermal expansion of piping can be controlled by properly locating anchors, guides, and snubbers. Where expansion cannot be controlled, flexibility is provided by use of bends, loops, or expansion joints (Gigliardi and Liberatore, 2000).

4.8.5.2.2 Pipe Support Systems

Pipe supports are normally used to carry dead weight and thermal expansion loads. These pipe supports may loosen in time, so they require periodic inspection. Along with normal expansion and contraction, vibration (water hammer or fluids traveling at high speeds and pressures) can cause the supports to loosen.

4.8.5.2.3 Valve Selection

Proper valve selection and routine preventive maintenance are critical to the proper operation and maintenance of any piping system. In wastewater piping systems, valves are generally used for isolating a section of the wastewater collection line, draining the wastewater line, throttling liquid flow, regulating wastewater storage levels, controlling water hammer, bleeding off air, or preventing backflow.

4.8.5.2.4 Isolation

Various valves are used in piping systems to provide for isolation; for example, gate valves are used to isolate specific areas (valve closed) of the system during repair work or to reroute wastewater flow (valve open) throughout the collection system. Service stop valves are commonly used to shut off service lines to individual homes or industries. Butterfly valves are also used for isolation purposes.

4.8.5.2.5 Preventing Backflow

Backflow, or reversed flow, could result in contaminated or polluted water entering the potable water system. Water distribution systems have numerous places where unsafe water may be drawn into the potable water mains if a temporary vacuum should occur in the system. In addition, contaminated water from a higher pressure source can be forced through a water system connection that is not properly controlled. A typical backflow condition from a recirculated system is illustrated in Figure 4.4.

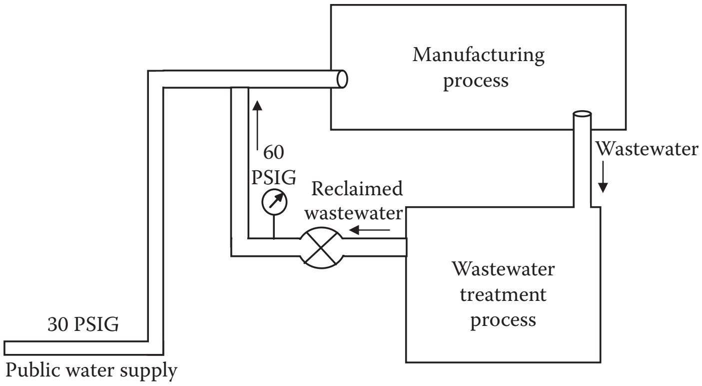


Figure 4.4 Backflow from recirculated system.

Note: Valves, air gaps, reduced-pressure-zone backflow preventers, vacuum breakers, and barometric loops are often used as backflow-prevention devices, depending on the situation.

4.8.5.2.6 Water Hammer

In wastewater operations specifically involving flow through piping, we often hear the term *water hammer*, which is actually a misnomer in that it implies that only water is involved and a hammering noise is heard. In fact, it has become a generic term for pressure wave effects in any liquid. By definition, water hammer (often called *surging*) is a pressure (acoustic) wave phenomenon created by relatively sudden changes in the liquid velocity. In pipelines, sudden changes in the flow (velocity) can occur as a result of (1) pump and valve operation in pipelines, (2) vapor pocket collapse, or even (3) the impact of water following the rapid expulsion of air out of a vent or a partially open valve (Marine, 1999). Water hammer can damage or destroy piping, valves, fittings, and equipment.

Key Point: When water hammer occurs, there is little the maintenance operator can do except to repair any damage that results.

4.8.5.2.7 Air Binding

Air enters a piping system from several sources, such as the release of air from the water, air carried in through vortices into the pump suction, air leaking in through joints that may be under negative pressure, and air present in the piping system before it is filled. The problem with air entry or air binding, because of air accumulation in piping, is that the effective cross-sectional area for wastewater flow in piping is reduced. This flow reduction can, in turn, lead to an increase in pumping costs through the resulting extra head loss.

4.8.5.2.8 Corrosion Effects

All metallic pipes are subject to corrosion. Many materials react chemically with metal piping to produce rust, scale, and other oxides. With regard to water treatment processes, when raw water is taken from wells, rivers, or lakes, the water solution is an extremely dilute liquid of mineral salts and gases. The dissolved mineral salts are a result of water flowing over and through the earth layers. The dissolved gases are atmospheric oxygen and carbon dioxide, picked up by water–atmosphere contact. Wastewater picks up corrosive materials mainly from industrial processes and from chemicals added to the wastewater during treatment. Several types of corrosion should be considered in wastewater collection piping systems (AWWA 1996):

Key Point: Materials such as acids, caustic solutions, and similar solutions are typical causes of pipe corrosion.

1. *Internal corrosion*, caused by aggressive water flowing through the pipes
2. *External corrosion*, caused by chemical and electrical conditions in the soil
3. *Bimetallic corrosion*, caused when components made of dissimilar metals are connected
4. *Stray-current corrosion*, caused by uncontrolled DC electrical currents flowing in the soil

4.8.5.3 Joining Metallic Pipe

Pipe joint design and selection can have a major impact on the initial cost, long-range operating costs, and performance of the piping system (Crocker, 2000). When determining the type of joint to be used in connecting pipe, certain considerations must be made; for example, initial considerations include material cost, installation labor cost, and degree of leakage integrity required. The operator is also concerned with periodic maintenance requirements and specific performance requirements. Metallic piping can be joined or connected in a number of ways. The method used depends on: (1) the nature of the metal sections (ferrous, nonferrous) being joined, (2) the kind of liquid or gas to be carried by the system, (3) pressure and temperature in the line, and (4) access requirements. A *joint* is defined simply as the connection between elements in a piping system. Five major types of joints, each for a special purpose, are used for joining metal pipe (see Figure 4.5):

1. Bell-and-spigot joints
2. Screwed or threaded joints
3. Flanged joints
4. Welded joints
5. Soldered joints

4.8.5.3.1 Bell-and-Spigot Joints

The bell-and-spigot joint has been around since its development in the late 1780s. The joint is used for connecting lengths of cast iron water and wastewater pipe (gravity flow only). The *bell* is the enlarged

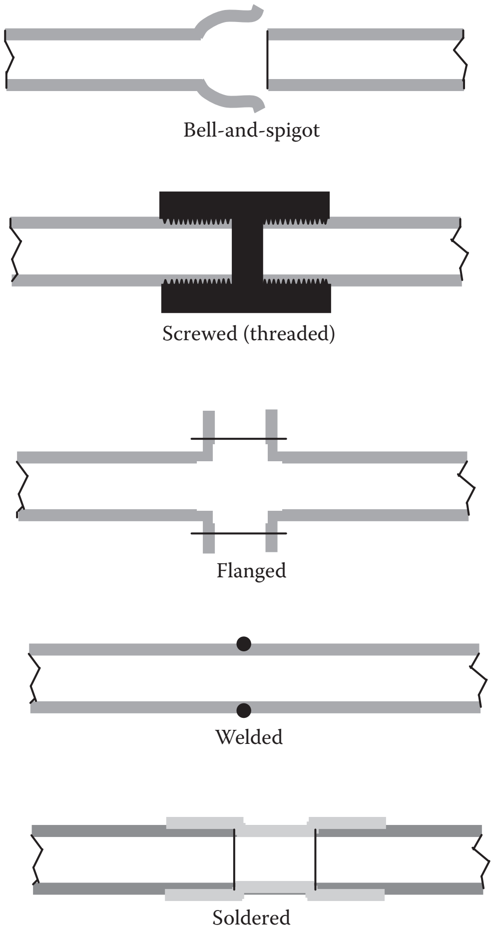


Figure 4.5 Common pipe joints.

section at one end of the pipe; the plain end is the *spigot* (see Figure 4.5). The spigot end is placed into the bell, and the joint is sealed. The joint sealing compound is typically made up of lead and oakum. Lead and oakum are the prevailing joint sealers for sanitary systems. Bell-and-spigot joints are usually reserved for sanitary sewer systems; they are no longer used in water systems.

Key Point: Bell-and-spigot joints are not used in ductile iron pipe.

4.8.5.3.2 Screwed or Threaded Joints

Screwed or threaded joints (see Figure 4.5) are commonly used to join sections of smaller diameter, low-pressure pipe; they are used in low-cost, noncritical applications such as domestic water, industrial cooling, and fire protection systems. Diameters of ferrous or nonferrous pipe joined by threading range from 1/8 in. up to 8 in. Most couplings have threads on the inside surface. The advantages of this type of connection are its relative simplicity, ease of installation (where disassembly and reassembly are

Key Point: Maintenance supervisors must ensure that screwed or threaded joints are used within the limitations imposed by the rules and requirements of the applicable code.

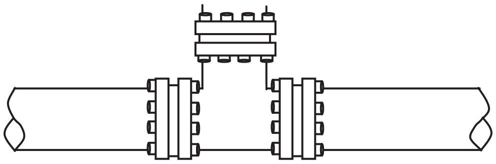


Figure 4.6 Flanged assembly.

necessary to accommodate maintenance needs or process changes), and high leakage integrity at low pressure and temperature where vibration is not encountered. Screwed construction is commonly used with galvanized pipe and fittings for domestic water and drainage applications.

4.8.5.3.3 Flanged Joints

Key Point: A flange with a raised face should never be joined to one with a plain face.

As shown in Figure 4.6, flanged joints consist of two machined surfaces that are tightly bolted together with a gasket between them. The flange is a rim or ring at the end of the fitting, which mates with another section. Flanges are joined by either being bolted together or welded together. Some flanges have raised faces and others have plain faces, as shown in Figure 4.7. Steel flanges generally have raised faces, and iron flanges usually have plain or flat faces.

Flanged joints are used extensively in water/wastewater piping systems because of their ease of assembly and disassembly; however, they are expensive. Contributing to the higher cost are the material costs of the flanges themselves and the labor costs for attaching the flanges to the pipe and then bolting the flanges each other. Flanged joints are not normally used for buried pipe because of their lack of flexibility to compensate for ground movement. Instead, flanged joints are primarily used in exposed locations where rigidity, self-restraint, and tightness are required (e.g., inside treatment plants and pumping stations).

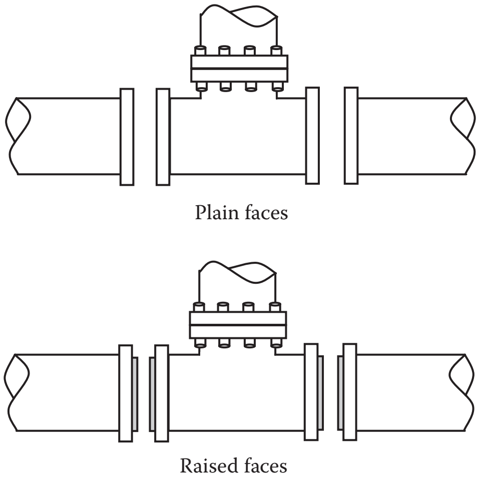
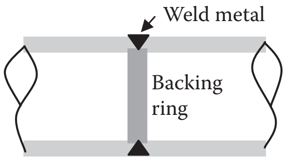
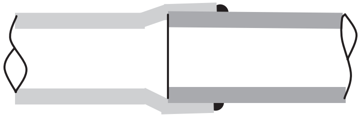


Figure 4.7 Flange faces.



Butt weld



Socket weld

Figure 4.8 Two kinds of welding pipe joints.

4.8.5.3.4 Welded Joints

For applications involving high pressures and temperatures, welded joints are preferred. Welding of joints is the process whereby metal sections to be joined are heated to such a high temperature that they melt and blend together. The advantage of welded joints is obvious: The pieces joined become one continuous piece. When a joint is properly welded, the joint is as strong as the piping itself.

The two basic welded joints are (see Figure 4.8):

1. *Butt-welded joints*, in which the sections to be welded are placed end to end; this is the most common method of joining pipe used in large industrial piping systems.
2. *Socket-welded joints*, in which one pipe fits inside the other, the weld being made on the outside of the lap; this type of joint is used in applications where leakage integrity and structural strength are important.

4.8.5.3.5 Soldered and Brazed Joints

Soldered and brazed joints are most often used to join copper and copper-alloy (nonferrous metal) piping systems, although brazing of steel and aluminum pipe and tubing is possible. The main difference between *brazing* and welding is the temperatures used with each process. Brazing is accomplished at far lower temperatures than those required for welding, but brazing, in turn, requires higher temperatures than *soldering*.

In both brazing and soldering, the joint is cleaned (using emery cloth) and then coated with flux that prevents oxides from forming. The clean, hot joint draws the solder or brazing rod (via capillary action) into the joint to form the connection. The parent metal does not melt in brazed or soldered construction.

4.9 NONMETALLIC PIPING

Although metal piping is in wide use today, nonmetallic piping (especially clay and cement) is of equal importance. New processes to make them more useful in meeting today's needs have modified these older materials. Relatively speaking, using metallic piping is a new practice. Originally, all piping was made from clay or wood, and stone soon followed. Open stone channels or aqueducts were used to transport water over long distances. After nearly 2000 years of service, some of these open channels are still in use today.

Common practice today is to use metal piping, although nonmetallic piping is of equal importance and has many applications in water/wastewater operations. Many of the same materials that have been used for centuries (clay, for example) are still used today, but now many new piping materials are available, and the choice depends on the requirements of the planned application. The development of new technological processes has enabled the modification of older materials for new applications in modern facilities and has brought about the use of new materials for old applications, as well. In this section, we discuss nonmetallic piping materials: what they are and where they are most commonly used. We also describe how to join sections of nonmetallic piping and how to maintain them.

4.9.1 Nonmetallic Piping Materials

Nonmetallic piping materials used in wastewater applications include clay, concrete, asbestos–cement pipe, and plastic. Other nonmetallic piping materials include glass (chemical porcelain pipe) and wood; for example, continuous-strip wooden pipes are used to carry water and waste chemicals in some areas, especially in the western part of the United States. These materials are not discussed in this text, however, because of their limited application in wastewater operations.

Key Point: As with the use of metallic piping, nonmetallic piping must be used in accordance with the specifications established and codified by a number of engineering societies and standards organizations. These codes were devised to help ensure personnel safety and protection of equipment.

4.9.1.1 Clay Pipe

Clay pipes are used to carry or collect industrial wastes, wastewater, and stormwater (they are not normally used to carry potable water). Clay pipes typically range in size from 4 to 36 inches in diameter and are available in more than one grade and strength. Clay pipe is used in nonpressurized systems. When used in drainpipe applications, for example, liquid flow is solely dependent on gravity; that is, it is used as an open channel pipe, whether partially or completely filled. Clay pipe is manufactured in two forms:

Key Point: *Vitrified clay pipe* is extremely corrosion proof. It is ideal for many industrial waste and wastewater applications.

- Vitrified (glass-like)
- Unglazed (not glassy)

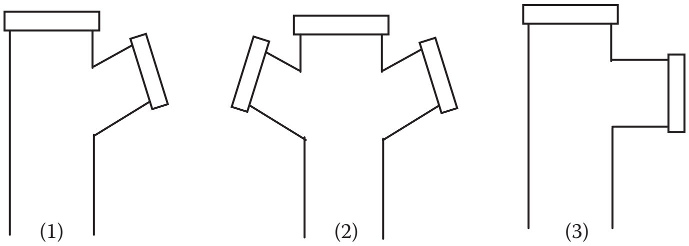


Figure 4.9 Section of bell-and-spigot fillings for clay pipe: (1) wye, (2) double wye, and (3) tee.

Note: McGhee (1991) recommends the use of wyes and tees (see Figure 4.9) for joining various sections of wastewater piping. Failure to provide wyes and tees in common wastewater lines invites builders to break the pipe to make new connections. Obviously, this practice should be avoided, because such breaks are seldom properly sealed and can be a major source of infiltration.

Both vitrified and unglazed clay pipe is made and joined with the same type of bell-and-spigot joint described earlier. The bell-and-spigot shape is shown in Figure 4.10. When joining sections of clay pipe, both ends of the pipe must first be thoroughly cleaned. The small (spigot) end of the pipe must be centered properly and then seated securely in the large (bell) end. The bell is then packed with fibrous material (usually jute) for solid joints, which is tamped down until about 30% of the space is filled. The joint is then filled with sealing compound. In flexible joint applications, the sealing elements are made from natural or synthetic rubber or from a plastic-type material.

Drainage and wastewater collection lines designed for gravity flow are laid downgrade at an angle, with the bell ends of the pipe pointing upgrade. The pipe is normally placed in a trench with strong support members (along its small dimension and not on the bell end). Vitrified clay pipe can be placed directly into a trench and covered with soil; however, unglazed clay pipe must be protected against the effects of soil contaminants and ground moisture.

4.9.1.2 Concrete Pipe

Concrete is another common pipe material and is sometimes used for sanitary sewers in locations where grades, temperatures, and wastewater characteristics prevent corrosion (ACPA, 1987). The pipe provides both high tensile and compressive strength and corrosion resistance. Concrete pipe is generally found in three basic forms: (1) nonreinforced concrete pipe; (2) reinforced concrete, cylinder, and noncylinder pipe; and (3) reinforced and prestressed concrete pressure pipe. With the exception of reinforced and prestressed pressure pipe, most concrete pipe is limited to low-pressure applications. Moreover, almost all concrete piping is used for conveying industrial wastes, wastewater, and stormwater; similarly, some is used for water service connections. Rubber gaskets are used to join sections of many nonreinforced concrete pipe. For

Figure 4.10 Bell-and-spigot ends of clay pipe sections.

circular concrete sewer and culvert pipe, however, flexible, watertight, rubber joints are used to join pipe sections. The general advantages of concrete pipe include the following:

- It is relatively inexpensive to manufacture.
- It can withstand relatively high internal pressure or external loads.
- It has high resistance to corrosion (internal and external).
- Generally, when installed properly, it has a very long, trouble-free life.
- Bedding requirements during installation are minimal.

Disadvantages of concrete pipe include:

- It is very heavy and thus expensive to ship long distances.
- Its weight makes special handling equipment necessary.
- Exact pipes and fittings must be laid out in advance for installation (AWWA, 1996).

4.9.1.2.1 Nonreinforced Concrete Pipe

Nonreinforced concrete pipe, or ordinary concrete pipe, is manufactured in from 4 to 24 inches. As in vitrified clay pipe, nonreinforced concrete pipe is made with bell-and-spigot ends. Nonreinforced concrete pipe is normally used for small wastewater (sewer) lines and culverts.

4.9.1.2.2 Reinforced Concrete Pipe

All concrete pipe made in sizes larger that 24 inches is reinforced; however, reinforced pipe can also be obtained in sizes as small as 12 inches. Reinforced concrete pipe is used for water conveyance (cylinder pipe) and carrying wastewater, stormwater, and industrial wastes. It is also used in culverts. It is manufactured by wrapping high-tensile-strength wire or rods about a steel cylinder that has been lined with cement mortar. Joints are either bell-and-spigot or tongue-and-groove in sizes up to 30 inches and exclusively tongue-and-groove above that size.

4.9.1.2.3 Reinforced and Prestressed Concrete Pipe

When concrete piping is to be used for heavy-load, high-pressure applications (up to 600 psi), it is strengthened by reinforcement and prestressing. Prestressed concrete pipe is reinforced by steel wire, rods, or bars embedded lengthwise in the pipe wall. If wire is used, it is wound tightly to prestress the core and is covered with an outer coating of concrete. Prestressing is accomplished by manufacturing the pipe with a permanent built-in compression force.

4.9.1.2.4 Asbestos–Cement (A-C) Pipe

Asbestos–cement pipe is composed of a mixture of Portland cement and asbestos fiber which is built up on a rotating steel mandrel and then compacted with steel pressure rollers. This pipe has been used for over 70 years in the United States. Because it has a very smooth inner surface, it has excellent hydraulic characteristics (McGhee, 1991). In wastewater operations, though, the ultimate removal and disposal of asbestos–cement pipe pose a problem for operators; for example, consider an underground wastewater line break that must be repaired.

Locating exactly where the line break is can sometimes be difficult, because A-C pipe is not as easily located as conventional pipe. When the line break has been located, the work crew must first excavate the soil covering the line break, being careful not to cause further damage (A-C pipe is relatively fragile). When the soil has been removed, exposing the line break, the damaged pipe section must be removed. In some instances, it may be more economical or practical to remove the damaged portion of the pipe only and to install a replacement portion, girdling it with a clamping mechanism (sometimes referred to as a *saddle clamp*).

To this point in the repair operation being described, the likelihood of exposure to asbestos by personnel is small because, to be harmful, asbestos-containing materials (ACMs) must release fibers that can be inhaled. The asbestos in undamaged A-C pipe is not *friable*; that is, it cannot readily be reduced to powder form by hand pressure when it is dry. Thus, it poses little or no hazard in this condition. If, however, the maintenance crew undertaking the pipe repair must cut, grind, or sand the A-C pipe section, the nonfriable asbestos will separate. This type of repair activity is capable of releasing friable airborne fibers, and herein lies the hazard of working with A-C pipe. To guard against the hazard of exposure to asbestos fibers, A-C pipe repairs must be accomplished in a safe manner. Operators must avoid any contact with an ACM that could disturb its position or arrangement, that could disturb its matrix or render it friable, or that could generate any visible debris.

Key Point: The presence of visibly damaged, degraded, or friable ACMs is always an indicator that surface debris or dust could be contaminated with asbestos. OSHA standards require that we assume that such dust or debris contains asbestos fibers (Coastal Video Communications, 1994).

In the A-C pipe repair operation described above, repairs to the A-C pipe require that prescribed U.S. Environmental Protection Agency (USEPA), Occupational Safety and Health Administration (OSHA), state, and local guidelines be followed. General USEPA/OSHA guidelines, at a minimum, require that trained personnel perform repairs on A-C pipe. The following safe work practices are provided for those who must work with A-C pipe (Spellman, 2001).

4.9.1.2.4.1 Safe Work Practices for A-C Pipe

1. When repairs or modifications are conducted that require cutting, sanding, or grinding on cement pipe containing asbestos, USEPA-trained asbestos workers or supervisors are to be called to the work site *immediately*.
2. Excavation personnel will unearth buried pipe to the point necessary to make repairs or modifications. The immediate work area will then be cleared of personnel as directed by the asbestos-trained supervisor.
3. The on-scene supervisor will direct the asbestos-trained workers as required to accomplish the work task.
4. The work area will be barricaded 20 feet in all directions to prevent unauthorized personnel from entering.
5. Asbestos-trained personnel will wear *all* required personal protective equipment (PPE). Required PPE includes Tyvek® totally enclosed suits, half-face respirators equipped with HEPA filters, rubber boots, goggles, gloves, and hard hats.
6. Supervisors will perform the required air sampling before entry.
7. Air sampling *must* be conducted using the NIOSH 7400 protocol.
8. A portable decontamination station will be set up as directed by the supervisors.
9. Workers will enter the restricted area *only* when directed by the supervisors and, using wet methods *only*, will either perform pipe cutting using a rotary cutter assembly or inspect the broken area to be covered with a repair saddle device.
10. After performing the required repair or modifications, workers will encapsulate bitter ends and fragmented sections.
11. After encapsulation, the supervisor can authorize entry into the restricted area for other personnel.
12. Broken ACM pipe pieces must be properly disposed of following EPA, state, and local guidelines.

Note: Although exposure to asbestos fibers is dangerous, it is important to note that studies by the USEPA, AWWA, and other groups have concluded that the asbestos in water mains does not generally constitute a health threat to the public (AWWA, 1996).

Because A-C pipe is strong and corrosion resistant, it is widely used for carrying water and wastewater. Standard sizes range from 3 to 36 inches. Although highly resistant to corrosion, A-C pipe should not be used for carrying highly acid solutions or unusually soft water, unless its inner and outer surface walls are specially treated. A-C pipe is preferred for use in many outlying areas because of its light weight, which offers greater ease of handling. An asbestos–cement sleeve joins A-C pipe. The inside diameter (I.D.) of the sleeve is larger than the outside diameter (O.D.) of the pipe. The ends of the pipes fit snugly into the sleeve and are sealed with a natural or synthetic rubber seal or gasket, which acts as an expansion joint.

4.9.1.3 Plastic Pipe

Plastic pipe has been used in the United States for about 60 years, and its use is becoming increasingly common. In fact, because of its particular advantages, plastic pipe is replacing both metallic and nonmetallic piping. The advantages of plastic piping include:

- High internal and external corrosion resistance
- Rarely requires insulating or painting
- Light weight
- Ease of joining
- Freedom from rot and rust
- Resistance to burning
- Lower cost
- Long service life
- Easy to maintain

Several types of plastic pipe are available; still, where plastic pipe is commonly used in wastewater service, polyvinyl chloride (PVC) is the most common plastic pipe for municipal water distribution systems. PVC is a polymer extruded (shaped by being forced through a die) under heat and pressure into a thermoplastic that is nearly inert when exposed to most acids, fuels, and corrosives. PVC is commonly used to carry cold drinking water because PVC is nontoxic and will not affect the taste of the water or cause an odor. The limitations of PVC pipe include its limited temperature range (approximately 150°F to 250°F) and low-pressure capability (usually 75 to 100 psi). Joining sections of plastic pipe is accomplished by welding (solvent, fusion, fillet), threading, and flanges.

Key Point: The strength of plastic piping *decreases* as the temperature of the materials it carries *increases*.

4.10 TUBING

Piping by another name might be tubing? A logical question might be "When is a pipe a tube, or a tube a pipe?" Does it really matter if we call piping or tubing by two distinct, separate, and different names? It depends, of course, on the differences between the two. When we think of piping and tubing, we think of tubular, which infers cylindrical products that are hollow. Does this description help us determine the difference between piping and tubing? No, not really. We need more—a better, more concise description.

Maybe *size* will work. When we normally think of pipe, we think in terms of either metallic or nonmetallic cylindrical products that are hollow and range in nominal size from about 0.5 inch (or less) to several feet in diameter. On the other hand, when we think of tubing, we think of cylindrical, hollow products that are relatively smaller in diameter compared to many other piping materials.

Maybe *application* will work. When we normally think of pipe, we think of any number of possible applications, from conveying raw petroleum from field to refinery, to the conveyance of raw water from source to treatment facility, to wastewater discharge point to treatment to outfall, and several others. On the other hand, when we think in terms of tubing applications and the products conveyed, the conveyance of compressed air, gases (including liquefied gas), steam, water, lubricating oil, fuel oil, chemicals, fluids in hydraulic systems, and waste products comes to mind.

On the surface, it is apparent that when we attempt to classify or differentiate piping and tubing, our effort is best characterized as somewhat arbitrary, capricious, vague, or ambiguous. It appears that piping by any other name is just piping. In reality, however, piping is not tubing and in the end (so to speak) the difference may come down to the end use.

4.10.1 Piping vs. Tubing: The Difference

Key Point: It is important to differentiate between piping and tubing, because they are different. They are different in physical characteristics and methods of installation, as well as in their advantages and disadvantages. In this chapter, these differences will become clear.

Piping and tubing are considered separate products, even though they are geometrically quite similar (Lohmeir and Avery, 2000). Moreover, the classification of "pipe" or "tube" is determined by end use. As mentioned, many of the differences between piping and tubing are related to physical characteristics and methods of installation, as well as the advantages and disadvantages. Simply, *tubing* refers to tubular materials (products) made to either an inside diameter (I.D.) or an outside diameter (O.D.), expressed in even inches or fractions. Tubing walls are generally much thinner than those of piping; thus, wall thickness in tubing is of particular importance. Tubing of different diameters has different wall thicknesses; for example, the wall thickness of a commercial type of 8-in. pipe is 0.406 in. Light-wall 8-in. copper tubing, by contrast, has a wall thickness of 0.050 in. When we compare these figures, it is clear that tubing has much thinner walls than piping of the same general diameter (Basavaraju, 2000).

Key Point: Wall thickness tolerance in tubing is held so closely that wall thickness is usually given in thousandths of an inch rather than as a larger fraction of an inch. Sometimes the gauge number indicates the thickness according to a given system.

Note: The range between *thick* and *thin* is narrower for tubing than it is for piping.

The list of tubing applications is a lengthy one. Some tubing types can be used not only as conduits for electrical wire but also to convey waste products, compressed air, hydraulic fluids, gases, fuel oil, chemicals, lubricating oil, steam, waters, and other fluids (i.e., both gaseous and liquid).

Tubing is made from both metals and plastics. Metal tubing is designed to be somewhat flexible but also strong. Metallic materials such as copper, aluminum, steel, and stainless steel are used in applications where fluids are carried under high pressure; some types of tubing (e.g., stainless steel) can accommodate very high pressures (>5000 psi). As the diameter of the tubing increases, the wall thickness increases accordingly (slightly).

Ranging in size from 1/32 to 12 in. in diameter, the smaller sizes are most commonly used. Standard copper tubing ranges from 1/32 to 10 in. in diameter, steel from 3/15 to 10-3/4 in., and aluminum from 1/8 in. to 12 in. Special alloy tubing is available up to 8 in. in diameter.

Typically, in terms of initial cost, metal tubing materials are more expensive than iron piping; however, high initial cost vs. the ability to accommodate a particular application as designed (as desired), is a consideration that cannot be overlooked or underemphasized. Consider, for example, an air compressor. Typically, while in operation, air compressors are mechanical devices that not only produce a lot of noise but also vibrate. Installing a standard rigid metal piping system on such a device might not be practical. Installing tubing that is flexible, however, may have no detrimental impact on its operation whatsoever. An even more telling example is the internal combustion engine. A lawnmower engine, like the air compressor, also vibrates and is used in less than static conditions (i.e., the lawnmower is typically exposed to various dynamic stresses). Obviously, we would *not* want the fuel lines (tubing) in such a device to be made with rigid pipe; instead, we would want the fuel lines to be durable but also somewhat flexible. Thus, flexible metal tubing is called for in this application, because it will hold up. Simply put, initial cost can be important; however, considerations such as maintenance requirements, durability, length of life, and ease of installation often favor the use of metallic tubing over the use of metallic pipe.

Although it is true that most metallic tubing materials have relatively thin walls, it is also true that most are quite strong. Small tubing material with thin walls (i.e., soft materials up to approximately 1 in. O.D.) can be bent quite easily by hand. Tubing with larger diameters requires special bending tools. The big advantage of flexible tubing should be obvious: Tubing can be run from one point to another with fewer fittings than if piping was used.

Note: Figure 4.11 shows how the use of tubing can eliminate several pipe fittings.

The advantages of the tubing type of arrangement shown in Figure 4.11 include the following:

- It eliminates 18 potential sources of leaks.
- The cost of the 18 90° elbow fittings required for the piping installation is eliminated.
- The time required to cut, gasket, and flange the separate sections of pipe is saved (obviously, it takes little time to bend tubing into the desired configuration).
- The tubing configuration is much lighter in weight than the separate lengths of pipe and the pipe flanges would have been.

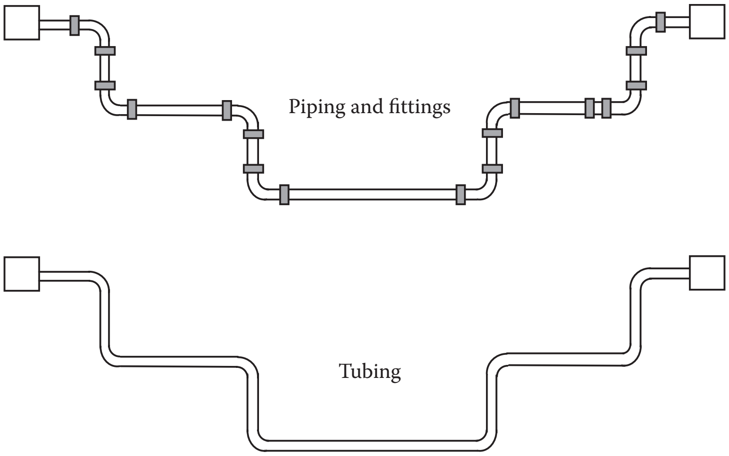
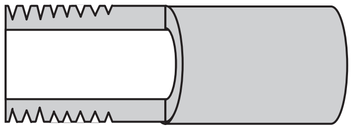


Figure 4.11 Tubing eliminates fittings.

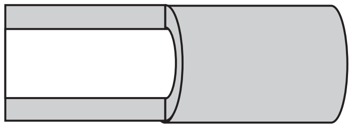
For the configuration shown in Figure 4.11, the amount of weight is considerably less for the copper tubing than the piping arrangement. Moreover, the single length of tubing bent to follow the same general conveyance route is much easier to install.

It may seem apparent to some readers that many of the weight and handling advantages of tubing compared to piping can be eliminated or at least matched simply by reducing the wall thickness of the piping. It is important to remember, however, that piping has a thick wall because it often has to be threaded to make connections. If the wall thickness of iron pipe, for example, was made comparable to the thickness of copper tubing, and then threaded at connection points, its mechanical integrity would be reduced. The point is that piping must have sufficient wall thickness left after threading not only to provide a tight fit but also to handle the fluid pressure. On the other hand, copper tubing is typically designed for brazed and soldered connections, rather than threaded ones; thus, its wall thickness can be made uniformly thin. This advantage of tubing over iron piping is illustrated in Figure 4.12.

Note: The lighter weight of tubing means greater ease of handling, as well as lower shipping costs.



Threaded pipe section



Pipe section without threads

Figure 4.12 Pipe wall thickness is important when threading is required.

4.10.2 Advantages of Tubing

To this point, with regard to the design requirements, reliability, and maintenance activities related to using tubing vs. piping, we have pointed out several advantages of tubing. These advantages can be classified as *mechanical* or *chemical* advantages.

4.10.2.1 Mechanical Advantages of Tubing

Probably the major mechanical advantage of using tubing is its relatively small diameter and its flexibility, which makes it user friendly in tight spaces where piping would be difficult to install and to maintain (e.g., for the tightening, repair, or replacement of fittings). Another mechanical advantage of tubing important to wastewater maintenance operators is the ability of tubing to absorb shock from *water hammer*. Water hammer can occur whenever fluid flow is started or stopped. In wastewater operations, certain fluid flow lines have a frequent on/off cycle. In a conventional piping system, this may produce vibration, which is transmitted along the rigid conduit, shaking joints, valves, and other fittings. The resulting damage usually results in leaks, which, of course, must be repaired. In addition, the piping supports can also be damaged. When tubing, with its built-in flexibility, is used in place of conventional iron piping, however, the conduit absorbs most of the vibration and shock. The result is far less wear and tear on the fittings and other appurtenances.

As mentioned, sections of tubing are typically connected by means of soldering, brazing, or welding rather than by threaded joints, although steel tubing is sometimes joined by threading. In addition to the advantages in cost and time savings, not using threaded joints precludes other problems. For example, any time piping is threaded it is weakened. At the same time, threading is commonly used for most piping systems and usually presents no problem.

Another advantage of tubing over iron piping is the difference in inner-wall surfaces between the two. Specifically, tubing generally has a smoother inner-wall surface than does iron piping. This smoother inner-wall characteristic aids in reducing turbulent flow (and the resulting wasted energy and decreased pressure) in tubing. Flow in the smoother walled tubing is more laminar; that is, it has less turbulence. Laminar flow is characterized as flow in layers—very thin layers. (Somewhat structurally analogous to this liquid laminar flow phenomenon is wood-type products such as kitchen cabinets, many of which are constructed of laminated materials.)

This might be a good time to address laminar flow inside a section of tubing. First, we need to discuss both laminar and turbulent flow to point out the distinct difference between them. Simply, in laminar flow, streamlines remain parallel to one another and no mixing occurs between adjacent layers. In turbulent flow, mixing occurs across the pipe. The distinction between the two regimes lies in the fact that the shear stress in laminar flow results from viscosity, while that in turbulent flow results from momentum exchanges occurring as a result of motion of fluid particles from one layer to another (McGhee 1991). Normally, flow inside tubing is laminar; however, if the inner wall of the tubing has any irregularities (dents, scratches, or bumps), the fluid will be forced across the otherwise smooth surface at different velocities which causes turbulence. Iron piping has more irregularities along its inner walls. This inner-wall surface roughness produces turbulence in the fluid flowing along the conduit. Ultimately, this turbulence can reduce the delivery rate of the piping system considerably.

4.10.2.2 Chemical Advantages of Tubing

The major chemical advantage in tubing as compared to piping comes from the corrosion-resistant properties of the metals used to make the tubing. Against some corrosive fluids, most tubing materials do very well. Some metals perform better than others, though, depending on the metal and the corrosive nature of the fluid. It is important to also point out that tubing must be compatible with the fluid it is conveying. When conveying a liquid stream from one point to another, the last thing we want is to add contamination from the tubing. Many tubing conveyance systems are designed for use in food-processing operations. If we were conveying raw milk to or from a unit process, for example, we certainly would not want to contaminate the milk. To avoid such contamination, where conditions of particular sanitation are necessary, stainless steel, aluminum, or appropriate plastic tubing must be used.

4.10.3 Connecting Tubing

The skill required to properly connect metal or nonmetallic tubing can be learned by just about anyone; however, significant practice and experience are required to ensure that the tubing is properly connected. Moreover, certain tools are required for connecting sections of tubing. The tools used to make either a soldered connection or a compression connection (where joint sections are pressed together) include:

- Hacksaw
- Tube cutter
- Scraper
- Flat file
- Burring tool
- Flaring tool
- Presetting tool for flareless fittings
- Assorted wrenches
- Hammer
- Tube bender

4.10.3.1 Cutting Tubing

No matter what type of connection is being made (soldered or compressed), it is important to cut the tubing cleanly and squarely. This can be accomplished using a tubing cutter. Use of a tubing cutter is recommended, because it provides a much smoother cut than that made with a hacksaw. A typical tubing cutter has a pair of rollers on one side and a cutting wheel on the other. The tubing cutter is turned all the way around the tubing, making a clean cut. After making the tubing cut, the rough edge of the cut must be smoothed with a *burring* tool to remove the small metal chads, burrs, or whiskers. If a hacksaw is used to cut the tubing, be sure that the rough cut is filed until it is straight and square to the length of the tubing.

Key Point: When cutting stainless steel tubing, cut the tubing as rapidly and safely as you can, with as few strokes as possible. This is necessary because as stainless steel is cut it hardens, especially when cut with a hacksaw.

4.10.3.2 Soldering Tubing

Soldering is a form of brazing in which nonferrous filler metals having melting temperatures below 800°F (427°C) are used. The filler metal is called *solder* (usually a tin–lead alloy, which has a low melting point) and is distributed between surfaces by capillary action. Whether soldering two sections of tubing together or connecting tubing to a fitting, such as an elbow, the soldering operation is the same. Using emery cloth or a wire brush, the two pieces to be soldered must first be cleaned (turned to bright metal). Clean, oxide-free surfaces are necessary to make sound soldered joints. Uniform capillary action is possible only when surfaces are completely free of foreign substances such as dirt, oil, grease, and oxide.

Key Point: During the cleaning process care must be taken to avoid getting the prepared adjoining surfaces too smooth. Surfaces that are too smooth will prevent the filler metal (solder) from effectively wetting the joining areas.

The next step is to ensure that both the tubing outside and the fitting inside are covered with soldering flux and fitted together. When joining two tubing ends, use a sleeve. The purpose of flux is to prevent or inhibit the formation of oxide during the soldering process. The two ends are fitted into the sleeve from opposite sides. Make sure the fit is snug. Next, heat the joint. First, heat the tubing next to the fitting then the fitting itself. When the flux begins to spread, solder should be added (this is known as *tinning*). The heat will suck the solder into the space between the tubing and the sleeve. The next step is to heat the fitting, on and off, and apply more solder until the joint is fully penetrated (Giachino and Weeks, 1985).

Key Point: During the soldering operation, it is important to ensure that the heat is applied evenly around the tubing. A continuous line of solder will appear where the fitting and tubing meet at each end of the sleeve. Also, ensure that the joined parts are held so that they will not move. After soldering the connection, wash the connection with hot water to prevent future corrosion.

The heat source normally used to solder is heated using an oxyacetylene torch or some other high-temperature heat source. Important soldering points to remember include:

1. **Always use the recommended flux when soldering.**
2. **Make sure parts to be soldered are clean and their surfaces fit closely together.**

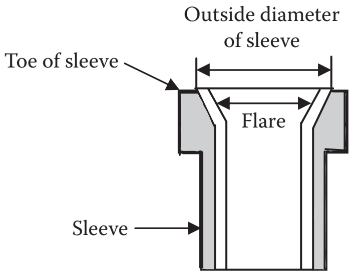


Figure 4.13 Flared tubing end.

3. During the soldering process, do not allow the parts to move while the solder is in a liquid state.
4. Be sure the soldering heat is adequate for the soldering job to be done, including the types of metal and the fluxes.
5. Wash the solder work in hot water to stop later corrosive action.

4.10.3.3 Connecting Flared/Nonflared Joints

In addition to being connected by brazing or soldering, tubing can also be connected by either *flared* or *nonflared* joints. Flaring is accomplished by evenly spreading the end of the tube outward, as shown in Figure 4.13. The accuracy of the angle of flare is important; it must match the angle of the fitting being connected. The flaring tool is inserted into the squared end of the tubing and then hammered or impacted into the tube a short distance, spreading the tubing end as required.

Figure 4.14 shows the resulting flared connection. The flared section is inserted into the fitting in such a way that the flared edge of the tube rests against the angled face of the male connector body—a sleeve supports the tubing. The nut is tightened firmly on the male connector body, making a firm joint that will not leak, even if the tubing ruptures because of excess pressure. Figure 4.15 shows a flareless fitting. The plain tube end is inserted into the body of the fitting. Notice that there are two threaded outer sections with a *ferrule* or bushing located between them. As the threaded members are tightened, the ferrule bites into the tubing, making a tight connection.

4.10.4 Bending Tubing

A type of tool typically used in water/wastewater maintenance applications for bending tubing is the *hand bender*, which is nothing more than a specifically sized, spring-type apparatus. Spring-type benders come in several different sizes (the size that fits the particular sized tubing to be bent is used to bend it). The spring-type tubing bender is slipped over the tubing section to be bent, then the spring and tubing are carefully bent by hand to conform to the angle of bend desired. When using any type of tubing bender, it is important to obtain the desired bend without damaging (flattening, kinking, or wrinkling) the tubing. As

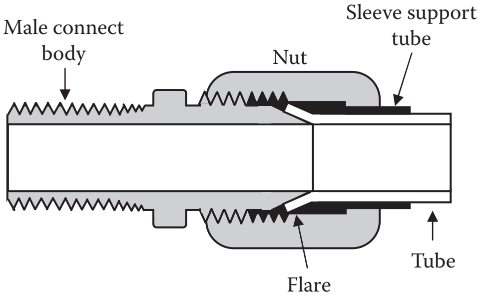


Figure 4.14 Flared fitting.

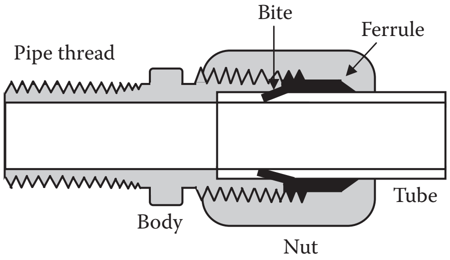


Figure 4.15 Flareless fitting.

mentioned, any distortion of the smooth, inner wall of a tubing section causes turbulence in the flow, which lowers the pressure. Figure 4.16 shows three different kinds of incorrect bends and one correct bend. From the figure, it should be apparent how the incorrect bends constrict the flow, causing turbulence and lower pressure.

4.10.5 Types of Tubing

Common types of metal tubing in industrial service include:

- *Copper* is seamless, fully annealed, and furnished in coils or in straight lengths. In water treatment applications, copper tubing has replaced lead and galvanized iron in service line installations because it is flexible, easy to install, corrosion resistant in most soils, and able to withstand high pressure. It is not sufficiently soluble in most water to be a health hazard, but corrosive water may dissolve enough copper to cause green stains on plumbing fixtures. Copper water service tubing is usually connected by either flare or compression fittings. Copper plumbing is usually connected with solder joints (AWWA, 1996).

Key Point: *Annealing* is the process of reheating a metal and then letting it cool slowly. In the production of tubing, annealing is performed to make the tubing softer and less brittle.

- *Aluminum* is seamless, annealed, and suitable for bending and flaring.
- *Steel* is seamless and fully annealed and is also available as a welded type, suitable for bending and flaring.

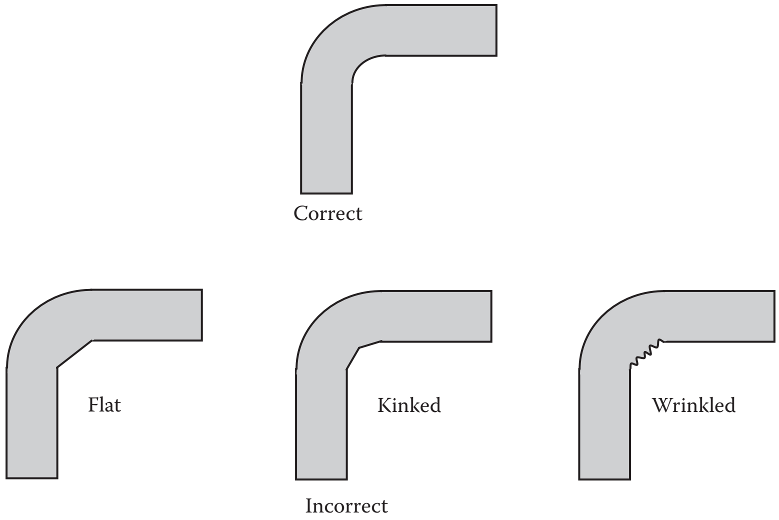


Figure 4.16 Correct and incorrect tubing bends

- *Stainless steel* is seamless and fully annealed and is also available as a welded type, suitable for bending and flaring.
- *Special alloy* is made for carrying corrosive materials.

Like metal piping, metal tubing is made in both welded and seamless styles. *Welded* tubing begins as flat strips of metal that are then rolled and formed into tubing. The seams are then welded. *Seamless* tubing is formed as a long, hot metal ingot and then shaped into a cylindrical shape. The cylinder is then extruded (passed through a die), producing tubing in the larger sizes and wall thicknesses. If smaller tubing (with thinner walls and closer tolerances) is desired, the extruded tubing is reworked by drawing it through another die.

4.10.6 Typical Tubing Applications

In a typical wastewater operation, tubing is used in unit processes and machinery. Heavy-duty tubing is used for carrying gas, oxygen, steam, and oil in many underground services, interior plumbing, and heating and cooling systems throughout the plant site. Steel tubing is used in high-pressure hydraulic systems. Stainless steel tubing is used in many chemical systems. In addition, in many plants, aluminum tubing is used as raceways or containers for electrical wires. Plastics have become very important as nonmetallic tubing materials. The four most common types of plastic tubing are Plexiglas® (acrylic), polycarbonate, vinyl, and polyethylene (PE). For plant operations, plastic tubing usage is most prevalent where it meets corrosion resistance demands and the temperatures are within its working range (primarily in chemical processes). Plastic tubing is connected either by fusing with solvent cement or by heating. Reducing the plastic ends of the tubing to a soft, molten state and then pressing them together produces a fused joint. In the solvent cement method, the ends of the tubing are coated with a solvent that dissolves the plastic. The tube ends are firmly pressed together, and as the plastic hardens they are securely joined. For heat fusion, the tubes are held against a hot plate. When molten, the ends are joined and the operation is complete.

4.11 INDUSTRIAL HOSES

Earlier we described the uses and merits of piping and tubing. This section describes industrial hoses, which are classified as a slightly different tubular product. Their basic function is the same, however, and that is to carry fluids (liquids and gases) from one point to another. The outstanding feature of industrial hose is its flexibility, which allows it to be used in applications where vibrations would make the use of rigid pipe impossible. Most wastewater treatment plants use industrial hoses to convey steam, water, air, and hydraulic fluids over short distances. It is important to point out that each application must be analyzed individually, and an industrial hose must be selected that is compatible with the system specification.

In this section, we study industrial hoses—what they are, how they are classified and constructed, and the ways in which sections of hose are connected to one another and to piping or tubing. We will also read about the maintenance requirements of industrial hoses and what to look for when we make routine inspections or checks for specific problems.

Industrial hoses, piping, and tubing all are used to convey a variety of materials under a variety of circumstances. Beyond this similar ability to convey a variety of materials, however, differences do exist among industrial hoses, piping, and tubing; for example, in their construction and in the advantages they offer, industrial hoses are different from piping and tubing. As mentioned, the outstanding advantage of hose is its flexibility; its ability to bend means that hose can meet the requirements of numerous applications that cannot be met by rigid piping and some tubing systems. Two examples of this flexibility are camel hose, which is used in wastewater collection systems to clean out interceptor lines or to remove liquid from excavations where broken lines are in need of repair, and the hose that supplies hydraulic fluids used on many forklifts. Clearly, rigid piping would be impractical to use in both situations.

Not only is industrial hose flexible but it also has a dampening effect on vibration. Certain tools used in wastewater maintenance activities must vibrate to do their jobs. Probably the most familiar such tool is the power hammer, or jackhammer. Obviously, the inherent rigidity of piping and tubing would not allow vibrating tools to last very long under normal operating conditions. Other commonly used tools and machines in wastewater operations have pneumatically or hydraulically driven components. Many of these devices are equipped with moving members that require the air or oil supply to move with them. In such circumstances, of course, rigid piping could not be used.

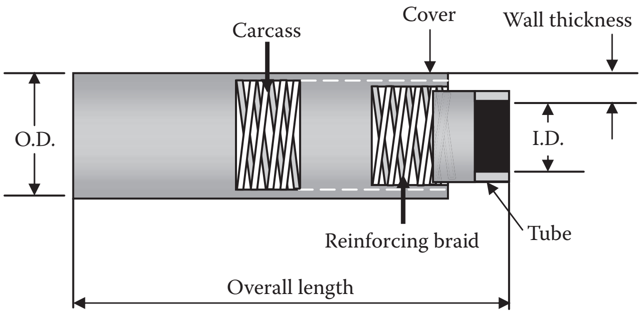


Figure 4.17 Common hose nomenclature.

It is important to note that the flexibility of industrial hose is not the only consideration that must be taken into account when selecting hose over either piping or tubing; that is, hose must be selected according to the potentially damaging conditions typical of a particular application. These conditions include the effects of pressure, temperature, and corrosion.

Hose applications include the use of lightweight ventilating hose (commonly called *elephant trunk*) to supply fresh air to maintenance operators working in manholes, vaults, or other tight places. In wastewater treatment plants, hoses are used to carry water, steam, corrosive chemicals and gases, and hydraulic fluids under high pressure. To meet such service requirements, hoses are manufactured from a number of different materials.

4.11.1 Hose Nomenclature

To gain a fuller understanding of industrial hoses and their applications, it is important to be familiar with the nomenclature or terminology normally associated with industrial hoses. Accordingly, in this section, we explain hose terminology that wastewater operators should be familiar with. Figure 4.17 is a cutaway view of a high-pressure air hose of the kind that supplies portable air hammers and drills and other pneumatic tools commonly used in water/wastewater maintenance operations. The hose is the most common type of reinforced nonmetallic hose in general use. Many of the terms used in the figure have already been mentioned. The I.D., which designates the hose size, refers to the inside diameter throughout the length of the hose body, unless the hose has enlarged ends. The O.D. is the diameter of the outside wall of the hose.

Key Point: If the ends of an industrial hose are enlarged, as shown in Figure 4.18, the letters E.E. are used (meaning *expanded* or *enlarged end*). Some hoses have enlarged ends to fit a fixed end of piping tightly (e.g., an automobile engine).

As shown in Figure 4.17, the *tube* is the inner section (i.e., the core) of the hose through which the fluid flows. Surrounding the tube is the *reinforcement* material, which provides resistance to pressure—either from the inside or outside. Notice that the hose shown in Figure 4.17 has two layers of reinforcement *braid* (fashioned from high-strength

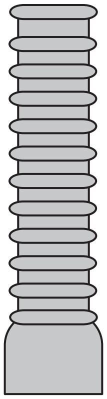


Figure 4.18 Expanded-end hose.

synthetic cord). The hose is said to be *mandrel braided*, because a spindle or core (the mandrel) is inserted into the tube before the reinforcing materials are put on. The mandrel provides a firm foundation over which the cords are evenly and tightly braided. The *cover* of the hose is an outer, protective covering. The hose in Figure 4.17 has a cover of tough, abrasion-resistant material.

The *overall length* is the true length of a straight piece of hose. Hose that is not too flexible is formed or molded in a curve (e.g., automobile hose used in heating systems) (see Figure 4.19). As shown in Figure 4.19, the *arm* is the section of a curved hose that extends from the end of the hose to the nearest centerline intersection. The *body* is the middle section or sections of the curved hose. Figure 4.20 shows the *bend radius* (i.e., the radius of the bend measured to the centerline) of the curved hose, designated as radius *R*. In a straight hose, bent on the job, the radius of the bend is measured to the surface of the hose (i.e., radius *r* in Figure 4.20).

Note: Much of the nomenclature used above does not apply to nonmetallic hose that is not reinforced; however, nonreinforced nonmetallic hose is not very common in water/wastewater treatment plant operations.

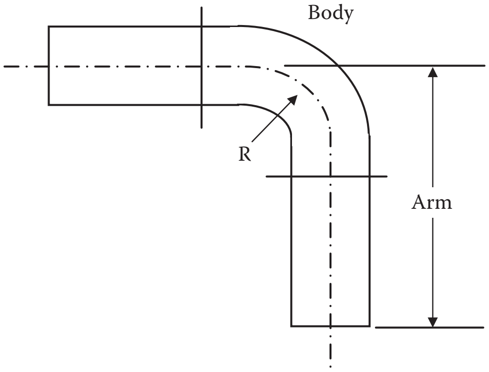


Figure 4.19 Bend radius.

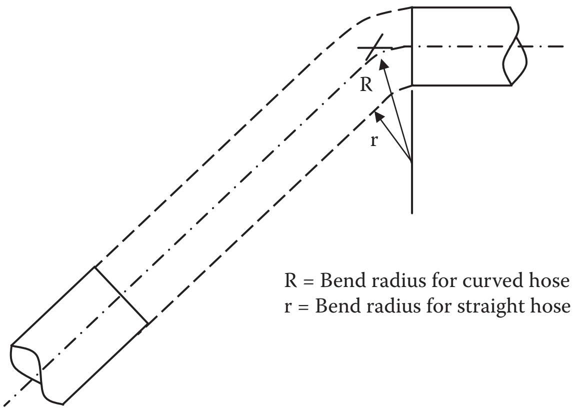


Figure 4.20 Bend radius measurement.

4.11.2 Factors Governing Hose Selection

The amount of *pressure* to which a hose will be exposed is one of the important factors governing hose selection. Typically, pressures fall into any of three general groups:

- <250 psi (low-pressure applications)
- 250 to 3000 psi (medium-pressure applications)
- 3000 to 6000+ psi (high-pressure applications)

Note: Some manufacturers have their own distinct systems for rating hose pressure; we cannot assume that a hose rated as a "low-pressure" hose will automatically be useful at 100 or 200 psi. It may, in fact, be built for pressures not to exceed 50 psi, for example. Therefore, whenever we replace a particular hose, we must ensure that the same type of hose with the same pressure rating as the original hose is used. In high-pressure applications, this precaution is of particular importance.

In addition to the pressure rating of a hose, we must also consider, for some applications, the *vacuum rating* of a hose which refers to suction hose applications in which the pressure outside the hose is greater than the pressure inside the hose. It is important, obviously, to know the degree of vacuum that can be created before a hose begins to collapse. A drinking straw, for example, collapses rather easily if too much vacuum is applied; thus, it has a low vacuum rating. In contrast, the lower automobile radiator hose (which also works under vacuum) has a relatively higher vacuum rating.

4.11.3 Standards, Codes, and Sizes

Just as they have for piping and tubing, authoritative standards organizations have devised standards and codes for hoses. Standards and codes are safety measures designed to protect personnel and equipment; for example, specifications are provided for working pressures, sizes, and material requirements. The working pressure of a hose, for example, is typically limited to one fourth, or 25%, of the amount of pressure required to burst the hose. Let's look at an example. If we have a hose that has a maximum rated working pressure of 200 psi, it should not rupture until 800 psi has been reached, and possibly not even then. Thus, the importance of using hoses that meet specified standards or codes is quite evident.

4.11.3.1 Hose Size

The parameter typically used to designate hose size is its inside diameter (I.D.). With regard to the classification of hose, ordinarily a *dash numbering* system is used. Current practice by most manufacturers is to use the dash system to identify both hose and fittings. To determine the size of a hose, we simply convert the size in 16ths; for example, a hose size of 1/2 in. (a hose with a 1/2-in. I.D.) is the same as 8/16 in. The numerator of the fraction (the top number, or 8 in this case) is the dash size of the hose. In the same way, a size of 1-1/2-in. can be converted to 24/16 in. and so is identified as a -24 (pronounced "dash 24") hose. By using the dash system, we can match a hose line to tubing or piping section and be sure the I.D. of both will be the same. This means, of course, that the nonturbulent flow of fluid will not be interrupted. Based on I.D., hoses range in size from 3/16 in. to as large as 24 in.

4.11.3.2 Hose Classifications

Hose is classified in a number of ways; for example, hose can be classified by type of service (hydraulic, pneumatic, corrosion-resistant), by material, by pressure, and by type of construction. Hose may also be classified by type. The three types include metallic, nonmetallic, and reinforced nonmetallic. Generally, terminology is the same for each type.

4.11.3.3 Nonmetallic Hose

Relatively speaking, the use of hose is not a recent development. Hoses, in fact, have been used for one application or another for hundreds of years. Approximately 100 years ago, after new developments in the processing of rubber, hoses were usually made by layering rubber around mandrels. Later, the mandrel was removed, leaving a flexible rubber hose. These flexible hoses tended to collapse easily, but they were an improvement over the earlier types. Manufacturers later added layers of rubberized canvas. This improvement gave hoses more strength and gave them the ability to handle higher pressures. Later, after the development of synthetic materials, manufacturers had more rugged and more corrosion-resistant rubber-type materials to work with. Today, neoprene, nitrile rubber, and butyl rubber are commonly used in hose. Current manufacturing practice is not to make hoses from a single material; instead, various materials form layers in the hose, reinforcing it in a variety of ways for strength and resistance to pressure. Hose manufactured today usually has a rubber-type inner tube or a synthetic (e.g., plastic) lining

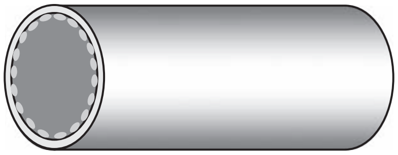


Figure 4.21 Vertical-braided hose.

surrounded by a *carcass* (usually braided) and cover, as shown earlier in Figure 4.17. The type of carcass braiding used is determined by the requirements of the application. To reinforce a hose, two types of braiding are used: *vertical* and *horizontal*. Vertical braiding strengthens the hose against pressure applied at right angles to the centerline of the hose. Horizontal braiding strengthens the hose along its length, giving it greater resistance to expansion and contraction. Descriptions of the types of nonmetallic hose follow, with references to their general applications.

4.11.3.3.1 Vertical-Braided Hose

Vertical-braided hose has an inner tube of seamless rubber (see Figure 4.21). The reinforcing wrapping (carcass) around the tube is made of one or more layers of braided yarn. This type of hose is usually made in lengths of up to 100 ft with inner diameters of up to 1.5 in. Considered a small hose, it is used in low-pressure applications to carry fuel oil; acetylene gas and oxygen for welding; water for lawns, gardens, and other household uses; and paint for spraying.

4.11.3.3.2 Horizontal-Braided Hose

Horizontal-braided hose is mandrel built; it is used to make hose with an I.D. of up to 3 in. Used in high-pressure applications, the seamless rubber tube is reinforced by one or more layers of braided fibers or wire. This hose is used to carry propane and butane gas and steam and for various hydraulic applications that require high working pressures.

4.11.3.3.3 Reinforced Horizontal Braided-Wire Hose

In this type of hose, the carcasses around the seamless tube are made up of two or more layers of fiber braid with steel wire reinforcement between them. The I.D. may be up to 4 in. Mechanically very strong, this hose is used where there are high working pressures or strong suction (vacuum) forces, such as in chemical transfer and petroleum applications.

4.11.3.3.4 Wrapped Hose

Made in diameters up to 24 in., wrapped hose is primarily used for pressure service rather than suction. The hose is constructed of mandrels to close tolerances (see Figure 4.22). It also has a smooth bore,

Figure 4.22 Wrapped hose.

which encourages laminar flow and prevents turbulence. Several plies (layers) of woven cotton or synthetic fabric make up the reinforcement. To achieve its resistance to corrosive fluids, the tube is made from a number of synthetic rubbers. It is also used in sandblasting applications.

4.11.3.3.5 Wire-Reinforced Hose

In this type of hose, wires wound in a spiral around the tube, or inside the carcass, in addition to a number of layers of wrapped fabrics provide the reinforcement (see Figure 4.23). With inner diameters of 16 to 24 in. common, this type of hose is used in oil suction and discharge situations that require special hose ends, maximum suction (without collapsing), or special flexing characteristics (must be able to bend in a small radius without collapsing), or a combination of all three of these requirements.

4.11.3.3.6 Wire-Woven Hose

Wire-woven hose (see Figure 4.24) has cords interwoven with wire running spirally around the tube; it is highly flexible, low in weight, and resistant to collapse even under suction conditions. This kind of hose is well suited for negative pressure applications.

4.11.3.3.7 Other Types of Nonmetallic Hose

Hoses are also made of other nonmetallic materials, many of them nonreinforced; for example, materials such as Teflon®, Dacron®, polyethylene, and nylon are being used in the manufacture of hose. Dacron remains flexible at very low temperatures, even as lows as –200°C (–350°F), nearly the temperature of liquid nitrogen. Consequently, these hoses are used to carry liquefied gas in cryogenic applications. Teflon is often used where corrosive fluids and fluids up to 230°C (450°F) are to be carried; it can also be used at temperatures as low as –55°C (–65°F). Usually sheathed in a flexible, braided metal covering, Teflon hoses are well protected against abrasion; they also have added resistance to pressure.

Nylon hoses (small-diameter) are commonly used as air hoses, supplying compressed air to small pneumatic tools. The large plastic hoses (up to 24 in.) used to ventilate manholes are made of such neoprene-coated materials as nylon fabric, glass fabric, and cotton duck. The cotton duck variety is for light-duty applications. The glass fabric type is used with portable heaters and for other applications involving hot air and fumes.

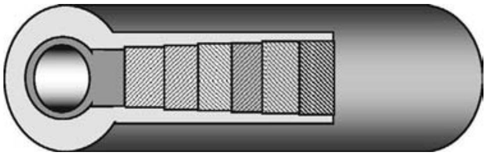


Figure 4.23 Wire-reinforced hose.

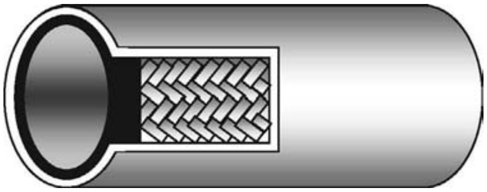


Figure 4.24 Wire-woven hose.

Various hoses made from natural latex, silicone rubber, and pure gum are available. The pure gum hose will safely carry acids, chemicals, and gases. Small hoses of natural latex, which can be sterilized, are used in hospitals for pharmaceuticals, blood, and intravenous solutions, as well as in food-handling operations and laboratories. Silicone rubber hose is used in situations where extreme temperatures and chemical reactions are possible. It is also used in aircraft starters, where it provides compressed air in very large volumes. Silicone rubber hose works successfully over a temperature range from –57°C (–70°F) to 232°C (450°F).

4.11.3.4 Metallic Hose

The construction of a braided, flexible, all-metal hose includes a tube of corrugated bronze. The tube is covered with the woven metallic braid to protect against abrasion and to provide increased resistance to pressure. Metal hose is also available in steel, aluminum, Monel®, stainless steel, and other corrosion-resistant metals in diameters up to 3 in. and in lengths of 24 in. In addition to providing protection against abrasion and resistance to pressure, flexible metal hose also dampens vibration. A plant air compressor, for example, produces a considerable amount of vibration. The use of flexible hoses in such machines increases their portability and dampens vibrations. Other considerations include constant bending at high temperatures and pressures, which can be extremely damaging to most other types of hoses.

Other common uses for metallic hoses include serving as steam lines, lubricating lines, gas and oil lines, and exhaust hose for diesel engines. The corrugated type, for example, is used for high-temperature, high-pressure leakproof service. Another type of construction is the *interlocked* flexible metal hose, used mainly for low-pressure applications. The standard shop oil can has a flexible hose for the flexible spout. Other metal hose, with a liner of flexible, corrosion-resistant material, is available in diameters of up to 24 in.

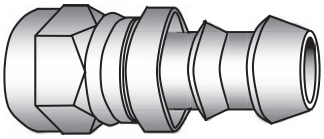


Figure 4.25 Low-pressure hose coupling.

Another type of metallic hose is used in ductwork. This type of hose is usually made of aluminum, galvanized steel, and stainless steel and is used to protect against corrosive fumes, as well as gases at extreme hot or cold temperatures. The hose is also fire resistant and usually does not burn.

4.11.4 Hose Couplings

The methods of connecting or coupling hoses vary. Hose couplings may be either permanent or reusable. They can also be manufactured for the obvious advantage of quick connect or quick disconnect. Probably the best example of the need for quick connect is fire hose—quick-disconnect couplings permit rapid connection between separate lengths of hose and between hose ends and hydrants or nozzles. Another good example of where the feature of quick connect and quick disconnect is user friendly is in plant or mobile compressed-air systems, where a single line may have a number of uses. Changes involve disconnecting one section and connecting another. In plant shops, for example, compressed air from a single source is used to power pneumatic tools, cleaning units, paint sprayers, and so on. Each unit has a hose that is equipped for rapid connecting and disconnecting at the fixed airline.

Caution: Before connections are broken, unless quick-acting, self-closing connectors are used, pressure must be released first.

For general low-pressure applications, a coupling like that shown in Figure 4.25 is used. To place this coupling on the hose by hand, first cut hose to the proper length, then oil the inside of the hose and outside of the coupling stem. Force the hose over the stem into the protective cap until it seats against the bottom of the cap. No brazing is involved, and the coupling can be used repeatedly. After the coupling has been inserted in the hose, a yoke is placed over it in such a way that its arms are positioned along opposite sides of the hose behind the fitting. The arms are then tightly strapped or banded.

Caution: Where the pressure demands are greater, such a coupling can be blown out of the tube. Hose couplings designed to meet high-pressure applications must be used.

A variation of this type uses a clamp that is put over the inner end of the fitting and is then tightly bolted, thus holding the hose firmly. In other cases, a plain clamp is used. Each size clamp is designed for a hose of a specified size (i.e., diameter). The

Key Point: For large hoses of rugged wall construction, it is not possible to insert push-on fittings by hand. Special bench tools are required.

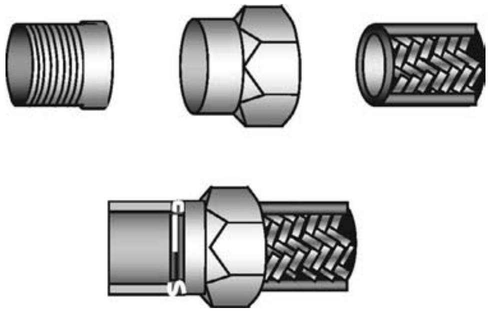


Figure 4.26 Coupling installation for all-metal hose.

clamp slides snugly over the hose and is then crimped tight by means of a special hand tool or with an air-powered tool. Coupling for all-metal hose, described earlier, involves two brazing operations, as shown in Figure 4.26. The sleeve is slipped over the hose end and brazed to it, and the nipple is then brazed to the sleeve.

Quick-connect, quick-disconnect hose couplings provide flexibility in many plant process lines where a number of different fluids or dry chemicals from a single source are either to be blended or routed to different vats or other containers. Quick-connect couplings can be used to pump out excavations, manholes, and so forth. They would not be used, however, where highly corrosive materials are involved.

4.11.5 Hose Maintenance

All types of equipment and machinery require proper care and maintenance, including hoses. Depending on the hose type and its application, some require more frequent checking than others. The maintenance procedures required for most hoses are typical and are outlined here as an example. To maintain a hose, we should:

1. Examine for cracks in the cover caused by weather, heat, oil, or usage.
2. Look for a restricted bore due to tube swelling or foreign objects.
3. Look for cover blisters, which allow material pockets to form between the carcass and cover.
4. Look for leaking materials, usually caused by improper couplings or faulty fastenings of couplings.
5. Look for corrosion damage to couplings.
6. Look for kinked or otherwise damaged hose.

Caution: Because any of the faults listed above can result in a dangerous hose failure, regular inspection is necessary. At the first sign of weakness or failure, replace the hose. System pressure and temperature gauges should be checked regularly. Do not allow the system to operate above design conditions—especially when hose is a component of the system.

4.12 PIPE AND TUBE FITTINGS

The term *piping* refers to the overall network of pipes or tubing, fittings, flanges, valves, and other components that comprise a conduit system used to convey fluids. Whether a piping system is used to simply convey fluids from one point to another or to process and condition the fluid, piping components serve an important role in the composition and operation of the system. A system used solely to convey fluids may consist of relatively few components, such as valves and fittings, whereas a complex chemical processing system may consist of a variety of components used to measure, control, condition, and convey the fluids. This section describes the characteristics and functions of various piping and tubing fittings (Geiger, 2000).

4.12.1 Fittings

The primary function of fittings is to connect sections of piping and tubing and to change direction of flow. Whether used in piping or tubing, fittings are similar in shape and type, even though pipe fittings are usually heavier than tubing fittings. Several methods can be used to connect fittings to piping and tubing systems; however, most tubing is threadless because it does not have the wall thickness required to carry threads. Most pipes, on the other hand, because they have heavier walls, are threaded.

With regard to changing direction of flow, the simplest way would be to bend the conduit, which, of course, is not always practical or possible. When piping is bent, it is usually accomplished by the manufacturer in the production process (in larger shops equipped with their own pipe-bending machines), but not by the maintenance operator on the job. Tube bending, on the other hand, is a common practice. Generally, a tubing line requires fewer fittings than a pipeline; however, in actual practice many tube fittings are used.

Key Point: Recall that improperly made bends can restrict fluid flow by changing the shape of the pipe and weakening the pipe wall.

Fittings are basically made from the same materials (and in the same broad ranges of sizes) as piping and tubing, including bronze, steel, cast iron, glass, and plastic. Various established standards are in place to ensure that fittings are made from the proper materials and are able to withstand the pressures required; they are also made to specific tolerances, so they will properly match the piping or tubing that they join. A fitting stamped “200 lb,” for example, is suitable (and safe) for use up to 200 psi.

4.12.2 Functions of Fittings

Fittings in piping and tubing systems have five main functions:

- Changing the direction of flow
- Providing branch connections
- Changing sizes of lines
- Sealing lines
- Connecting lines

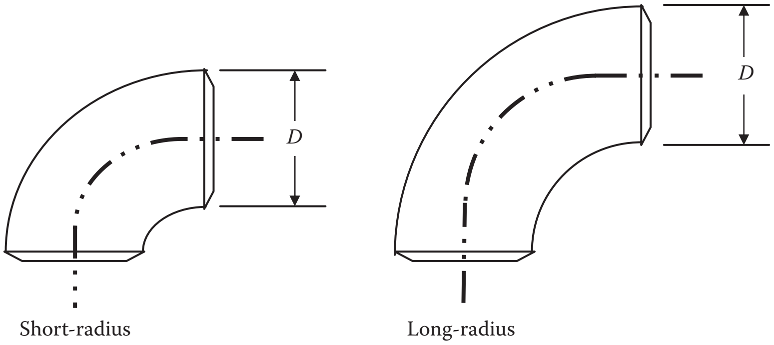


Figure 4.27 Short- and long-radius elbows.

4.12.2.1 Changing the Direction of Flow

Usually, a 45° or 90° *elbow* (or "ell") fitting is used to change the direction of flow. Elbows are among the most commonly used fittings in piping and are occasionally used in tubing systems. Two types of 90° elbows are shown in Figure 4.27. From the figure, it is apparent that the *long-radius* fitting (the most preferred elbow) has the more gradual curve of the two. This type of elbow is used in applications where the rate of flow is critical and space presents no problem. Flow loss caused by turbulence is minimized by the gradual curve. The *short-radius* elbow (see Figure 4.27) should not be used in a system made up of long lines that has many changes in direction. Because of the greater frictional loss in the short-radius elbow, heavier, more expensive pumping equipment may be required. Figure 4.28 shows a *return bend* fitting that carries fluid through a 180° ("hairpin") turn. This type of fitting is used for piping in heat exchangers and heater coils. Note that tubing, which can be bent into this form, does not require any fittings in this kind of application.

4.12.2.2 Providing Branch Connections

Because they are often more than single lines running from one point to another point, piping and tubing systems usually have a number of intersections. In fact, many complex piping and tubing systems resemble the layout of a town or city.

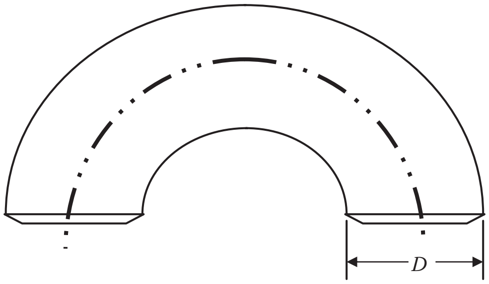


Figure 4.28 Long-radius return bend.

4.12.2.3 *Changing Sizes of Lines*

For certain applications, it is important to reduce the volume of fluid flow or to increase flow pressure in a piping or tubing system. To accomplish this a *reducer* (which reduces a line to a smaller pipe size) is commonly used.

Note: Reducing is also sometimes accomplished by means of inserting a bushing into the fitting.

4.12.2.4 *Sealing Lines*

Pipe *caps* are used to seal or close off the end of a pipe or tube (similar to corking a bottle). Usually, caps are used in a part of the system that has been dismantled. To seal off openings in fittings, *plugs* are used. Plugs also provide a means of access into the piping or tubing system, in case the line becomes clogged.

4.12.2.5 *Connecting Lines*

To connect two lengths of piping or tubing together, a coupling or union is used. A *coupling* is simply a threaded sleeve. A *union* is a three-piece device that includes a threaded end, an internally threaded bottom end, and a ring. A union does not change the direction of flow, close off the pipe, or provide for a branch line. Unions make it easy to connect or disconnect pipes without disturbing the position of the pipes. Figure 4.29 is a diagram of a shortened piping system that illustrates how some fittings are used in a piping system. (Figure 4.29 is only for illustrative purposes; it is unlikely that such a system with so many fittings would actually be used.)

4.12.3 Types of Connections

Pipe connections may be screwed, flanged, or welded. Each method is widely used, and each has its own advantages and disadvantages.

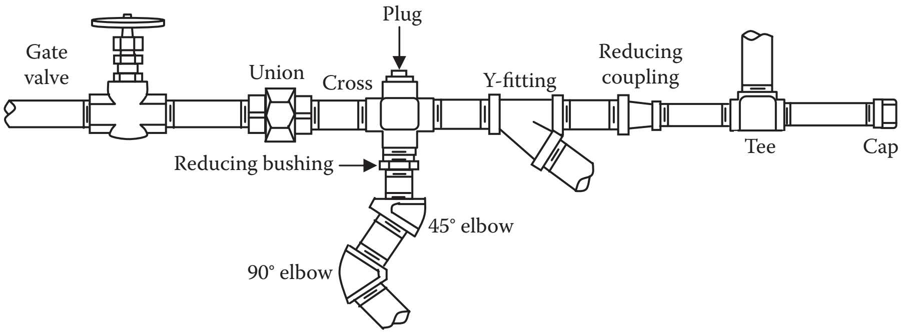


Figure 4.29 Diagram of a hypothetical shortened piping system.

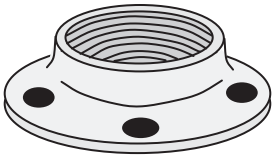


Figure 4.30 Flanged fitting.

4.12.3.1 Screwed Fittings

Screwed fittings are joined to the pipe by means of threads. The main advantage of using threaded pipe fittings is that they can be easily replaced. The actual threading of a section of replacement pipe can be accomplished on the job. The threading process itself, however, which cuts right into the pipe material, may weaken the pipe in the joint area. The weakest links in a piping system are the connection points. Because threaded joints can be potential problem areas, especially where higher pressures are involved, the threads must be properly cut to ensure that the weakest link is not further compromised. Typically, the method used to ensure a good seal in a threaded fitting is to coat the threads with a paste dope. Another method is to wind the threads with Teflon® tape.

4.12.3.2 Flanged Connections

Figure 4.30 shows a flanged fitting. *Flanged* fittings are forged or cast iron pipe. The *flange* is a rim at the end of the fitting that mates with another section. Pipe sections are also made with flanged ends. Flanges are joined either by being bolted or welded together. The flange faces may be ground and lapped to provide smooth, flat mating surfaces. Obviously, a tight joint must be provided to prevent leakage of fluid and pressure. Figure 4.31 shows a typical example of a flanged joint. The mating parts are bolted together with a gasket inserted between their faces to ensure a tight seal. The procedure requires proper alignment of clean parts and tightening of bolts.

Key Point: Some flanges have raised faces and others have plain faces. Like faces must be matched—a flange with a raised face should never be joined to one with a plain face.

4.12.3.3 Welded Connections

Currently, because of improvements in piping technology and welding techniques and equipment, the practice of using welded joints is increasing. When properly welded, a piping system forms a continuous system that combines piping, valves, flanges, and other fittings. Along with providing a long leakproof and maintenance-free life, the smooth joints simplify insulation and take up less room.

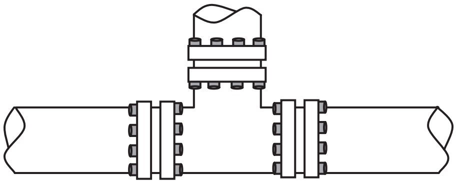


Figure 4.31 Flanged joint.

4.12.4 Tubing Fittings and Connections

Tubing is connected by brazed or welded flange fittings, compression fittings, and flare fittings. The *welded flange* connection is a reliable means of connecting tubing components. The flange welded to the tube end fits against the end of the fitting. The locknut of the flange is then tightened securely onto the fitting. The *compression fitting* connection uses a ferrule that pinches the tube as the locknut is tightened on the body of the fitting. The *flare fitting* connection uses tubing flared on one end of the tubing that matches the angle of the fitting. The flared end of the tube is butted against the fitting, and a locknut is screwed tightly onto the fitting, sealing the tube connection properly.

Other fittings used for flanged connections include *expansion joints* and *vibration dampeners*. Expansion joints function to compensate for slight changes in the length of pipe by allowing joined sections of rigid pipe to expand and contract with changes in temperature. They also allow pipe motion, either along the length of the pipe or to the side, as the pipe shifts around slightly after installation. Finally, expansion joints also help dampen vibration and noise carried along the pipe from distant equipment (e.g., pumps). One type of expansion joint has a leakproof tube that extends through the bore and forms the outside surfaces of the flanges. Natural or synthetic rubber compounds are normally used, depending on the application. Other types of expansion joints include metal corrugated types, slip-joint types, and spiral-wound types. In addition, high-temperature lines are usually made up with a large bend or loop to allow for expansion. Vibration dampeners absorb vibrations that, unless reduced, could shorten the life of the pipe and the service life of the operating equipment. They also eliminate line humming and hammering (water hammer) carried by the pipes.

4.13 VALVES

Any wastewater operation will have many valves that require attention. A maintenance operator must be able to identify and locate different valves to inspect them, adjust them, and repair or replace them. For this reason, the operator should be familiar with all valves, especially those that are vital parts of a piping system. A *valve* is defined as any device by which the flow of fluid may be started, stopped, or regulated by a movable part that opens or obstructs passage. As applied in fluid power systems, valves are used for controlling the flow, the pressure, and the direction of the fluid flow through a piping system. The fluid may be a liquid, a gas, or some loose material in bulk (such as a biosolids slurry). Designs of valves vary, but all valves have two features in common: a passageway through which fluid can flow and some kind of movable (usually machined) part that opens and closes the passageway (*Valves*, 1998).

Key Point: It is all but impossible, obviously, to operate a practical fluid power system without some means of controlling the volume and pressure of the fluid and directing the flow of fluid to the operating units. This is accomplished by incorporating various types of valves.

Whatever type of valve is used in a system, it must be accurate in the control of fluid flow and pressure and the sequence of operation. Leakage between the valve element and the valve seat is reduced to a

TABLE 4.1 VALVES: MATERIALS OF CONSTRUCTION

Cast iron	Gray cast iron; also referred to as *flake graphite iron*
Ductile iron	May be malleable iron or spheroidal graphite (nodular) cast iron
Carbon steel	May be as steel forgings, or steel castings, according to the method of manufacture; may also be manufactured by fabrication using wrought steels
Stainless steel	May be in the form of forgings, castings, or wrought steels for fabrication
Copper alloy	May be gunmetal, bronze, or brass; aluminum bronze may also be used
High-duty alloys	Usually nickel or nickel molybdenum alloys manufactured under various trade names
Other metals	Pure metals having extreme corrosion resistance, such as titanium, or aluminum
Nonmetals	Typically plastic materials such as PVC or polypropylene

negligible quantity by precision-machined surfaces, resulting in carefully controlled clearances. This is, of course, one of the very important reasons for minimizing contamination in fluid power systems. Contamination causes valves to stick, plugs small orifices, and causes abrasions of the valve seating surfaces, resulting in leakage between the valve element and valve seat when the valve is in the closed position. Any of these can result in inefficient operation or complete stoppage of the equipment. Valves may be controlled manually, electrically, pneumatically, mechanically, or hydraulically, or by combinations of two or more of these methods. Factors that determine the method of control include the purpose of the valve, the design and purpose of the system, the location of the valve within the system, and the availability of the source of power.

Valves are made from bronze, cast iron, steel, Monel®, stainless steel, and other metals. They are also made from plastic and glass (see Table 4.1). Special valve trim is used where seating and sealing materials are different from the basic material of construction (see Table 4.2). (*Valve trim* usually refers to those internal parts of a valve controlling the flow and in physical contact with the line fluid.) Valves are made in a full range of sizes that match pipe and tubing sizes. Actual valve size is based on the internationally agreed-upon definition of nominal size (DN), which is a numerical designation of size that is common to all components in a piping system other than components designated by outside diameters. It is a convenient number for reference purposes and is only loosely related to manufacturing dimensions.

Valves are made for service at the same pressures and temperatures that piping and tubing is subject to. Valve pressures are based on the internationally agreed definition of nominal pressure (PN), which is a pressure that is conventionally accepted or used for reference purposes. All equipment of the same nominal size (DN) designated by the same nominal pressure (PN) number must have the same mating dimensions appropriate to the type of end connections. The permissible working

TABLE 4.2 VALVE TRIM

Metal seating	Commonly used in gate and globe valves, particularly in the latter for control applications where seatings may additionally be coated with hard metal.
Soft seating	Commonly used in ball, butterfly, and diaphragm valves; seatings may be made from a wide variety of elastomers and polymers including fluorocarbons.
Lined	Usually made in cast iron with an internal lining of elastomer of polymer material. Inorganic materials such as glass, together with metals such as titanium, are also used for lining. Lining thickness will depend on the design and type of material used. In many cases, the valve lining will also form the seating trim.

TABLE 4.3 VALVE END CONNECTIONS

Flanged	Valves are normally supplied with flanges conforming to either BS4505 (equivalent to DIN) or BS 1560 (equivalent to ANSI), according to specifications. Manufacturers may be able to supply valves with flanges to other standards.
Threaded	Valves are normally supplied with threads to BS21 (ISO/7), parallel or taper.
Other	End connections include butt or socket weld, and wafer valves are designed to fit between pipe flanges.

TABLE 4.4 VALVE SPECIAL FEATURES

High temperature	Valves are usually able to operate continuously on services above 250°C.
Cryogenic	Valves will operate continuously on services in the range of –50°C to 196°C.
Bellows sealed	Valves are glandless designs having a metal bellows for stem sealing.
Actuated	Valves may be operated by a gearbox, pneumatic or hydraulic cylinder (including diaphragm actuator), or electric motor and gearbox.
Fire-tested design	Valves have passed a fire test procedure specified in an appropriate inspection standard.

pressure depends on materials, design, and working temperature and should be selected from the (relevant), pressure–temperature tables. The pressure rating of many valves is designated under the ANSI class system. The equivalent class rating to PN ratings is based on international agreement. Valves are also covered by various codes and standards, as are the other components of piping and tubing systems.

Usually, valve end connections are classified as *flanged*, *threaded*, or *other* (see Table 4.3). Many valve manufacturers offer valves with special features. Table 4.4 lists a few of these special features; however, this is not an exhaustive list and the manufacturer should be consulted for more details of other features. The various types of valves used in fluid power systems, their classifications, and the applications are discussed in this section.

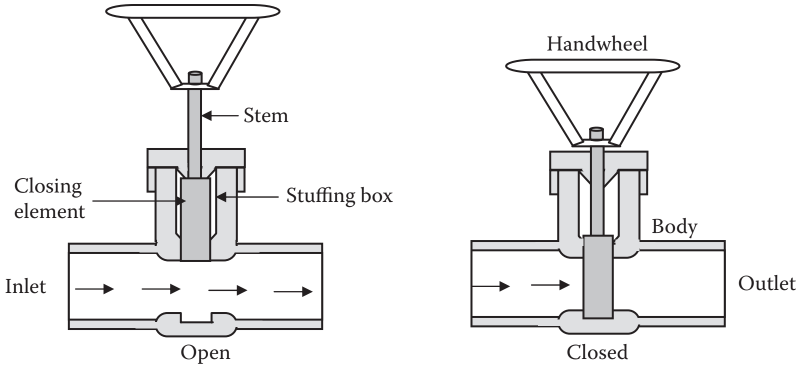


Figure 4.32 Basic valve operation.

4.13.1 Valve Construction

Figure 4.32 shows the basic construction and principle of operation of a common valve type. Fluid flows into the valve through the inlet. The fluid flows through passages in the body and past the opened element that closes the valve. It then flows out of the valve through the outlet or discharge. If the closing element is in the closed position, the passageway is blocked. Fluid flow is stopped at that point. The closing element keeps the flow blocked until the valve is opened again. Some valves are opened automatically, whereas manually operated hand wheels control others. Other valves, such as check valves, operate in response to pressure or the direction of flow. To prevent leakage whenever the closing element is positioned in the closed position, a seal is used. In Figure 4.32, the seal consists of a *stuffing box* fitted with packing. The closing element fits against the *seat* in the valve body to keep the valve tightly closed.

4.13.2 Types of Valves

The types of valves covered in this text include:

- Ball valves
- Gate valves
- Globe valves
- Needle valves
- Butterfly valves
- Plug valves
- Check valves
- Quick-opening valves
- Diaphragm valves
- Regulating valves
- Relief valves
- Reducing valves

Each of these valves is designed to control the flow, pressure, and direction of fluid flow or for some other special application. With a few exceptions, these valves take their names from the type of internal element that controls the passageway. The exceptions are the check valve, quick-opening valve, regulating valve, relief valve, and reducing valve.

4.13.2.1 Ball Valves

Ball valves, as the name implies, are stop valves that use a ball to stop or start fluid flow. The ball performs the same function as the disk in other valves. As the valve handle is turned to open the valve, the ball rotates to a point where part or all of the hole through the ball is in line with the valve body inlet and outlet, allowing fluid to flow through the valve. When the ball is rotated so the hole is perpendicular to the flow openings of the valve body, the flow of fluid stops. Most ball valves are the quick-acting type and require only a 90° turn to either completely open or close the valve; however, many are operated by planetary gears. This type of gearing allows the use of a relatively small hand wheel and operating force to operate a large valve; however, it increases the operating time for the valve. Some ball valves also contain a swing check located within the ball to give the valve a check valve feature. The two main advantages of using ball valves are that: (1) the fluid can flow through it in either direction, as desired; and (2) when closed, pressure in the line helps to keep it closed.

4.13.2.2 Gate Valves

Gate valves are used when a straight-line flow of fluid and minimum flow restriction are necessary; they are the most common type of valve found in a water distribution system. Gate valves are so named because the part that either stops or allows flow through the valve acts somewhat like a gate. The gate is usually wedge shaped. When the valve is wide open, the gate is fully drawn up into the valve bonnet. This leaves an opening for flow through the valve the same size as the pipe in which the valve is installed. For these reasons, the pressure loss (pressure drop) through these types of valves is about equal to the loss in a piece of pipe of the same length. Gate valves are not suitable for throttling purposes (i.e., controlling the flow by means of intermediate steps between fully open and fully closed). The control of flow is difficult because of the design of the valve, and the flow of fluid slapping against a partially open gate can cause extensive damage to the valve.

Key Point: Gate valves are well suited to service on equipment in distant locations, where they may remain in the open or closed position for a long time. Generally, gate valves are not installed where they will have to be operated frequently because they require too much time to operate from fully open to closed (AWWA, 1996).

4.13.2.3 Globe Valves

Probably the most common valve type in existence, the globe valve is commonly used for water faucets and other household plumbing. As illustrated in Figure 4.33, the valves have a circular disk (the globe) that

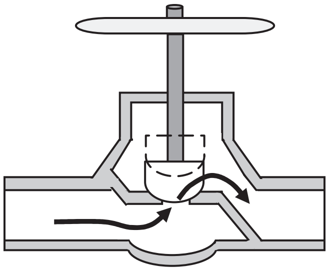


Figure 4.33 Globe valve.

presses against the valve seat to close the valve. The disk is the part of the globe valve that controls flow. The disk is attached to the valve stem. As shown in Figure 4.33, fluid flow through a globe valve is at right angles to the direction of flow in the conduits. Globe valves seat very tightly and can be adjusted with fewer turns of the wheel than gate valves; thus, they are preferred for applications that call for frequent opening and closing. On the other hand, globe valves create high head loss when fully open; thus, they are not suited in systems where head loss is critical.

Key Point: The globe valve should never be jammed in the open position. After a valve is fully opened, the hand wheel should be turned toward the closed position approximately one-half turn. Unless this is done, the valve is likely to seize in the open position, making it difficult, if not impossible, to close the valve. Another reason for not leaving globe valves in the fully open position is that it is sometimes difficult to determine if the valve is open or closed (*Valves*, 1998).

4.13.2.4 Needle Valves

Although similar in design and operation to the globe valve (a variation of globe valves), the needle valve has closing element in the shape of a long tapered point, which is at the end of the valve stem. Figure 4.34 shows a cross-sectional view of a needle valve. As you can see in the figure, the long taper of the valve closing element permits a much smaller seating surface area than that of the globe valve; accordingly, the needle valve is more suitable as a throttle valve. In fact, needle valves are used for very accurate throttling.

4.13.2.5 Butterfly Valves

Figure 4.35 shows a cross-sectional view of a butterfly valve. The valve itself consists of a body in which a disk ("butterfly") rotates on a shaft to open or close the valve. Butterfly valves may be flanged or wafer design, the latter intended for fitting directly between pipeline flanges. In the full open position, the disk is parallel to the axis of the pipe and the flow of fluid. In the closed position, the disk seals against a rubber

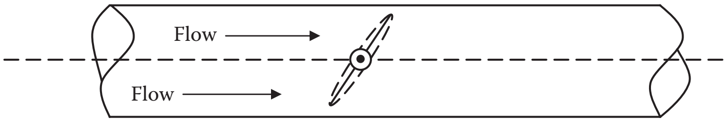


Figure 4.34 Common needle valve.

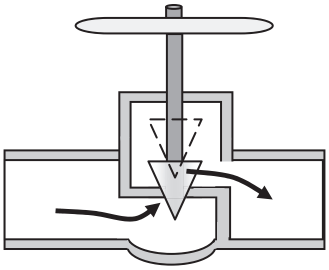


Figure 4.35 Cross-section of butterfly valve.

gasket-type material bonded either on the valve seat of the body or on the edge of the disk. Because the disk of a butterfly valve stays in the fluid path in the open position, the valve creates more turbulence (higher resistance to flow and thus higher pressure loss) than a gate valve. On the other hand, butterfly valves are compact. They can also be used to control flow in either direction. This feature is useful in water treatment plants that periodically backwash to clean filter systems.

4.13.2.6 Plug Valves

Similar to ball valves, plug valves (also known as *cock*s or *petcocks*):

- Offer high-capacity operation (1/4 turn operation).
- Use either a cylindrical or conical plug as the closing member.
- Are directional.
- Offer moderate vacuum service.
- Allow flow throttling with interim positioning.
- Are of a simple construction (O-ring seal).
- Are not necessarily full on and off.
- Are easily adapted to automatic control.
- Can safely handle gases and liquids.

4.13.2.7 Check Valves

Check valves are usually self-acting and designed to allow the flow of fluid in one direction only. They are commonly used at the discharge of a pump to prevent backflow when the power is turned off. When the direction of flow is moving in the proper direction, the valve remains open. When the direction of flow reverses, the valve closes automatically from the fluid pressure against it. Several types of check valves are used in wastewater operations, including:

- Slanting disk check valves
- Cushioned swing check valves
- Rubber-flapper swing check valves

- Double-door check valves
- Ball check valves
- Foot valves
- Backflow-prevention devices

In each case, pressure from the flow in the proper direction pushes the valve element to an open position. Flow in the reverse direction pushes the valve element to a closed position.

Note: Check valves are also commonly referred to as *nonreturn* or *reflux valves*.

4.13.2.8 Quick-Opening Valves

Quick-opening valves are nothing more than adaptations of some of the valves already described. Modified to provide a quick on/off action, they use a lever device in place of the usual threaded stem and control handle to operate the valve. This type of valve is commonly used in wastewater operations where deluge showers and emergency eyewash stations are installed in work areas where chemicals are loaded or transferred or where chemical systems are maintained. They also control the air supply for some emergency alarm horns around chlorine storage areas, for example. Moreover, they are usually used to cut off the flow of gas to a main or to individual outlets.

4.13.2.9 Diaphragm Valves

Diaphragm valves are glandless valves that use a flexible elastomeric diaphragm (a flexible disk) as the closing member and in addition effect an external seal. They are well suited to service in applications where tight, accurate closure is important. The tight seal is effective whether the fluid is a gas or a liquid. This tight closure feature makes these valves useful in vacuum applications. Diaphragm valves operate similar to globe valves and are usually multi-turn in operation; they are available as weir type and full bore. A common application of diaphragm valves in wastewater operations is to control fluid to an elevated tank.

4.13.2.10 Regulating Valves

As their name implies, regulating valves regulate either pressure or temperature in a fluid line, keeping them very close to a preset level. If the demands and conditions of a fluid line remained steady at all times, no regulator valve would be needed. In the real world, however, ideal conditions do not occur. *Pressure-regulating* valves regulate fluid pressure levels to meet flow demand variations. Flow variations vary with the number of pieces of equipment in operation and with changes in demand as pumps and other machines operate. In such fluid line systems, demands are constantly changing. Probably the best example of this situation is seen in the operation of a low-pressure air supply system. For shop

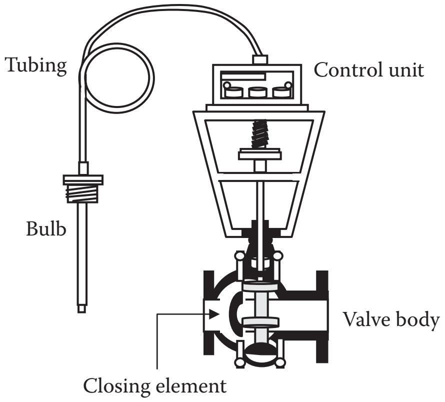


Figure 4.36 Pressure-regulating valve system.

use, no more than 30 psi air is usually required (depending on required usage, of course). The air is supplied by an air compressor, which normally operates long enough to fill an accumulator with pressurized air at a set pressure level.

When shop air is required, for whatever reason, compressed air is drawn from the connection point in the shop. The shop connection point is usually connected via a pressure reducer (sets the pressure at the desired usage level) that, in turn, is fed from the accumulator, where the compressed air is stored. If the user draws a large enough quantity of compressed air from the system (from the accumulator), a sensing device within the accumulator will send a signal to the air compressor to start, which will produce compressed air to recharge the accumulator. In addition to providing service in airlines, pressure-regulating valves are also used in liquid lines. The operating principle is much the same for both types of service. Simply, the valve is set to monitor the line and to make needed adjustments in response to a signal from a sensing device.

Temperature-regulating valves (also referred to as *thermostatic control valves*) are closely related to pressure-regulating valves (see Figure 4.36). Their purpose is to monitor the temperature in a line or process solution tank and to regulate it—to raise or lower the temperature as required. In wastewater operations, probably the most familiar application for temperature-regulating valves (see Figure 4.37) is in *heat exchangers*. A heat exchanger type of water system utilizes a water-to-coolant heat exchanger for heat dissipation. This is an efficient and effective method to dispose of unwanted heat. Heat exchangers are equipped with temperature-regulating valves that automatically modulate the shop process water, limiting usage to just what is required to achieve the desired coolant temperature.

4.13.2.11 Relief Valves

Some fluid power systems, even when operating normally, may temporarily develop excessive pressure; for example, whenever an unusually strong work resistance is encountered, dangerously high pressure

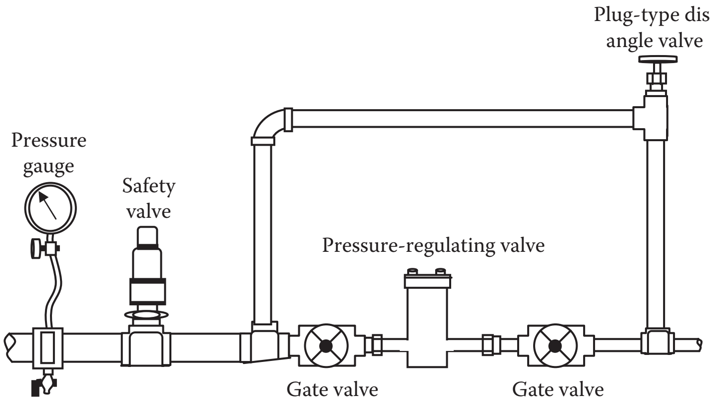


Figure 4.37 Temperature-regulating valve assembly.

may develop. Relief valves are used to control this excess pressure. Such valves are automatic valves; they begin to open at a preset pressure but require a 20% overpressure to open wide. As the pressure increases, the valve continues to open farther until it has reached its maximum travel. As the pressure drops, it starts to close and finally shuts off at about the set pressure. Main system relief valves are generally installed between the pump or pressure source and the first system isolation valve. The valve must be large enough to allow the full output of the hydraulic pump to be delivered back to the reservoir.

Note: Relief valves do not maintain flow or pressure at a given amount but prevent pressure from rising above a specific level when the system is temporarily overloaded.

4.13.2.12 Pressure-Reducing Valves

Pressure-reducing valves provide a steady pressure into a system that operates at a lower pressure than the supply system. In practice, they are very much like pressure-regulating valves. A pressure-reducing valve reduces pressure by throttling the fluid flow. A reducing valve can normally be set for any desired downstream pressure within the design limits of the valve. Once the valve is set, the reduced pressure will be maintained regardless of changes in supply pressure (as long as the supply pressure is at least as high as the reduced pressure desired) and regardless of the system load, providing the load does not exceed the design capacity of the reducer.

4.13.3 Valve Operators

In many modern wastewater operations, devices called *operators* or *actuators* mechanically operate many valves. These devices may be operated by air, electricity, or fluid—that is, by pneumatic, hydraulic, and magnetic operators.

4.13.3.1 Pneumatic and Hydraulic Valve Operators

Pneumatic and hydraulic valve operators are similar in appearance and work in much the same way. Hydraulic cylinders using either plant water pressure or hydraulic fluid frequently operate valves in treatment plants and pumping stations (AWWA, 1996). In a typical pneumatic ball-valve actuator, the cylinder assembly is attached to the ball-valve stem close to the pipe. A piston inside the cylinder can move in either direction. The piston rod is linked to the valve stem, opening or closing the valve, depending on the direction in which the piston is traveling. As a fail-safe feature, some of these valves are spring loaded. In case of hydraulic or air pressure failure, the valve operator returns the valve to the safe position.

Note: Valve operators and positioners usually require more maintenance than the valves themselves (Casada, 2000).

4.13.3.2 Magnetic Valve Operators

Magnetic valve operators use electric solenoids. A *solenoid* is a coil of magnetic wire, roughly in the shape of a doughnut. When a bar of iron is inserted as a plunger mechanism inside an energized coil, it moves along the coil because of the magnetic field that is created. If the plunger (the iron bar) is fitted with a spring, it returns to its starting point when the electric current is turned off. Solenoids are used as operators for many different types of valves used in water/wastewater operations; for example, in a direct-operating valve, the solenoid plunger is used in place of a valve stem and hand wheel. The plunger is connected directly to the disk of a globe valve. As the solenoid coil is energized or de-energized, the plunger rises or falls, operating or closing the valve.

4.13.4 Valve Maintenance

As with any other mechanical device, effective valve maintenance begins with its correct operation. As an example of incorrect operation, consider the standard household water faucet. As the faucet washers age, they harden and deteriorate. The valve becomes more difficult to operate properly, and eventually the valve begins to leak. A common practice is simply to apply as much force as possible to the faucet handle. Doing so, however, damages the valve stem and the body of the valve body. Good maintenance includes preventive maintenance, which, in turn, includes inspection of valves, correct lubrication of all moving parts, and the replacement of seals or stem packing.

4.14 PIPING SYSTEM PROTECTIVE DEVICES

Piping systems must be protected from the harmful effects of undesirable impurities (solid particles) entering the fluid stream. Because of the considerable variety of materials carried by piping systems, an equal range of choices in protective devices is available. Such protective devices include strainers, filters, and traps. In this section, we describe the design and function of strainers, filters, and traps. The major maintenance considerations of these protective devices also are explained.

4.14.1 Applications

Key Point: A very large percentage (estimated to be >70%) of all plant facilities in the United States make use of steam in some type of application.

Filters, strainers, and traps are normally thought of in terms of specific components used in specific systems; however, it is important to keep in mind that the basic principles apply in many systems. Although the examples used in this chapter include applications found in wastewater treatment, collection, and distribution systems, the applications are also found in almost every plant—hot and cold water lines, lubricating lines, pneumatic and hydraulic lines, and steam lines. With regard to steam lines, it is important to point out that in our discussion of traps, their primary application is in steam systems, where they remove unwanted air and condensate from lines.

Other system applications of piping protective devices include the conveyance of hot and chilled water for heating and air conditioning and lines that covey fluids for various processes. Any foreign contamination in any of these lines can cause potential trouble. Piping systems can become clogged, thereby causing greatly increased friction and lower line pressure. Foreign contaminants (dirt and other particles) can also damage valves, seals, and pumping components.

Note: Foreign particles in a high-pressure line can damage a valve by clogging the valve so it cannot close tightly. In addition, foreign particles may wear away the closely machined valve parts.

4.14.2 Strainers

Strainers, usually wire mesh screens, are used in piping systems to protect equipment sensitive to contamination that may be carried by the fluid. Strainers can be used in pipelines conveying air, gas, oil, steam, water, wastewater, and nearly any other fluid conveyed by pipes. Generally, strainers are installed ahead of valves, pumps, regulators, and traps to protect them against the damaging effects of corrosion products that may become dislodged and conveyed throughout the piping system (Geiger, 2000).

A common strainer is shown in Figure 4.38. This type of strainer is generally used upstream of traps, control valves, and instruments. This strainer resembles a lateral branch fitting with the strainer element installed in the branch. The end of the lateral branch is removable to permit servicing of the strainer. In operation, the fluid passes through the strainer screen, which catches most of the contaminants. Then the fluid passes back into the line. Contaminants in the fluid are caught in two ways—either they do not make it through the strainer screen or they do not make the sharp turn that the fluid must take as it leaves the unit. The bottom of the unit serves as a sump where the solids

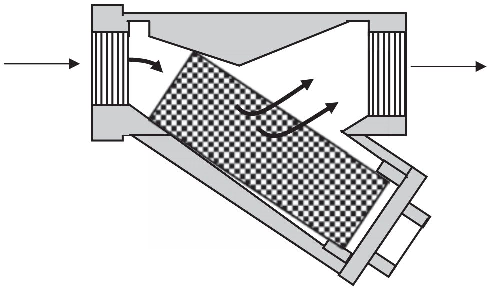


Figure 4.38 A common strainer.

collect. A blow-out connection may be provided in the end cap to flush the strainer. The blow-out plug can be removed, and pressure in the line can be used to blow the fixture clean.

Caution: Before removing the blow-out plug, the valve system must be locked out/tagged out first.

4.14.3 Filters

The purpose of any filter is to reduce or remove impurities or contaminants from a fluid (liquid or gas) to an acceptable or predetermined level. This is accomplished by passing the fluid through some kind of porous barrier. Filter cartridges have replaceable elements made of paper, wire cloth, nylon cloth, or fine-mesh nylon cloth between layers of coarse wire. These materials filter out unwanted contaminants that collect on the entry side of the filter element. When clogged, the element is replaced. Most filters operate in two ways: (1) they cause the fluid to make sharp changes in direction as it passes through (this is important, because the larger particles are too heavy to change direction quickly), or (2) they contain some kind of barrier that will not let larger contaminants pass.

4.14.4 Traps

Traps, used in steam processes, are automatic valves that release condensate (condensed steam) from a steam space while preventing the loss of live steam. Condensate is undesirable because water produces rust, and water plus steam leads to water hammer. In addition, steam traps remove air and noncondensate from the steam space. The operation of a trap depends on what is called *differential pressure* (or delta-P), measured in psi. Differential pressure is the difference between the inlet and outlet pressures. A trap will not operate correctly at a differential pressure higher than the one for which it was designed.

Many types of steam traps are available because of their many different types of applications. Each type of trap has a range of applications for which it is best suited; for example, thermostatic and float-and-thermostatic are two general types of traps. *Thermostatic traps* have a corrugated bellows-operating element that is filled with an alcohol mixture that has a

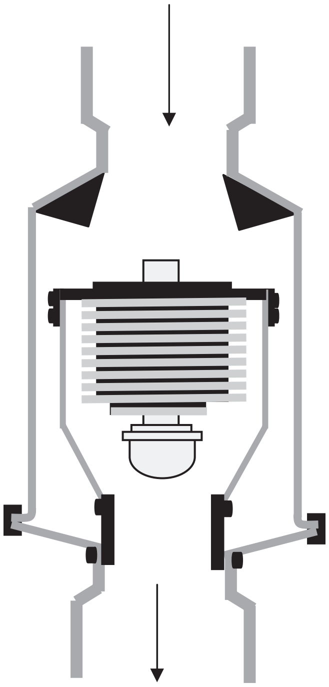


Figure 4.39 A thermostatic trap (shown in the open position).

boiling point lower than that of water (see Figure 4.39). The bellows contracts when in contact with condensate and expands when steam is present. If a heavy condensate load occurs, the bellows will remain in the contracted state, allowing condensate to flow continuously. As steam builds up, the bellows closes. Thus, at times the trap acts as a "continuous flow" type, while at other times it acts intermittently as it opens and closes to condensate and steam, or it may remain totally closed (Bandes and Gorelick, 2000).

Key Point: The thermostatic trap is designed to operate at a definite temperature drop a certain number of degrees below the saturated temperature for the existing steam pressure.

A *float-and-thermostatic* trap is shown in Figure 4.40. It consists of a ball float and a thermostatic bellows element. As condensate flows through the body, the float rises and falls, opening the valve according to the flow rate. The thermostatic element discharges air from the steam lines. They are suitable for heavy and light loads and on high and low pressure, but they are not recommended where water hammer is a possibility.

4.14.4.1 Trap Maintenance and Testing

Because they operate under constantly varying pressure and temperature conditions, traps used in steam systems require maintenance. Just as significant, because of these varying conditions, traps can fail. When they do fail, most traps fail in the open mode, which may require the boiler to work harder to perform a task which, in turn, can create high backpressure to the condensate system. This reduces the discharge capacities of some traps, which may be operating beyond their rating and thus cause system inefficiency. A closed trap produces condensate

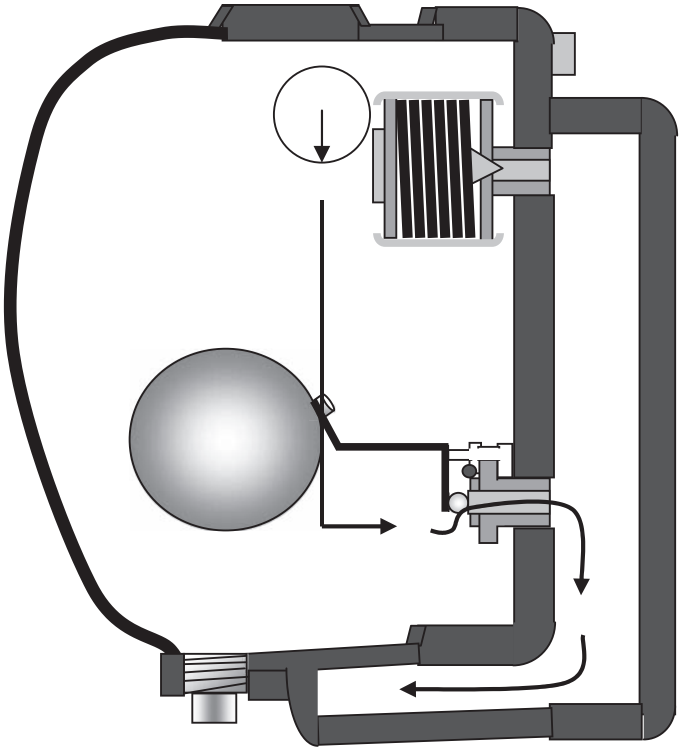


Figure 4.40 A float-and-thermostatic trap.

back up into the steam space, and the equipment cannot produce the intended heat. Consider, as an example, a four-coil dryer with only three of the coils operating. In this setup, it will take longer for the dryer to dry a product, which has a negative effect on production.

Note: Most traps will operate with backpressure, but they do so only at a percentage of their rating, affecting everything down the line of the failed trap. Steam quality and product can be affected.

4.14.4.1.1 Trap Maintenance

Excluding design problems, two of the most common causes of trap failure are oversizing and dirt. Oversizing causes the traps to work too hard. In some cases, this can result in blowing of live steam. Certain trap types, for example, can lose their prime due to an abrupt change in pressure. This will cause the valve to open. Traps tend to accumulate dirt (sludge) that prevents tight closing. The moving parts of the traps are subject to wear. Because the moving parts of traps operate in a mixture of steam and water, or sometimes in a mixture of compressed air and water, they are difficult to lubricate. Trap maintenance includes periodic cleaning, removing dirt that interferes with valve action, adjusting the mechanical linkage between moving parts and valves, and reseating the valves when necessary. If these steps are not taken, the trap will not operate properly.

Key Point: Dirt (sludge) is generally produced from pipe scale or from overtreatment of chemicals in a boiler.

4.14.4.1.2 Trap Testing

Note: A word of caution is advised before testing any steam trap. Inspectors should be familiar with the particular function and types of traps and should know the various pressures within the system. This can help to ensure inspector safety, help avoid misdiagnosis, and allow proper interpretation of trap conditions.

The three main categories of online trap inspection are visual, thermal, and acoustic. *Visual* inspection depends on a release valve situated downstream of certain traps. A maintenance operator opens these valves and looks to see if the trap is discharging condensate or steam. *Thermal* inspection relies on upstream/downstream temperature variations in a trap. It includes pyrometry, infrared, heat bands (which are wrapped around a trap and change color as temperature increases), and heat sticks (which melt at various temperatures). *Acoustic* techniques require a maintenance operator to listen to and detect steam trap operations and malfunction. This method includes various forms of listening devices such as medical stethoscopes, screwdrivers, mechanical stethoscopes, and ultrasonic detection instruments.

Note: A simple trap test—just listening to the trap action—tells us how the trap is opening and closing. Moreover, if the trap has a bypass line around it, leaky valves will be apparent when the main line to the trap is cut off, forcing all of the fluid through the bypass.

4.15 PIPING ANCILLARIES

Earlier, we described various devices associated with process piping systems designed to protect the system. In this section, we discuss some of the most widely used ancillaries (or accessories) designed to improve the operation and control the system. These include pressure and temperature gauges, vacuum breakers, accumulators, receivers, and heat exchangers. It is important for us to know how these ancillary devices work, how to care for them, and, more importantly, how to use them.

4.15.1 System Parameters

To properly operate a system, any system, the operator must know certain things. As an example, to operate a plant air compressor the operator must know: (1) how to operate it, (2) how to maintain it, (3) how to monitor its operation, and, in many cases, (4) how to repair it. In short, the operator must know system parameters and how to monitor them. Simply, *operating parameters* refer to the physical indications of system operation. The term *parameter* refers to the limits or restrictions of a system. Let's consider, again, an air compressor. Obviously, it is important to know how the air compressor operates or at least how to start and place the compressor online properly; however, it is also just as important to determine if the compressor is operating as per design. Experienced operators know that to ensure that the air compressor is operating correctly (i.e., as per design) they must monitor its operation. Again, they do this by monitoring the operation of the air compressor by observing certain parameters.

Before starting any machine or system, however, we must first perform a prestart check to ensure that it has the proper level of lubricating oil, etc. Then, after starting the compressor, we need to determine (observe) if the compressor is actually operating (normally, this is not difficult to discern, considering that most air compressor systems make a lot of noise while in operation). Once in operation, our next move is to double check the system line-up to ensure that various valves in the system are correctly positioned (opened or closed). We might even go to a remote compressed-air service outlet to make sure that the system is producing compressed air. (Keep in mind that some compressed-air systems have a supply of compressed air stored in an air receiver; thus, when an air outlet is opened, air pressure might be present even if the compressor is not functioning as per design.) On the other hand, instead of using a remote outlet to test for compressed-air supply, we could look at the compressor air-pressure gauge. This gauge should indicate that the compressor is producing compressed air.

Gauges are the main devices that provide us with the information we need to evaluate equipment or system operation. With regard to the air compressor, the parameter we are most concerned about now is air pressure (gauge pressure). Not only is correct pressure generation by the compressor important, but maintaining the correct pressure in system pipes, tubes, and hoses is also essential. Keeping air pressure at the proper level is necessary mainly for four reasons:

1. Safe operation
2. Efficient, economic conveyance of air through the entire system, without waste of energy
3. Delivery of compressed air to all outlet points in the system (the places where the air is to be used) at the required pressure
4. Prevention of too much or too little pressure (either condition can damage the system and become hazardous to personnel)

We pointed out that, before starting the air compressor, certain prestart checks must be made. This is important for all machinery, equipment, and systems. In the case of our air compressor example, we want to ensure that proper lubricating oil pressure is maintained. This is important, of course, because pressure failure in the lubricating line that serves the compressor can mean inadequate lubrication of bearings, and, in turn, expensive mechanical repairs.

4.15.2 Pressure Gauges

Many pressure-measuring instruments are called *gauges*. Generally, pressure gauges are located at key points in piping systems. Usually expressed in pounds per square inch (psi), there is a difference between *gauge pressure* (psig) and *absolute pressure* (psia). Gauge pressure refers to the pressure level indicated by the gauge; however, even when the gauge reads 0, it is subject to ambient atmospheric pressure (i.e., 14.7 psi at sea level). When a gauge reads 50 psi, that is 50 pounds *gauge pressure* (psig). The true pressure is the 50 pounds shown plus the 14.7 pounds of atmospheric pressure acting on the gauge. The total pressure is the absolute pressure, which is the gauge pressure plus the atmospheric pressure (50 psi + 14.7 psi = 64.7). It is written as 64.7 psia.

Key Point: Pressure in any fluid pushes equally in all directions. The total force on any surface is the psi multiplied by the area in square inches; for example, a fluid under a pressure of 10 psi, pushing against an area of 5 in.^{2}, produces a total force against that surface of 50 lb (10 × 5).

4.15.2.1 Spring-Loaded Pressure Gauges

Pressure, by definition, must operate against a surface. Thus, the most common method of measuring pressure in a piping system is to have the fluid press against some type of surface—a flexible surface that moves slightly. This movable surface, in turn, is linked mechanically to a gear-lever mechanism that moves the indicator arrow to indicate the pressure on the dial (i.e., a pressure gauge). The surface that the pressure acts against may be a disk or diaphragm, the inner surface of a coiled tube, a set of bellows, or the end of a plunger. No matter the element type, if the mechanism is fitted with a spring that resists the pressure and returns the element (i.e., the indicator pointer) back to the zero position when the spring drops to zero, it is a spring-loaded gauge.

4.15.2.2 Bourdon Tube Gauges

Many pressure gauges in use today use a coiled tube as a measuring element called a *Bourdon tube*. (The gauge is named for its inventor, Eugene Bourdon, a French engineer.) The Bourdon tube is a device that senses pressure and converts the pressure to displacement. Under pressure, the fluid fills the tube (see Figure 4.41). Because the Bourdon tube displacement is a function of the pressure applied, it may be mechanically amplified and indicated by a pointer. Thus, the pointer position indirectly indicates pressure.

Note: The Bourdon tube gauge is available in various tube shapes: helical, C-shaped or curved, and spiral. The size, shape, and material of the tube depend on the pressure range and the type of gauge desired.

4.15.2.3 Bellows Gauge

Figure 4.42 shows how a simplified *bellows* gauge works. The bellows itself is a convoluted unit that expands and contracts axially with changes in pressure. The pressure to be measured can be applied to either the outside or the inside of the bellows; in practice, most bellows measuring devices have the pressure applied to the outside of the bellows. When pressure is released, the spring returns the bellows and the pointer to the zero position.

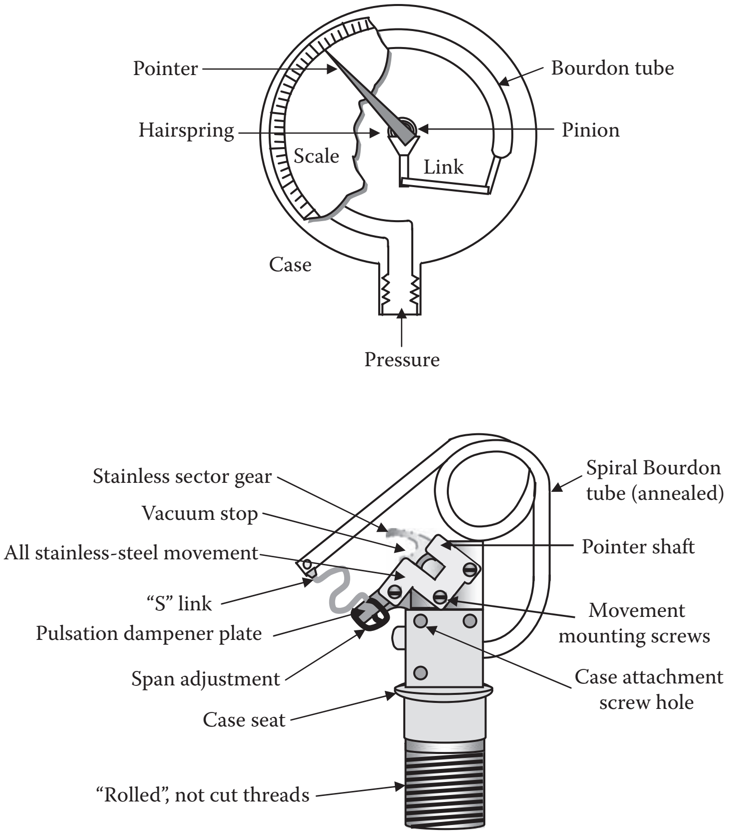


Figure 4.41 (Top) Bourdon tube gauge; (bottom) internal components.

4.15.2.4 Plunger Gauge

Most of us are familiar with the simple tire-pressure gauge. This device is a type of plunger gauge. Figure 4.43 shows a plunger gauge used in industrial hydraulic systems. The plunger gauge is a spring-loaded gauge where pressure from the line acts on the bottom of a cylindrical plunger in the center of the gauge and moves it upward. At full pressure, the plunger extends above the gauge, indicating the measured pressure. As the pressure drops, the spring contracts to pull the plunger downward, back into the body (the zero reading indication).

Note: Spring-loaded gauges are not extremely accurate, but they are entirely adequate when more precise readings are not necessary.

4.15.3 Temperature Gauges

Ensuring that system pressures are properly maintained in equipment and piping systems is critical to safe and proper operation. Likewise, ensuring that the temperature of fluids in industrial equipment and piping systems is correct is just as critical. Various temperature-measuring devices are available for measuring the temperature of fluids in industrial systems.

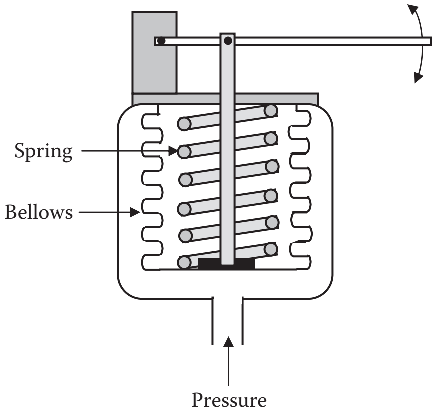


Figure 4.42 Bellows gauge.

Temperature has been defined in a variety of ways. One approach defines temperature as the measure of heat (thermal energy) associated with the movement (kinetic energy) of the molecules of a substance. This definition is based on the theory that molecules of all matter are in continuous motion, which is sensed as heat. For our purposes, we define temperature as the degree of hotness or coldness of a substance measured on a definite scale.

Temperature is measured when a measuring instrument (e.g., a thermometer) is brought into contact with the medium being measured. All temperature-measuring instruments use some change in a material to indicate temperature. Some of the effects that are used to indicate temperature are changes in physical properties and altered physical dimensions (e.g., the change in the length of a material in the form of expansion and contraction).

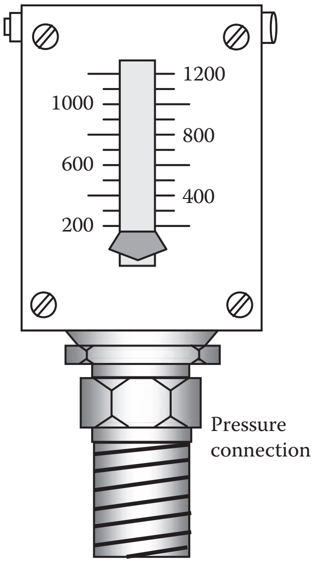


Figure 4.43 Plunger gauge.

Several temperature scales have been developed to provide a standard for indicating the temperatures of substances. The most commonly used scales include the Fahrenheit, Celsius, Kelvin, and Rankine temperature scales (see Figure 4.44). The Celsius scale is also called the *centigrade scale*. The Fahrenheit (°F) and Celsius (°C) scales are based on the freezing point and boiling point of water. The freezing point of a substance is the temperature at which it changes its physical state from a liquid to a solid. The boiling point is the temperature at which a substance changes from a liquid state to a gaseous state.

Note: Thermometers are classified as mechanical temperature-sensing devices because they produce some type of mechanical action or movement in response to temperature changes. The many types of thermometers include liquid-, gas-, and vapor-filled systems and bimetallic thermometers.

Figure 4.44 shows an industrial-type thermometer that is commonly used for measuring the temperature of fluids in industrial piping systems. This type of measuring instrument is nothing more than a rugged version of the familiar mercury thermometer. The bulb and capillary tube are contained inside a protective metal tube called a *well*. The thermometer is attached to the piping system (vat, tank, or other component) by a union fitting. Another common type of temperature gauge is the *bimetallic* gauge shown in Figure 4.45. If two materials with different linear coefficients of expansion (i.e., how much a material expands with heat) are bonded together, their rates of expansion will be different as the temperature changes. This will cause the entire assembly to bend in an arc. When the temperature is raised, an arc is formed around the material with the smaller expansion coefficient. The amount of arc is reflected in the movement of the pointer on the gauge. Because two dissimilar materials form the assembly, it is known as a *bimetallic element*, which is also commonly used in thermostats.

4.15.4 Vacuum Breakers

A common ancillary device found in pipelines is a vacuum breaker (see Figure 4.46). A vacuum breaker is a mechanical device that allows air into the piping system, thereby preventing backflow that could otherwise be caused by the siphoning action created by a partial vacuum. In other words, a vacuum breaker is designed to admit air into the line whenever a vacuum develops. A vacuum, obviously, is the absence of air. Vacuum in a pipeline can be a serious problem; for example, it can cause fluids to run in the wrong direction, possibly mixing contaminants with purer solutions. In water systems, backsiphonage can occur when a partial vacuum pulls nonpotable liquids back into the supply lines (AWWA, 1996). In addition, it can cause the collapse of tubing or equipment.

As illustrated in Figure 4.46, this particular type of vacuum breaker uses a ball that usually is held against a seat by a spring. The ball is contained in a retainer tube mounted inside the piping system or inside the component being protected. If a vacuum develops, the ball is forced (sucked) down into the retainer tube, where it works against the spring.

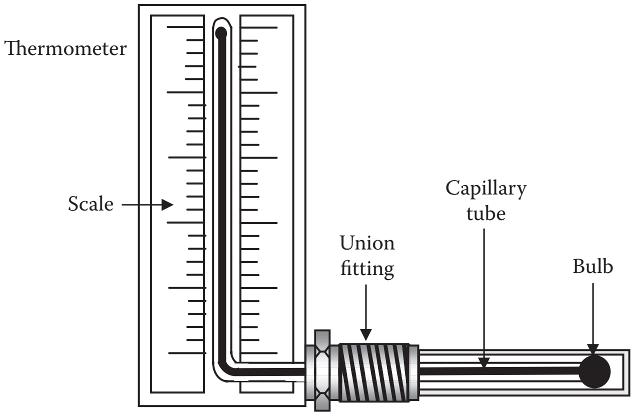


Figure 4.44 Industrial thermometer.

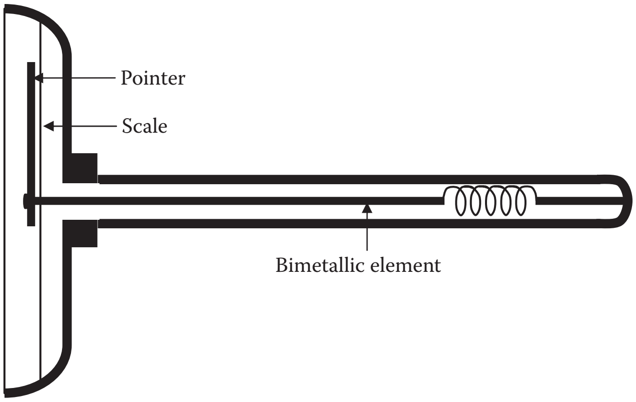


Figure 4.45 Bimetallic gauge.

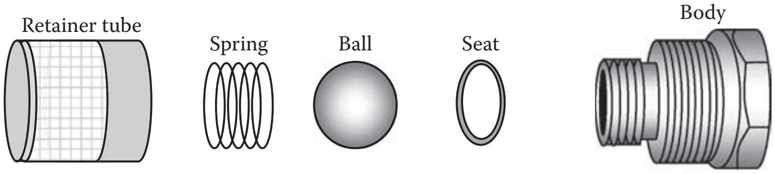


Figure 4.46 Vacuum breaker components.

Air flows into the system to fill the vacuum. In water systems, when air enters the line between a cross-connection and the source of the vacuum, then the vacuum will be broken and backsiphonage is prevented (AWWA, 1996). The spring then returns the ball to its usual position, which acts to seal the system again.

4.15.5 Accumulators

As mentioned, in a plant compressed-air system, a means of storing and delivering air as needed is usually provided. An air receiver normally accomplishes this. In a hydraulic system, an accumulator provides the

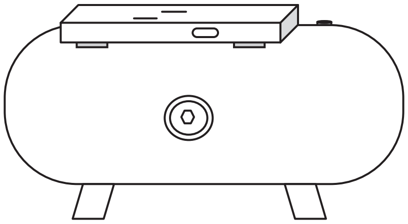


Figure 4.47 Air receiver.

functions provided by an air receiver for an air system. That is, the accumulator (usually a dome-shaped or cylindrical chamber or tank attached to a hydraulic line) in a hydraulic system works to help store and deliver energy as required. Moreover, accumulators work to help keep pressure in the line smoothed out. If, for example, pressure in the line rises suddenly, the accumulator absorbs the rise, preventing shock to the piping. If pressure in the line drops, the accumulator acts to bring it up to normal.

Note: The primary function of an accumulator in a hydraulic system is to supplement pump flow.

4.15.6 Air Receivers

As shown in Figure 4.47, an air receiver is a tank or cylindrical type of vessel used for a number of purposes. Most important is their ability to store compressed air. Much like accumulators, they cushion shock from sudden pressure rises in an airline. In this way, the air receiver serves to absorb the shock of valve closure and load starts, stops, and reversals. There is no liquid in an air receiver. The air compresses as pressure rises. As pressure drops, the air expands to maintain pressure in the line.

Note: OSHA has a standard, 29 CFR 1910.169(a), requiring that air receivers be drained. Specifically, the standard states, "A drain pipe and valve shall be installed at the lowest point of every air receiver to provide for the removal of accumulated oil and water" (OSHA 1978). This is an item that should be taken seriously, not only for safety reasons but also because it is a compliance item that OSHA inspectors often check.

4.15.7 Heat Exchangers

Operating on the principle that heat flows from a warmer body to a cooler one, heat exchangers are devices used for adding or removing heat and cold from a liquid or gas. The purpose may be to cool one body or to warm the other; nonetheless, whether used to warm or to cool, the principle remains the same. Various designs are used in heat exchangers. The simplest form consists of a tube or possibly a large coil of tubing placed inside a larger cylinder. In an oil lubrication system, the purpose of a heat exchanger is to cool the hot oil; however, a heat exchanger system can also be used to heat up a process fluid circulating through part of the heat exchanger while steam circulates through its other section.

Final Note: We have discussed the major ancillary or accessory equipment used in many piping systems. It is important to point out that other accessories are commonly used in piping systems (e.g., rotary pressure joints, actuators, intensifiers, pneumatic pressure line accessories); however, discussion of these accessories is beyond the scope of this text.

4.16 CHAPTER REVIEW QUESTIONS

4.1 What is an expansion joint?

4.2 A ______________ is defined as any substance or material that flows.

4.3 Compressed air is considered to be a ______________.

4.4 Sections or lengths of pipe are ______________ with fittings.

4.5 The ____________ of fluids through a pipe is controlled by valves.

4.6 Friction causes ______________ in a piping system.

4.7 As friction ______________ in a piping system, the output pressure decreases.

4.8 Relief valves are designed to open ______________.

4.9 What is used to help keep the fluids carried in piping systems hot or cold?

4.10 The major problems in piping systems are caused by ______________ and corrosion.

4.11 If the speed of fluid in a pipe doubled, the friction is ____________.

4.12 What is the most important factor in keeping a piping system operating efficiently?

4.13 Pipe sizes above ______________ inches are usually designated by outside diameter.

4.14 The difference in ______________ numbers represents the difference in the wall ______________ of pipes.

4.15 When pipe wall thickness ______________, the I.D. decreases.

4.16 A ______________ metal contains iron.

4.17 As the temperature ______________, the viscosity of a liquid decreases.

4.18 What is another name for rust?

4.19 Sections of ______________ water pipe are usually connected with a bell-and-spigot joint.

4.20 A ferrous metal always contains ______________.

4.21 Asbestos–cement pipe has the advantage of being highly resistant to ______________.

4.22 As temperature increases, the strength of plastic pipe ______________.

4.23 Name four basic nonmetallic piping materials.

4.24 Vitrified clay pipe is the most ______________ pipe available for carrying industrial wastes.

4.25 Cast iron pipe can be lined with ______________ to increase its resistance to corrosion.

4.26 A joint made so that the sections of tubing are ______________ together is called a *compression joint*.

4.27 Incorrect tube bends can cause ______________ flow and ______________ pressure.

4.28 What kind of tubing do high-pressure hydraulic systems use?

4.29 One process used to join plastic tubing is called ______________ welding.

4.30 Compared to pipe, tubing is more ______________.

4.31 ______________ tubing is most likely used in food-processing applications.

4.32 Before tubing can be bent or flared, it should be ______________.

4.33 Plastic tubing is usually joined by ______________.

4.34 The materials used most commonly for tubing are ______________ and ______________.

4.35 Smooth fluid flow is called ______________ flow.

4.36 What is the most common type of hose in general use?

4.37 The type of hose construction most suitable for maximum suction conditions is ______________.

4.38 ______________ is the nonmetallic hose best suited for use at extremely low temperatures.

4.39 Each size of hose clamp is designed for hose of a specific ______________.

4.40 What is the outstanding advantage of hose?

4.41 Applied to hose, the letters ______________ stand for enlarged end.

4.42 Hose is ______________ in order to provide strength and greater resistance to ______________.

4.43 Dacron hose remains ______________ at extremely low temperatures.

4.44 What fitting allows for a certain amount of pipe movement?

4.45 What fitting helps reduce the effects of water hammer?

4.46 A flange that has a plain face should be joined to a flange that has a ______________ face.

4.47 Improperly made ______________ restrict fluid flow in a pipeline.

4.48 The designation “200 lb” refers to the ______________ at which a fitting can safely be used.

4.49 Close off an unused outlet in a fitting with a(n) ______________.

4.50 What connects two or more pipes of different diameters?

4.51 ______________ control fluid flow through piping systems.

4.52 Valves can be used to ______________, ______________, and ______________ flow.

4.53 What type of valve is better suited for throttling service than a gate valve?

4.54 What type of valve is a fast-operating shut-off valve commonly used in large water-circulating systems?

4.55 A pressure-regulating valves keeps the ______________ at a ______________ level.

4.56 ______________ in a fluid line can clog the closing element of a valve.

4.57 Before removing a strainer for cleaning, the line should be ______________.

4.58 Because stream traps operate in a mixture of steam and water, it is often difficult to ______________ stream traps.

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CHAPTER **5**

WASTEWATER COLLECTION AND PRELIMINARY TREATMENT

In the late 1970s and early 1980s, under the Code of Federal Regulations (CFR), 40 CFR Part 403 was established to help Publicly Owned Treatment Works (POTW) control industrial discharges to sewers. These regulations were designed to prevent pass-through and interference at the treatment plants and interference in the collection and transmission systems. *Pass-through* occurs when pollutants literally "pass through" a POTW without being properly treated, resulting in an effluent violation for the POTW or an increase in the magnitude or duration of a violation. *Interference* occurs when a pollutant discharge causes a POTW to violate its permit by inhibiting or disrupting treatment processes, treatment operations, or processes related to sludge use or disposal.

5.1 INTRODUCTION

Figure 5.1 shows a basic schematic of an example wastewater treatment process providing primary and secondary treatment using the *activated sludge process*. This is the model, the prototype, the paradigm used in this handbook. Although secondary treatment (which provides BOD removal beyond what is achievable by simple sedimentation) commonly utilizes three different approaches—trickling filter, activated sludge, and oxidation ponds—our focus throughout this handbook, for instructive and illustrative purposes, is on only the activated sludge process. Figure 5.1 allows the reader to follow the treatment process step by step as it is presented (and as it is actually configured in the real world) and to assist in demonstrating how all of the various unit

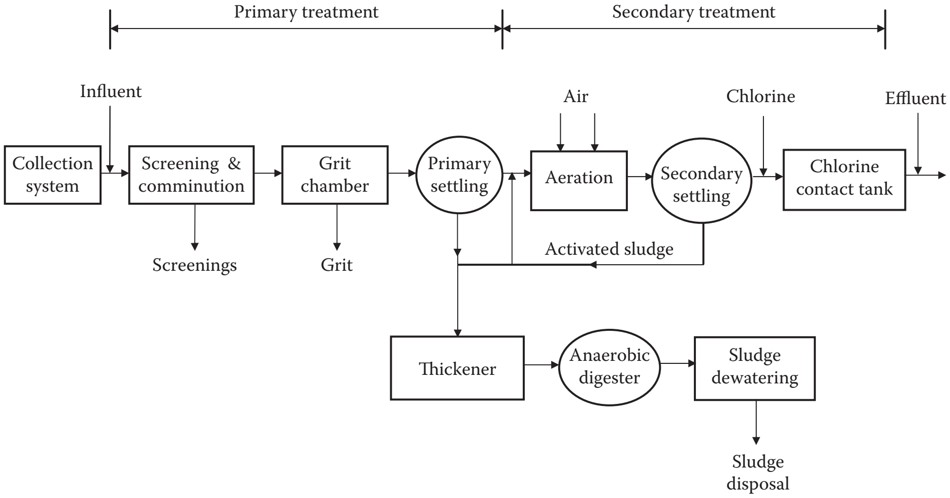

Figure 5.1 Schematic of standard wastewater treatment process providing primary and secondary treatment using activated sludge process.

processes sequentially follow and tie into each other. Sections that discuss unit processes will make frequent reference to Figure 5.1, because wastewater treatment is a series of individual steps (unit processes) that treat the wastestream as it makes its way through the entire process. A pictorial presentation of the treatment process, along with pertinent written information, enhances the learning process. It should also be pointed out, however, that even though the model shown in Figure 5.1 does not include all of the unit processes currently used in wastewater treatment, this handbook does not ignore the other major processes: trickling filters, rotating biological contactors (RBCs), and oxidation ponds.

5.2 WASTEWATER COLLECTION SYSTEMS

Wastewater collection systems collect and convey wastewater to the treatment plant. 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.

5.2.1 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 (fps); otherwise, at lower velocities, solids will settle out, causing clogged lines, overflows, and offensive odors. To keep collection systems lines at a reasonable depth, wastewater must be lifted (pumped) periodically so that it can continue flowing “downhill” to the treatment plant. Pump stations are installed at selected points within the system for this purpose.

5.2.2 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. The use of the force main system allows the 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 because the content of the lines is under pressure.

Key Point: Extra care must be taken when performing maintenance on force main systems because the content of the collection system is under pressure.

5.2.3 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 a large amount of maintenance to perform properly. Generally, the vacuum-type collection systems are not economically feasible.

5.2.4 Pumping Stations

Pumping stations provide the motive force (energy) to keep the wastewater moving at the desired velocity. They are used in both the force main and gravity systems. They are designed in several different configurations and may use different sources of energy to move the wastewater (i.e., pumps, air pressure, or vacuum). One of the more commonly used types of pumping station designs is the wet-well/dry-well design.

5.2.4.1 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 (including, in many cases, the motors and controllers) is located in a second section, known as the dry well. Many different designs for this type of system are available, but in most cases the pumps selected for this system are of a centrifugal design. Among the major considerations in 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) this type of design 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 the OSHA Confined Space Entry Standard (29 CFR 1910.146) is required.

5.2.4.2 Wet-Well Pumping Stations

Another type of pumping station design is the wet-well type, which has a single compartment that collects the wastewater flow. The pump is submerged in the wastewater with motor controls located in the space or has a weatherproof motor housing located above the wet well. In this type of station, a submersible centrifugal pump is normally used.

5.2.4.3 Pneumatic Pumping Stations

The pneumatic pumping station consists of a wet well and a control system that controls the inlet and outlet value 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 wastewater in the wet well reaches a predetermined level, an automatic valve is activated which 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 the discharge line.

5.2.4.4 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; however, on occasion, 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., to check the pumping rate of the constant speed pump) or pump capacity with influent (e.g., to check how many gallons per minute the pump is discharging). In this section, we use examples to describe instances on how and where these two calculations are made.

■ ***Example 5.1. Determining Pump Capacity without Influent***

Problem: A pumping station wet well is 10 ft by 9 ft. To check the pumping rate of the constant-speed pump, the operator closed the influent valve to the wet well for a 5-min test. 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 find the volume of water removed by the pump during the test:

$$\text{Area} \times \text{Depth} = \text{Volume} \tag{5.1}$$

$$90 \text{ ft}^2 \times 2.2 \text{ ft} = 198 \text{ ft}^3$$

One cubic foot of water holds 7.48 gal. We can convert this volume in cubic feet to gallons:

$$198\ \text{ft}^3 \times \frac{7.48\ \text{gal}}{1\ \text{ft}^3} = 1481\ \text{gal}$$

The test was done for 5 min. From this information, a pumping rate can be calculated:

$$\text{Pumping Rate} = \frac{1481\ \text{gal}}{5\ \text{min}} = \frac{296.2}{1\ \text{min}} = 296.2\ \text{gpm}$$

■ *Example 5.2. Determining Pump Capacity with Influent*

Problem: A wet well is 8.2 ft by 9.6 ft. The influent flow to the well, measured upstream, is 365 gpm. If the wet well rises 2.2 in. in 5 min, how many gallons per minute is the pump discharging?

Solution:

$$\text{Influent} = \text{Discharge} + \text{Accumulation} \tag{5.2}$$

$$\frac{365\ \text{gal}}{1\ \text{min}} = \text{Discharge} + \text{Accumulation}$$

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 5.2 (Influent = Discharge + 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 gallons each minute.

5.3 PRELIMINARY TREATMENT

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

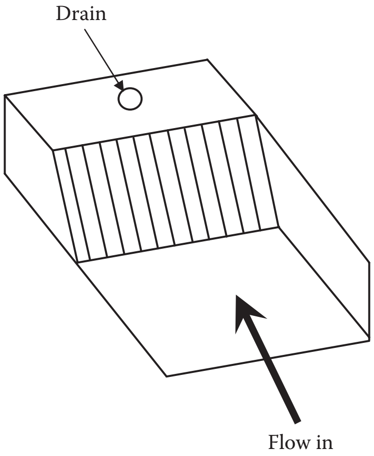

Figure 5.2 Basic bar screen.

(trash). 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 is designed to remove a specific type of material that poses a potential problem for the treatment process. Processes include wastewater collections, influent pumping, screening, shredding, grit removal, flow measurement, preaeration, chemical addition, and flow equalization; the major processes are shown in Figure 5.1. In this section, we describe and discuss each of these processes and their importance in the treatment process.

Note: As mentioned, not all treatment plants will include all of the processes shown in Figure 5.1. Specific processes have been included to facilitate discussion of major potential problems with each process and its operation; this is information that may be important to the wastewater operator.

5.3.1 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 5.2). The wastestream passes through the screen, and the large solids (*screenings*) are trapped on the bars for removal. 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 (bars or screens are placed at an angle of 30° for easier solids removal; see Figure 5.2) or mechanically cleaned (bars are placed at a 45° to 60° angle to improve mechanical cleaning operations). 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.

Key Point: The screenings must be removed frequently enough to prevent accumulation that will block the screen and cause the water level in front of the screen to build up.

5.3.1.1 Manually Cleaned Screens

Manually cleaned screens are cleaned at least once per shift (or often enough to prevent buildup that may cause 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, which 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 removal later in the process.

5.3.1.1.1 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 modify the design 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, flies, and other insects, it may be necessary to dispose of screenings more frequently.

5.3.1.2 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 equipment and maintaining it in accordance with 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.

5.3.2.1.1 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, or 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 also have others, including the cleaner not operating at all or the rake not operating even though the motor is. 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.

5.3.1.3 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 enter enclosed bar screen areas should be equipped with personal air monitors. 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 any safety devices on mechanical equipment. Overrides can result in dangerous conditions, injuries, and major mechanical failure.

5.3.1.4 Screenings Removal Calculations

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:

$$\text{Screenings Removed (ft}^3\text{/day)} = \frac{\text{Screenings (ft}^3\text{)}}{\text{Days}} \tag{5.3}$$

$$\text{Screenings Removed (ft}^3\text{/MG)} = \frac{\text{Screenings (ft}^3\text{)}}{\text{Flow (MG)}} \tag{5.4}$$

■ ***Example 5.3***

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 ft^3/day?

Solution: First, convert gallons screenings to cubic feet:

$$\frac{65\text{ gal}}{7.48\text{ gal/ft}^3} = 8.7\text{ ft}^3\text{ screenings}$$

Next, calculate screenings removed as ft^3/day:

$$\text{Screenings Removed} = \frac{8.7\text{ ft}^3}{1\text{ day}} = 8.7\text{ ft}^3\text{/day}$$

■ ***Example 5.4***

Problem: During one week, a total of 310 gal of screenings was removed from the wastewater screens. What is the average screenings removal in ft^3/day?

Solution: First, gallons of screenings must be converted to cubic feet of screenings:

$$\frac{310\text{ gal}}{7.48\text{ gal/ft}^3} = 41.4\text{ ft}^3\text{ screenings}$$

$$\text{Screenings Removed} = \frac{41.4\text{ ft}^3}{7} = 5.9\text{ ft}^3\text{/day}$$

5.3.2 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 to “cut up”) and barminution devices.

5.3.2.1 Comminution

The *comminutor* is the most common shredding device used in wastewater treatment. In this device, all of 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 the plant's O&M manual.

5.3.2.1.1 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, 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.

5.3.2.2 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 the 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 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.

5.3.3 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 the organic solids, which should be kept in suspension for treatment in subsequent processes. Grit removal may be accomplished in grit chambers or by the centrifugal separation of sludge. Processes use gravity and velocity, aeration, or centrifugal force to separate the solids from the wastewater.

5.3.3.1 Gravity-/Velocity-Controlled Grit Removal

Gravity-/velocity-controlled grit removal is normally accomplished in a channel or tank where the speed or the velocity of the wastewater is controlled to about 1 foot per second (fps), ideally, so the grit will settle while organic matter remains suspended. As long as the velocity is controlled within the range of 0.7 to 1.4 fps, the grit removal process will remain effective. Velocity is controlled by regulating 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.

5.3.3.1.1 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.

5.3.3.1.2 Operational Considerations

As noted above, 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 grit settles while organic matter remains 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, or mechanical problems, as well as to grit storage and disposal (housekeeping).

5.3.3.2 Aeration

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 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.

5.3.3.3 Centrifugal Force

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 rotten egg odor in the grit chamber (hydrogen sulfide formation), which can lead to metal and concrete corrosion problems. Low recovery rate of grit is another typical problem. Bottom scour, overaeration, or not enough detention time normally causes this. When these problems occur, the operator must make the required adjustments or repairs.

5.3.3.4 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.

5.3.3.4.1 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.

5.3.3.5 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 flow occurring during storm events. Generally, grit is disposed of in sanitary landfills. Because of this practice, for planning purposes, 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:

$$\text{Grit Removed (ft}^3\text{/MG)} = \frac{\text{Grit Volume (ft}^3\text{)}}{\text{Flow (MG)}} \tag{5.5}$$

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:

$$\text{Grit Removed (yd}^3\text{)} = \frac{\text{Total Grit (ft}^3\text{)}}{27\ \text{ft}^3\text{/yd}^3} \tag{5.6}$$

■ ***Example 5.5***

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 5.6***

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 5.7***

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 grit disposal if the pit is to have a 90-day capacity?

Solution: First, calculate the grit generated each day:

$$\frac{2.5\text{ ft3}}{\text{MG}} \times 2.5\text{ MGD} = 6.25\text{ ft}^3\text{/day}$$

The cubic feet of grit generated for 90 days would be:

$$\frac{6.25\text{ ft}^3}{\text{day}} \times 90\text{ days} = 562.5\text{ ft}^3$$

Convert cubic feet of grit to cubic yards of grit:

$$\frac{562.5\text{ ft}^3}{27\text{ ft}^3\text{/yd}^3} = 21\text{ yd}^3$$

5.3.4 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.

5.3.4.1 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. The operator 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.

TABLE 5.1 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

5.3.5 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 in the additional costs associated with construction and operation of the flow equalization facilities.

5.3.5.1 Operational Considerations

During normal operations, the operator must monitor all mechanical systems involved with flow equalization, watch for mechanical problems, and take appropriate corrective action. The operator also monitors dissolved oxygen levels, the impact of equalization on influent, and water levels in equalization basins, in addition to making any necessary adjustments.

5.3.6 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 5.1.

5.3.7 Preliminary Treatment Process Control Calculations

5.3.7.1 Channel Velocity

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 allow 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 flow and channel dimensions.

5.3.7.1.1 Velocity by Float and Stopwatch

$$\text{Velocity (fps)} = \frac{\text{Distance Traveled (ft)}}{\text{Time Required (s)}} \tag{5.7}$$

■ ***Example 5.8***

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 5.9***

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:

$$\text{Velocity} = \frac{37\text{ ft}}{30\text{ s}} = 1.2\text{ fps}$$

5.3.7.1.2 Velocity by Flow and Channel Dimensions

$$\text{Velocity (fps)} = \frac{\text{Flow (MGD)} \times 1.55\text{ cfs/MGD}}{\begin{bmatrix}\text{No. of Channels in Service} \\ \times \text{Channel Width (ft)} \times \text{Water Depth (ft)}\end{bmatrix}} \tag{5.8}$$

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.

■ *Example 5.10*

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 5.11*

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:

$$\text{Velocity} = \frac{4.0\text{ MGD} \times 1.55\text{ cfs/MGD}}{2\text{ Channels} \times 3\text{ ft} \times 1.3\text{ ft}} = \frac{6.2\text{ cfs}}{7.8\text{ ft}^2} = 0.79\text{ fps}$$

Because 0.79 is within the 0.7 to 1.4 level, the operator of this unit would not make any adjustments.

5.3.7.2 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 in a laboratory.

$$\text{Settling Time (s)} = \frac{\text{Liquid Depth (ft)}}{\text{Settling Velocity (fps)}} \tag{5.9}$$

■ *Example 5.12*

Problem: The grit channel of a plant 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:

$$\text{Settling Time} = \frac{2.2\text{ ft}}{0.085\text{ fps}} = 25.9\text{ s}$$

■ *Example 5.13*

Problem: The grit channel of a plant 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:

$$\text{Settling Time} = \frac{2.3\text{ ft}}{0.080\text{ fps}} = 28.7\text{ s}$$

5.3.7.3 Required Channel Length

This calculation can be used to determine the length of channel required to remove an object with a specified settling velocity:

$$\text{Required Channel Length} = \frac{\text{Channel Depth (ft)} \times \text{Flow Velocity (fps)}}{\text{Settling Velocity (fps)}} \tag{5.10}$$

■ *Example 5.14*

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 ft long. Is the channel long enough to remove the desired sand particle size?

Solution:

$$\text{Required Channel Length} = \frac{3\text{ ft} \times 0.80\text{ fps}}{0.070\text{ fps}} = 34.3\text{ ft}$$

Yes, the channel is long enough to ensure that all of the sand will be removed.

■ *Example 5.15*

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.

5.4 CHAPTER REVIEW QUESTIONS

5.1 While making rounds of the bar screens, you detect the smell of rotten eggs. What does this indicate?

5.2 What is the purpose of preliminary treatment?

5.3 What is the purpose of the bar screen?

5.4 What two methods are available for cleaning a bar screen?

5.5 Name two ways to dispose of screenings.

5.6 What is a Parshall flume used for?

5.7 What must be done to the cutters in a comminutor to ensure proper operation?

5.8 What controls the velocity in a gravity-type grit channel?

5.9 A plant has three channels in service. Each channel is 3 ft wide and has a water depth of 2.5 ft. What is the velocity in the channel when the flow rate is 9.0 MGD?

5.10 A section of sprocket chain is broken on the mechanically cleaned screen. To ensure your safety while replacing the chain, you should first secure all energy sources to the machine. What should you do next?

5.11 List three reasons why you might wish to include preaeration in the preliminary treatment portion of your plant.

5.12 Name two reasons why we would want to remove grit.

5.13 How slow should the flow of wastewater be in order to settle the grit?

5.14 Below what velocity will grit settle in the screening channel?

5.15 An empty screenings hopper 4 ft by 6 ft is filled to an even depth of 24 in. over the course of 64 hr. If the average plant flow rate was 4.0 MGD during this period, how many cubic feet of screenings were removed per million gallons of wastewater received?

5.16 The decomposition process that results in the production of methane gas is known as ______________ decomposition.

5.17 A V-notch weir is normally used to measure ______________.

5.18 If untreated organic wastes are discharged to a stream, the dissolved oxygen level of the stream will ______________.

5.19 The main purpose of the grit chamber is to ______________.

5.20 The main purpose of primary treatment is to ______________.

5.21 List four applications for chemical addition as a preliminary treatment process.

5.22 Calculate the weir loading for a sedimentation tank that has an outlet weir 500 ft long and a flow of 4.5 MGD. Your answer should be in gpd/ft.

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CHAPTER 6

PRIMARY TREATMENT (SEDIMENTATION)

6.1 INTRODUCTION

The purpose of primary treatment (primary sedimentation or primary clarification) is to remove settleable organic and floatable solids. Each primary clarification unit can be expected to remove 90 to 95% settleable solids, 40 to 60% total suspended solids, and 25 to 35% 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. In this chapter, we focus on primary treatment, or primary clarification, which uses large basins in which primary settling is achieved 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.

6.2 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 treatment. 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.

6.2.1 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 the density, size, and shapes of particles)
  - Performance of pretreatment processes
  - Nature and amount of any wastes recycled to the primary clarifier
- Key factors in primary clarifier operation include:

$$\text{Retention Time (hr)} = \frac{\text{Volume (gal)} \times 24\text{ hr/day}}{\text{Flow (gpd)}}$$

$$\text{Surface Loading Rate (gpd/ft}^2\text{)} = \frac{Q\text{ (gpd)}}{\text{Surface Area (ft}^2\text{)}}$$

$$\text{Solids Loading Rate (lb/day/ft}^2\text{)} = \frac{\text{Solids into Clarifier (lb/day)}}{\text{Surface Area (ft}^2\text{)}}$$

$$\text{Weir Overflow Rate (gpd/linear ft)} = \frac{Q\text{ (gpd)}}{\text{Weir Length (linear ft)}}$$

6.2.2 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, but plain settling tanks are normally used for secondary or advanced wastewater treatment processes.

6.2.2.1 Septic Tanks

Septic tanks are prefabricated tanks that serve as combined settling and skimming tanks and as unheated, unmixed anaerobic digesters. 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.

6.2.2.2 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.

6.2.2.3 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 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 frequently as to cause hydraulic overloading of the scum removal system. Settling tanks require housekeeping and maintenance. Baffles (prevent floatable solids, scum, from leaving the tank), scum troughs, scum collectors, effluent troughs, and effluent weirs require frequent cleaning to prevent heavy biological growths 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 carried out.

6.2.3 Operator Considerations

Before identifying a primary treatment problem and proceeding with the 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. In the following section, we discuss the important operational parameters and normal observations.

6.2.3.1 Primary Clarification: Normal Operation

In primary clarification, wastewater enters a settling tank or basin. Velocity reduces to approximately 1 fpm. Solids heavier than water settle to the bottom, while solids 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 treatment. Detention time, temperature, tank design, and condition of the equipment control the efficiency of the process.

Note: Again, notice that 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.

6.2.3.2 Primary Clarification: Operational Parameters

- *Flow distribution*—Normal flow distribution is indicated by flow to each in-service unit being equal and uniform with 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*—Normal, 6.5 to 9.0
- *Dissolved oxygen*—Normal, <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*—Normal, 4 to 8%
- *Percent volatile matter*—Normal, 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.

6.3 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 us to determine values for each function performed. Keep in mind that an optimally operated primary clarifier should have values in an expected range.

6.3.1 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%

6.3.2 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*.

6.3.3 Surface Loading 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 overflow rate* and *surface settling rate*.

$$\text{Surface Settling Rate (gpd/ft}^2\text{)} = \frac{\text{Flow (gpd)}}{\text{Settling Tank Area (ft}^2\text{)}} \tag{6.1}$$

■ *Example 6.1*

Problem: A settling tank is 120 ft in diameter, and the 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 6.2***

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:

$$\text{Area} = 0.785 \times 50\text{ ft} \times 50\text{ ft}$$

$$\text{Surface Overflow Rate} = \frac{\text{Flow (gpd)}}{\text{Area (ft}^2\text{)}} = \frac{2{,}150{,}000}{0.785 \times 50\text{ ft} \times 50\text{ ft}} = 1096\text{ gpd/ft}^2$$

6.3.4 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.

$$\text{Weir Overflow Rate (gpd)} = \frac{\text{Flow (gpd)}}{\text{Weir Length (ft)}} \tag{6.2}$$

■ ***Example 6.3***

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:

$$\text{Weir Overflow Rate} = \frac{2.55\text{ MGD} \times 1{,}000{,}000\text{ gal/MG}}{3.14 \times 90\text{ ft}} = 9023\text{ gpd/ft}$$

6.3.5 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.

$$\text{Solids (lb/day)} = \text{Pump Rate} \times \text{Pump Time} \times 8.34\text{ lb/gal} \times \text{\%Solids} \tag{6.3}$$

$$\begin{aligned}\text{Volatile Matter (lb/day)} = {} & \text{Pump Rate} \times \text{Pump Time} \times 8.34\text{ lb/gal} \\ & \times \text{\% Solids} \times \text{\% Volatile Matter}\end{aligned} \tag{6.4}$$

■ ***Example 6.4***

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%

$$\begin{aligned}\text{Volatile Solids} &= 20\text{ gpm} \times (20\text{ min/hr} \times 24\text{ hr/day}) \times 8.34\text{ lb/gal} \times 0.052 \times 0.66\\ &= 2748\text{ lb/day}\end{aligned}$$

6.3.6 Percent Total Solids (%TS)

■ ***Example 6.5***

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 the dry solids weighed 22.3 g. What is the percent total solids (%TS) of the sample?

Solution:

Sample + dish	74.69 g	Dish + dry solids	22.3 g
Dish alone	–21.2 g	Dish alone	–21.2 g
Sample weight	53.49 g	Dry solids weight	1.1 g

$$\frac{1.1\text{ g}}{53.49\text{ g}} \times 100\% = 2\%$$

6.3.7 BOD and SS Removal (lb/day)

To calculate the pounds of biochemical oxygen demand (BOD) or suspended solids (SS) 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:

$$\text{SS Removed (lb/day)} = \text{SS (mg/L)} \times \text{MGD} \times 8.34\text{ lb/gal} \qquad (6.5)$$

■ ***Example 6.6***

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 6.7***

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:

$$\text{BOD Removed (lb/day)} = 130 \text{ mg/L} \times 1.6 \text{ MGD} \times 8.34 \text{ lb/gal} = 1735 \text{ lb/day}$$

6.4 PROBLEM ANALYSIS

In primary treatment (as is also clear in the operation of other unit processes), the primary function of the operator is to identify causes of process malfunctions, develop solutions, and prevent recurrence. In other words, the operator's goal is to perform problem analysis or troubleshooting on unit processes when required and to restore the unit processes to optimal operating condition. Obviously, the immediate goal in problem analysis is to solve the immediate problem. The long-term goal is to ensure that the problem does not pop up again, causing poor performance in the future. In this section, we cover a few indicators or observations of operational problems with the primary treatment process. The observations presented are not all inclusive but do highlight the most frequently confronted problems.

6.4.1 Causal Factors for Poor Suspended Solids Removal (Primary Clarifier)

- Hydraulic overload
- Sludge buildup in tanks and decreased volume allowing solids to scour out tanks
- Strong recycle flows
- Industrial waste concentrations
- Wind currents
- Temperature currents

6.4.2 Causal Factors for Floating Sludge

- Sludge becoming septic in tank
- Damaged or worn collection equipment
- Recycled waste sludge
- Primary sludge pumps malfunctions

- Sludge withdrawal line plugged
- Return of well-nitrified waste activated sludge
- Too few tanks in service
- Damaged or missing baffles

6.4.3 Causal Factors for Septic Wastewater or Sludge

- Hydraulic overload
- Overpumping of sludge
- Collection system problems
- Decreased influent solids loading

6.4.4 Causal Factors for Too Low Primary Sludge Solids Concentrations

- Hydraulic overload
- Overpumping of sludge
- Collection system problem
- Decreased influent solids loading

6.4.5 Causal Factors for Too High Primary Sludge Solids Concentrations

- Excessive grit and compacted material
- Primary sludge pump malfunction
- Sludge withdrawal line plugged
- Sludge retention time too long
- Increased influent loadings

6.5 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), which is 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) require both phosphorus and ammonia.

6.6 CHAPTER REVIEW QUESTIONS

6.1 What is the purpose of sedimentation?

6.2 The sludge pump operates 20 minutes every 3 hours. The pump delivers 70 gpm. If the sludge is 5.0% solids and has a volatile matter content of 64%, how many pounds of volatile solids are removed from the settling tank each day?

6.3 A circular settling tank is 90 ft in diameter and has a depth of 10 ft. The flow rate is 2.5 MGD. What are the detention time in hours, surface loading rate in gpd/ft^2, and weir overflow rate in gpd/foot?

6.4 What is the recommended procedure to follow when removing sludge intermittently from a primary settling tank?

6.5 Why is there normally a baffle at the effluent end of the primary settling tank?

6.6 How much of the settleable solids are removed by primary settling?

6.7 What is an average detention time in a primary clarifier?

6.8 A settling tank 90 ft long, 25 ft wide, and 10 ft deep receives a flow rate of 1.6 MGD. What is the surface overflow rate in gpd/ft^2?

6.9 A settling tank with a total weir length of 90 ft receives a flow rate of 1.35 MGD. What is the weir overflow rate in gpd/ft?

6.10 A wastewater treatment plant has 6 primary tanks. Each tank is 90 ft long and 15 ft wide with a side water depth of 10 ft and a total weir length of 80 ft. The flow rate to the plant is 6 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.

6.11 A primary settling tank is 80 ft in diameter and 10 ft deep. What is the detention time when the flow is 3.25 MGD? Your answer should be in hours.

6.12 A circular settling tank is 90 ft in diameter and has a depth of 10 ft. The effluent weir extends around the circumference of the tank. The flow rate is 3.70 MGD. What is the detention time in hours, surface loading rate in gpd/ft^2, and weir overflow rate in gpd/ft?

6.13 An underflow pump operates 30 minutes every 3 hours. The pump delivers 80 gpm. If an underflow is 5.0% solids and has a volatile matter content of 66%, how many pounds of volatile solids are removed from the settling tank each day?

6.14 A circular settling tank is 80 ft in diameter and has a depth of 9 ft. The effluent weir extends around the circumference of the tank. The flow rate is 2.60 MGD. What are the detention time in hours, surface loading rate in gpd/ft^2, and weir overflow rate in gpd/ft?

6.15 Several large clumps of black, odorous solids are floating on the surface of the primary clarifier. The total solids concentration of the underflow from the clarifier at the beginning of the 20-minute pumping cycle is 10%. After 10 minutes of pumping, the solids concentration drops to 1.0%. What is happening, and what should the operator do to correct the problem?

6.16 The effluent from a primary clarifier contains an excess amount of suspended solids. The theoretical detention times based on flow rates and clarifier volume are well within the design range for the clarifier. A dye introduced into the clarifier influent appears in the clarifier effluent in 12 minutes and is no longer seen in the clarifier after 25 minutes. What is the most likely problem? What are the possible causes and the appropriate solutions to the problem?

6.17 The primary settling tank is 150 ft long, 90 ft wide, and 12 ft deep. The average daily flow is 134 MGD. What is the hydraulic detention time in hours?

CHAPTER 7

SECONDARY TREATMENT

7.1 INTRODUCTION

The main purpose of *secondary treatment* (sometimes referred to as *biological treatment*) is to provide biochemical oxygen demand (BOD) removal beyond what is achievable by primary treatment. 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), however, 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 the next chapter, we shift focus to the activated sludge process, the secondary treatment process that is used primarily in large installations and is the main focus of this handbook.

Secondary treatment refers to those treatment processes that use biological processes to convert dissolved, suspended, and colloidal organic wastes to more stable solids that 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 not 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) 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 while providing 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.

7.2 TREATMENT PONDS

Wastewater treatment can be accomplished using *ponds*. Ponds 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 a much lower cost. It is the cost advantage 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 can be followed by a pond or a pond can be followed by other treatment processes.

7.2.1 Types of Ponds

Ponds can be classified (named) based on their location in the system, by the type of wastes they receive, and by the main biological process occurring in the pond. First, we will take a look at the types of ponds according to their location and the type wastes they receive: *raw sewage stabilization ponds*, *oxidation ponds*, and *polishing ponds*. Then, we will look at ponds classified by the type of processes occurring within the pond: *aerobic ponds*, *anaerobic ponds*, *facultative ponds*, and *aerated ponds*.

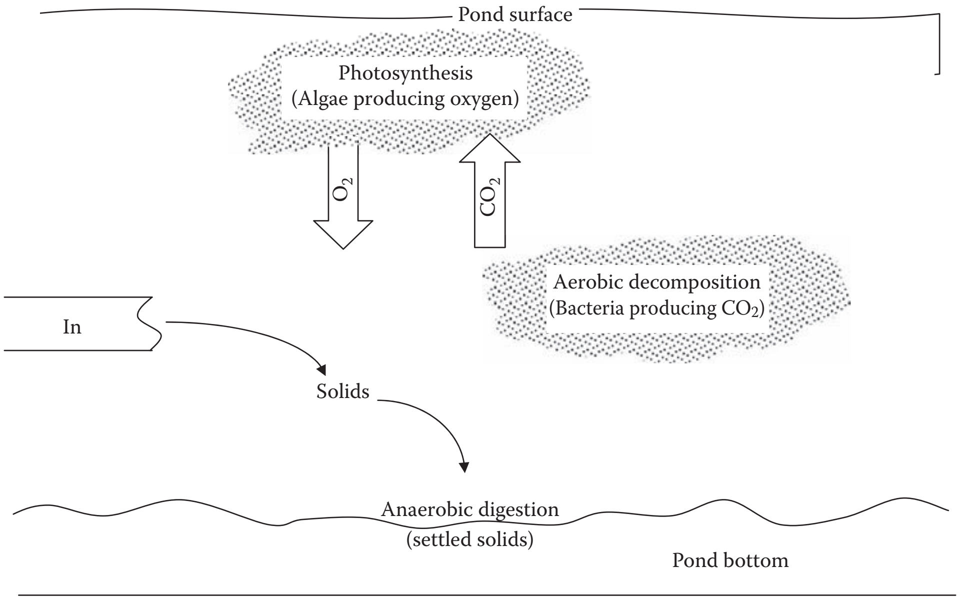

Figure 7.1 Stabilization pond processes.

7.2.1.1 Ponds Based on Location and Types of Wastes They Receive

7.2.1.1.1 Raw Sewage Stabilization Pond

The raw sewage stabilization pond is the most common type of pond (see Figure 7.1). 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 of detention time and to receive no more than 30 lb 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 permit selection of the best quality effluent. Normal operating depth of the pond is 3 to 5 ft. 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 text.

When wastewater enters the stabilization pond, several processes begin to occur. These include settling, aerobic decomposition, anaerobic decomposition, and photosynthesis (see Figure 7.1). Solids in the wastewater will settle to the bottom of the pond. In addition to the solids in the wastewater entering the pond, solids that are 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 (normally in 20 to 30 years), 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, and stable solids, which may settle out, as well as 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) that are dissolved in the water, stable solids, and more organisms. Near the surface of the pond, a population of green algae develops that 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, in part, to photosynthesis occurring in the system. Also, natural processes occurring in the system will cause the levels of dissolved oxygen and pH in the pond to vary throughout the day.

7.2.1.1.2 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.

7.2.1.1.3 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, fecal coliform, and some nutrients. They are designed to provide 1 to 3 days of detention time and normally operate at a depth of 5 to 10 ft. Excessive detention time or too shallow a depth will result in alga growth, which increases influent suspended solids concentrations.

7.2.1.2 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.

7.2.1.2.1 Aerobic Ponds

In aerobic ponds, which are not widely used, oxygen is present throughout the pond. All biological activity is aerobic decomposition.

7.2.1.2.2 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.

7.2.1.2.3 Facultative Ponds

The facultative pond is the most common type of pond (based on processes occurring). Oxygen is present in the upper portions of the pond, and aerobic processes are occurring. No oxygen is present in the lower levels of the pond where the processes occurring are anoxic and anaerobic.

7.2.1.2.4 Aerated Ponds

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.

7.2.2 Process Control Calculations for 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—it is simply not possible to master the licensing examinations without being able to perform the required calculations. Thus, whenever possible, example process control problems are provided to enhance your knowledge and skill.

7.2.2.1 Pond Area in Acres

$$\text{Area (ac)} = \frac{\text{Area (ft}^2\text{)}}{\text{43,560 ft}^2\text{/acre}} \tag{7.1}$$

7.2.2.2 Pond Volume in Acre-Feet

$$\text{Volume (ac-ft)} = \frac{\text{Volume (ft}^3\text{)}}{\text{43,560 ft}^3\text{/ac-ft}} \tag{7.2}$$

7.2.2.3 Flow Rate in Acre-Feet/Day

$$\text{Flow (ac-ft/day)} = \text{Flow (MGD)} \times 3.069 \text{ ac-ft/MG} \tag{7.3}$$

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.

7.2.2.4 Flow Rate in Acre-Inches/Day

$$\text{Flow (ac-in./day)} = \text{Flow (MGD)} \times 36.8 \text{ ac-in./MG} \tag{7.4}$$

7.2.2.5 Hydraulic Detention Time in Days

$$\text{Hydraulic Detention Time (Days)} = \frac{\text{Pond Volume (ac-ft)}}{\text{Influent Flow (ac-ft/day)}} \tag{7.5}$$

Note: Normally, hydraulic detention time ranges from 30 to 120 days for stabilization ponds.

■ *Example 7.1*

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:

$$\text{Flow} = 0.30 \text{ MGD} \times 3.069 = 0.92 \text{ ac-ft/day}$$

$$\text{Detention Time} = \frac{53.5 \text{ ac}}{0.92 \text{ ac-ft/day}} = 58.2 \text{ days}$$

7.2.2.6 Hydraulic Loading in Inches/Day (Overflow Rate)

$$\text{Hydraulic Loading (in./day)} = \frac{\text{Influent Flow (ac-in./day)}}{\text{Pond Area (ac)}} \tag{7.6}$$

$$\text{Population Loading} = \frac{\text{Population Served by System}}{\text{Pond Area (ac)}} \tag{7.7}$$

Note: Population loading normally ranges from 50 to 500 people per acre.

7.2.2.7 Organic Loading

Organic loading can be expressed as pounds of BOD_5 per day per acre (most common), pounds BOD_5 per day per acre-foot, or people per day per acre.

$$\begin{array}{l}\text{Organic Loading}\\ (\text{lb BOD}_5\text{/day/ac})\end{array} = \frac{\text{BOD}_5\ (\text{mg/L}) \times \text{Influent Flow (MGD)} \times 8.34}{\text{Pond Area (ac)}} \tag{7.8}$$

Note: Normal range is from 10 to 50 lb BOD_5 per day per acre.

■ *Example 7.2*

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 day per acre (lb/day/ac)?

Solution:

$$725\text{ ft} \times 380\text{ ft} \times \frac{1\text{ ac}}{43{,}560\text{ ft}^2} = 6.32\text{ ac}$$

$$0.12\text{ MGD} \times 160\text{ mg/L} \times 8.34\text{ lb/gal} = 160.1\text{ lb/day}$$

$$\frac{160.1\text{ lb/day}}{6.32\text{ ac}} = 25.3\text{ lb/day/ac}$$

7.3 TRICKLING FILTERS

Trickling filters have been used to treat wastewater since the 1890s. It was found that when settled wastewater 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 7.2. 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 7.3). 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

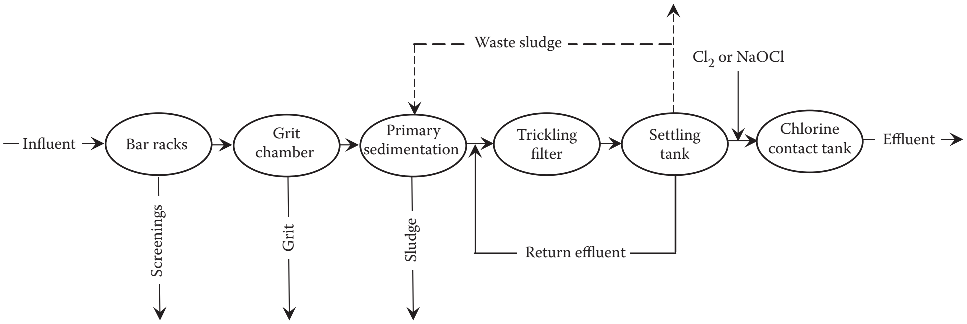

Figure 7.2 Simplified flow diagram of trickling filter used for wastewater treatment.

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 individual media materials (see Figure 7.4) that collect at the bottom of the filter, along with the treated wastewater, and are passed on to the secondary settling tank for removal. The overall performance of the trickling filter is dependent on hydraulic and organic loading, temperature, and recirculation.

7.3.1 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 or plant are already familiar to operators.)

Biological towers—A type of trickling filter that is very deep (10 to 20 ft). Filled with a 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 the solids inventory in the activated sludge process, it is sometimes also referred to as *zoogleal slime.*

Distributor 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 direct the flow toward a central channel for removal.

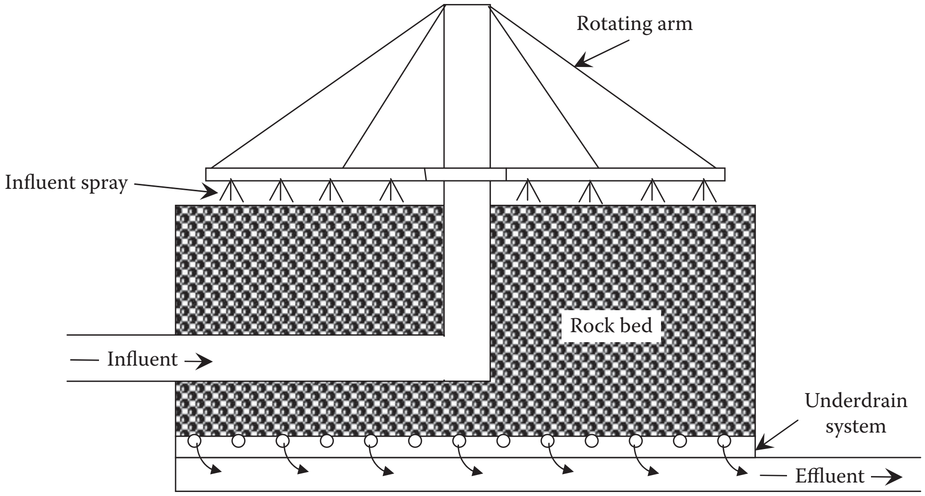

Figure 7.3 Schematic of cross-section of a trickling filter.

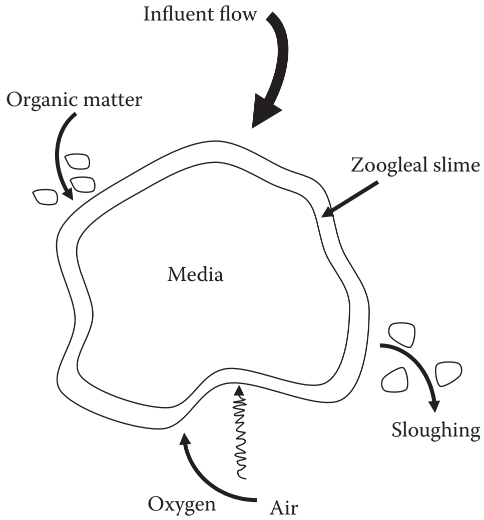

Figure 7.4 Filter media showing biological activities that take place on the surface area.

High-rate trickling filters—A classification (see Table 7.1) in which the organic loading is in the range of 25 to 100 lb of 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.

TABLE 7.1 TRICKLING FILTER CLASSIFICATION

Filter Class	Standard Rate	Intermediate Rate	High Rate	Super High Rate	Roughing
Hydraulic loading (gpd/ft^2)	25–90	90–230	230–900	350–2100	>900
Organic loading (lb 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%

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 COD contributed to any recirculated flow and is commonly expressed as pounds of 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 7.1) in which the organic matter is in excess of 200 lb of 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.

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.

7.3.2 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 rocks—which also requires the construction of beds that are quite wide, in many applications up to 60 feet in diameter. When synthetic media are used, the bed can be much deeper.

No matter which type of media is selected, the primary consideration is that the media 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 ft or more in depth.

The 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.

Note: To ensure sufficient airflow to the filter, the underdrains should never be allowed to flow more than 50% full of wastewater.

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. Design, construction, and operation are similar to those for 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.

7.3.3 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-rate are the filter types most commonly used. The *standard-rate filter* has a hydraulic loading that varies from 25 to 90 gpd/ft^3. It has a seasonal sloughing frequency and does not employ recirculation. It typically has an 80 to 85% BOD$_5$ removal rate and 80 to 85% TSS removal rate. The *high-rate filter* has a hydraulic loading of 230 to 900 gpd/ft^3. It has a continuous sloughing frequency and always employs recirculation. It 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. It has a continuous sloughing frequency and does not normally include recirculation. It typically has a 40 to 65% BOD$_5$ removal rate and 40 to 65% TSS removal rate.

7.3.4 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 performance and to monitor the process 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 observation for a settling tank should also be performed.

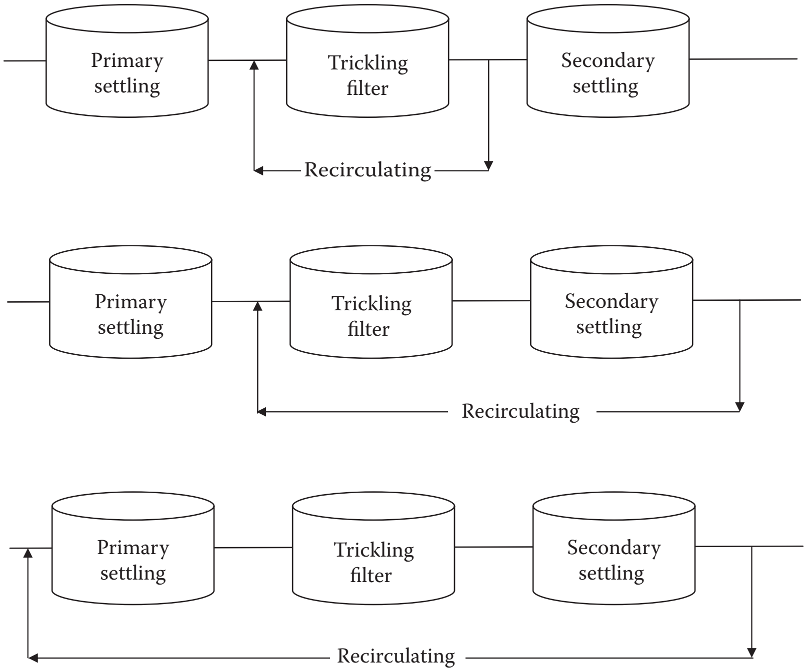

Figure 7.5 Common forms of recirculation.

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. 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 7.5.

Maintenance requirements include lubrication of mechanical equipment, removal of debris from the surface and orifices, adjustment of flow patterns, and maintenance associated with the settling tank.

7.3.5 General Process Description

The trickling filter process involves spraying wastewater over a solid media such as rock, plastic, or redwood slats (or laths). As the wastewater trickles over the surface of the media, a growth of microorganisms (bacteria, protozoa, fungi, algae, helminthes or worms, and larvae) develops. This growth is visible as a shiny slime very similar to the slime found on rocks in a stream. As the wastewater passes over this slime, the slime adsorbs the organic matter. This organic matter is used for food by the microorganisms. At the same time, air moving through the open spaces in the filter transfers oxygen to the wastewater. This oxygen is then transferred to the slime to keep the outer layer aerobic. As the microorganisms use the food and oxygen, they produce more organisms, carbon dioxide, sulfates, nitrates, and other stable byproducts; these materials are then discarded from the slime back into the wastewater flow and are carried out of the filter.

$$\text{Organics} + \text{Organisms} + O_2 = \text{More Organisms} + CO_2 + \text{Solid Wastes} \quad (7.9)$$

The growth of the microorganisms and the buildup of solid wastes in the slime make it thicker and heavier. When this slime becomes too thick, the wastewater flow breaks off parts of the slime. These must be removed in the final settling tank. In some trickling filters, a portion of the filter effluent is returned to the head of the trickling filter to level out variations in flow and improve operations (recirculation).

7.3.5.1 Overview and Brief Summary of Trickling Filter Process

A trickling filter consists of a bed of coarse media, usually rocks or plastic, covered with microorganisms.

Note: Trickling filters that use ordinary rock are normally only about 10 ft in depth because of structural problems caused by the weight of rocks—which also requires the construction of beds that are quite wide, in many applications up to 60 ft in diameter. When synthetic media are used, the bed can be much deeper.

- The wastewater is applied to the media at a controlled rate, using a rotating distributor arm or fixed nozzles. Organic material is removed by contact with the microorganisms as the wastewater trickles down through the media openings. The treated wastewater is collected by an underdrain system.

Note: To ensure sufficient air flow to the filter, the underdrains should never be allowed to flow more than 50% full of wastewater.

- The trickling filter is usually built into a tank that contains the media. The filter may be square, rectangular, or circular.
- The trickling filter does not provide any actual filtration. The filter media provide a large amount of surface area that the microorganisms can cling to and grow in a slime that forms on the media as they feed on the organic material in the wastewater.
- The slime growth on the trickling filter media periodically sloughs off and is settled and removed in a secondary clarifier that follows the filter.

Key factors in trickling filter operation include the following:

Hydraulic loading rate

$$\frac{\text{gpd}}{\text{ft}^2} = \frac{\text{Flow (including recirculation) (gpd)}}{\text{Media Top Surface (ft}^2\text{)}}$$

Organic loading rate

$$\frac{\text{lb/day}}{1000\ \text{ft}^3} = \frac{\text{BOD in filter (lb/day)}}{\text{Media Volume (1000 ft}^3\text{)}}$$

Recirculation ratio

$$\text{Ratio} = \frac{\text{Recirculation Flow (MGD)}}{\text{Average Influent Flow (MGD)}}$$

7.3.5.2 Operator Considerations

Trickling filter operation requires routine observations, meter readings, process control sampling and testing, and process control calculations. Comparison of daily results with expected normal ranges is the key to identifying problems and appropriate corrective actions.

- *Slime*—The operator checks the thickness of slime to ensure that it is thin and uniform (normal) or thick and heavy (indicates organic overload); the operator is also concerned with ensuring that excessive recirculation is not taking place and checks slime toxicity (if any). The operator is also concerned about the color of the slime: green slime is normal, dark green/black slime indicates organic overload, and other colors may indicate industrial waste or chemical additive contamination. The operator should check the subsurface growth of the slime to ensure that it is normal (thin and translucent). If growth is thick and dark, organic overload conditions are indicated. Distributor arm operation is a system function important to slime formation, and it must be checked regularly for proper operation; for example, the distribution of slime should be even and uniform. Striped conditions indicate clogged orifices or nozzles.
- *Flow*—Flow distribution must be checked to ensure uniformity. If nonuniform, the arms are not level or the orifices are plugged. Flow drainage is also important. Drainage should be uniform and rapid. If not, ponding may occur from media breakdown or debris on the surface.
- *Distributor*—Movement of the distributor is critical to proper operation of the trickling filter. Movement should be uniform and smooth. Chattering, noisy operation may indicate bearing failure. The distributor seal must be checked to ensure that there is no leakage.

- *Recirculation*—The operator must check the rate of recirculation to ensure that it is within design specifications. Rates above design specifications indicate hydraulic overloading; rates under design specifications indicate hydraulic underloading.

Note: 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. Because the second number in the ratio is always 1, the 1 is sometimes dropped, and the ratio is written as a single number.

- *Media*—The operator should check the uniformity of the media.

7.3.6 Process Control Sampling and Testing

To ensure proper operation of the trickling filter, sampling and scheduling are important; however, for samples and the tests derived from the samples to be beneficial, operators must perform a variety of daily or variable tests. Individual tests and sampling may be required daily, weekly, or monthly, depending on seasonal change. Frequency may be lower during normal operations and higher during abnormal conditions. The information gathered through the collection and analysis of samples from various points in the trickling filter process is helpful in determining the current status of the process as well as identifying and correcting operational problems. The following routine sampling points and types of tests will allow the operator to identify normal and abnormal operating conditions.

Filter influent tests

- Dissolved oxygen
- pH
- Temperature
- Settleable solids
- BOD_5
- Suspended solids
- Metals

Recirculated flow tests

- Dissolved oxygen
- pH
- Flow rate
- Temperature

Filter effluent tests

- Dissolved oxygen
- pH
- Jar tests

Process effluent tests

- Dissolved oxygen
- pH
- Settleable solids
- BOD_5
- Suspended solids

7.3.7 Troubleshooting Operational Problems[*]

The following sections are not all inclusive; that is, they do not cover all of the operational problems associated with the trickling filter process. They do, however, provide information on the most common operational problems.

7.3.7.1 Ponding

Symptoms

- Small pools or puddles of water on the surface of the media
- Decreased performance in the removal of BOD and TSS
- Possible odors due to anaerobic conditions in the media
- Poor air flow through the media

Causal factors

- Inadequate hydraulic loading to keep the media voids flushed clear
- Application of high-strength wastes without sufficient recirculation to provide dilution
- Nonuniform media
- Degradation of the media due to aging or weathering
- Uniform media that is too small
- Debris (moss, leaves, sticks) or living organisms (snails) that clog the void spaces

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[*] Much of the information in this section is based on Culp, G.L. and Heim, N.F., *Field Manual for Performance Evaluation and Troubleshooting at Municipal Wastewater Treatment Facilities*, U.S. Environmental Protection Agency, Washington, D.C., 1978.

Corrective actions (listed in *increasing* impact on the quality of the plant effluent)

- Remove all leaves, sticks, and other debris from the media.
- Increase recirculation of dilute, high-strength wastes to improve sloughing to keep voids open.
- Use a high-pressure stream of water to agitate and flush the ponded area.
- Rake or fork the ponded area.
- Dose the filter with chlorine solution for 2 to 4 hr. The specific dose of chlorine required will depend on the severity of the ponding problem. When using elemental chlorine, the dose must be sufficient to provide a residual at the orifices of 1 to 50 mg/L. If the filter is severely clogged, the higher residuals may be required to unload the majority of the biomass. If the filter cannot be dosed by elemental chlorine, chlorinated lime or hypochlorite powder may be used. Dosing should be in the range of 8 to 10 lb of chlorine per 1000 ft^2 of media.
- If the filter design permits, the filter media can be flooded for a period of 4 hr. Remember, if the filter is flooded, care must be taken to prevent hydraulic overloads of the final settling tank. The trickling filter should be drained slowly at low flow periods.
- Dry the media. By stopping the flow to the filter, the slime will dry and loosen. When the flow is restarted, the loosened slime will flow out of the filter. The amount of drying time will be dependent on the thickness of the slime and the amount of removal desired. Time may range from a few hours to several days.

Note: Portions of the media can be dried without taking the filter out of service by plugging the orifices that normally service the area.

If these corrective actions do not provide the desired improvement, the media must be carefully inspected. Remove a sample of the media from the affected area. Carefully clean the sample, inspect it for its solidity, and determine its size uniformity (3 to 5 in.). Media that appear to be decomposing or are not uniform should be replaced.

7.3.7.2 Odors

Frequent offensive odors usually indicate an operational problem. These foul odors occur within the filter periodically and are normally associated with anaerobic conditions. Under normal circumstances, a slight anaerobic slime layer forms due to the inability of oxygen to penetrate all the way to the media; however, under normal operation, the outer slime layers will remain aerobic, and no offensive odors are produced.

Causal factors

- Excessive organic loading due to poor filter effluent quality (recirculation), poor primary treatment operation, poor control of sludge treatment process that results in high BOD_5 recycle flows
- Poor ventilation because of submerged or obstructed underdrains, clogged vent pipes, or clogged void spaces
- Overloaded filter (hydraulically or organically)
- Poor housekeeping

Corrective actions

- Evaluate the operation of the primary treatment process. Eliminate any short-circuiting. Determine any other actions that can be taken to improve the performance of the primary process.
- Evaluate and adjust control of the sludge treatment processes to reduce the BOD_5 or recycle flows.
- Increase the recirculation rate to add additional dissolved oxygen (DO) to the filter influent. Do not increase the recirculation rate if the flow rate through the underdrains would cause less than 50% open space.
- Maintain aerobic conditions in the filter influent.
- Remove debris from media surfaces.
- Flush underdrains and vent pipes.
- Add a commercially available masking agent to reduce odors and prevent complaints.
- Add chlorine at a 1- to 2-mg/L residual for several hours at low flow to reduce activity and cut down on the oxygen demand. Chlorination only treats symptoms; a permanent solution must be determined and instituted.

7.3.7.3 High Clarifier Effluent Suspended Solids or BOD

Symptoms

- The effluent from the trickling filter process settling unit contains a high concentration of suspended solids.

Causal factors

- Recirculated flows are too high, causing hydraulic overloading of the settling tank. In multiple unit operations, the flow is not evenly distributed.
- Settling tank baffles or skirts have corroded or broken.
- The sludge collection mechanism is broken or malfunctioning.

- Effluent weirs are not level.
- Short-circuiting is occurring because of temperature variations.
- Withdrawal rate or frequency is not correct.
- Excessive solids loading is occurring due to excessive sloughing.

Corrective actions

- Check hydraulic loading and adjust recirculated flow if the hydraulic loading is too high.
- Adjust flow to ensure equal distribution.
- Inspect sludge removal equipment; repair broken equipment.
- Monitor the sludge blanket depth and sludge solids concentration; adjust the withdrawal rate and frequency to maintain aerobic conditions in the settling tank.
- Adjust the effluent weir to obtain equal flow over all parts of the weir length.
- Determine temperature in the clarifier at various points and depths throughout the clarifier. If depth temperatures are consistently 1 to 2°F lower than surface readings, a temperature problem exists. Baffles may be installed to help to break up these currents.
- Determine whether high sloughing rates caused by biological activity or temperature changes are creating excessive solids loading. The addition of 1 to 2 mg/L of cationic polymer may be helpful in improving solids capture. Remember, if polymer addition is used, solids withdrawal must be increased.
- Control high sloughings due to organic overloading, toxic wastes, or wide variations in influent flow at their source.

7.3.7.4 Filter Flies

Symptoms

- The trickling filter and surrounding area become populated with large numbers of very small flying insects (*Psychoda* moths).

Causal factors

- Poor housekeeping
- Insufficient recirculation
- Intermittent wet and dry conditions
- Warm weather

Corrective actions (note that corrective actions for filter fly problems revolve around the need to disrupt the fly's life cycle—about 7 to 10 days in warm weather)

- Increase the recirculation rate to obtain a hydraulic loading of at least 200 gpd/ft^2. At this rate, filter fly larvae are normally flushed out of the filter.
- Clean filter walls and remove weeds, brush, and shrubbery around the filter. This removes some of the area for fly breeding.
- Dose the filter periodically with low chlorine concentrations (less than 1 mg/L). This normally destroys larvae.
- Dry the filter media for several hours.
- Flood the filter for 24 hr.
- Spray the area around the filter with insecticide. Do not use insecticide directly on the media because of the chance of carryover and unknown effects on the slime populations.

7.3.7.5 Freezing

Symptoms

- Decreased air temperature results in visible ice formation and decreased performance.
- Distributed wastes are in a thin film or spray. This is more likely to cause ice formation.

Causal factors

- Recirculation causes increased temperature drops and losses.
- Strong prevailing winds cause heat losses.
- Intermittent dosing allows water to stand too long, causing freezing.

Corrective actions (all are based on a need to reduce heat loss as the wastes move through the filter)

- Reduce recirculation as much as possible to minimize cooling effects.
- Operate two-stage filters in parallel to reduce heat loss.
- Adjust splash plates and orifices to obtain a coarse spray.
- Construct a windbreak or plant evergreens or shrubs in the direction of the prevailing wind.
- If intermittent dosing is used, leave dump gates open.
- Cover pump wet wells and dose tanks to reduce heat losses.

- Cover filter media to reduce heat loss.
- Remove ice before it becomes large enough to block the arms.

Note: During periods of cold weather, the filter will show decreased performance; however, the filter should not be shut off for extended periods. Freezing of the moisture trapped within the media causes expansion and may cause structural damage.

7.3.8 Process Calculations

Several calculations are useful in the operation of a trickling filter, including total flow, hydraulic loading, and organic loading.

7.3.8.1 Total Flow

If the recirculated flow rate is given, total flow is:

$$\text{Total Flow (MGD)} = \text{Influent Flow (MGD)} + \text{Recirculation Flow (MGD} \quad (7.10)$$

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

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 7.3*

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:

$$\text{Total Flow} = 3.65\ \text{MGD} \times (1.5 + 1.0) = 9.13\ \text{MGD}$$

7.3.8.2 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 7.4*

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,

$$0.488 \text{ MGD} + 0.566 \text{ MGD} = 1.054 \text{ MGD} = 1{,}054{,}000 \text{ gpd}$$

$$\text{Circular surface area} = 0.785 \times (\text{Diameter})^2 = 0.785 \times (90 \text{ ft})^2 = 6359 \text{ ft}^2$$

$$\frac{1{,}054{,}000 \text{ gpd}}{6359 \text{ ft}^2} = 165.7 \text{ gpd/ft}^2$$

7.3.8.3 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 7.5

Problem: A trickling filter, 50 ft in diameter, receives a primary effluent flow rate of 0.445 MGD. Calculate the organic loading rate in units of pounds of BOD applied per day per 1000 ft^3 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 the units together:

$$\frac{315.5 \text{ lb} \times 1000}{17{,}662.5 \text{ ft}^3} \times \frac{\text{lb BOD/day}}{1000 \text{ ft}^3} = 17.9 \text{ lb BOD/day/1000 ft}^3$$

7.3.8.4 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.

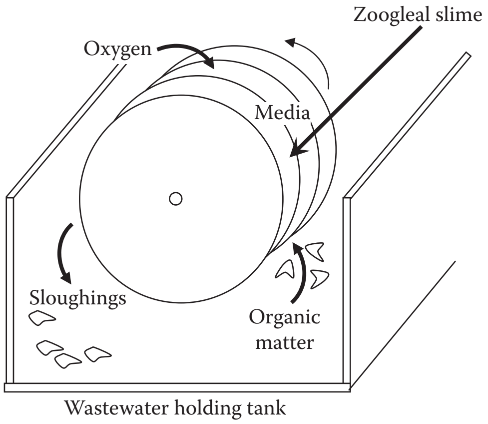

Figure 7.6 Rotating biological contactor (RBC) cross-section and treatment system.

7.4 ROTATING BIOLOGICAL CONTACTORS

The rotating biological contactor (RBC) is a biological treatment system (see Figure 7.6) that is a variation of the attached growth idea provided by the trickling filter. Because it relies on microorganisms that grow on the surface of a medium, the basic biological process of this fixed-film biological treatment device is similar to that of 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 m in diameter and attached to a rotating horizontal shaft (see Figure 7.6).

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 7.7), simply because a single contactor is not sufficient to achieve the desired level of treatment; the resulting treatment achieved exceeds conventional 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 medium 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.

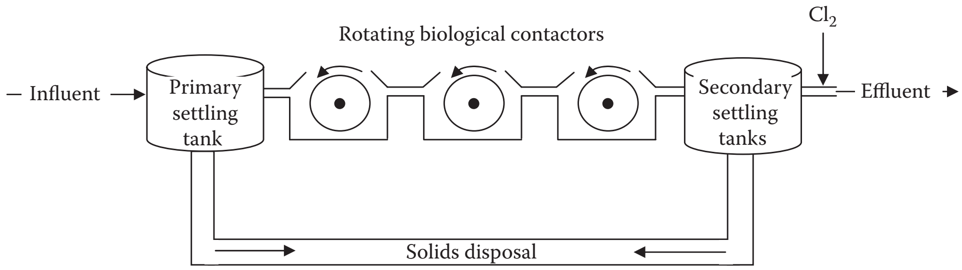

Figure 7.7 Rotating biological contactor (RBC) treatment system.

7.4.1 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 rotating biological contactor consists of circular sheets of synthetic material (usually plastic) mounted side by side on a shaft. The *sheets* (media) contain large amounts of surface area for growth of the biomass. The *center shaft* provides the support for the disks of media and must be strong enough to support the weight of the media and the biomass; experience indicates that a major problem is collapse of the support shaft. The *drive system* provides the motive force to rotate the disks and 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 permit variation of the liquid depth and detention time. Baffles are required to permit 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 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* is 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-hr detention times to permit settling of lighter biological solids.

7.4.2 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 performed to aid in assessing performance.

7.4.3 RBC Expected Performance

The RBC normally produces a high-quality effluent with BOD_5 removal 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.

7.4.4 Operator Observations

Rotating biological filter operation requires routine observation, process control sampling and testing, troubleshooting, and process control calculations. Comparison of daily results with expected normal ranges is the key to identifying problems and appropriate corrective actions.

Note: If the RBC is covered, observations may be limited to the portion of the media that can be viewed through the access door.

- *Rotation*—The operator routinely checks the operation of the RBC to ensure that smooth, uniform rotation is occurring (normal operation). Erratic, nonuniform rotation indicates a mechanical problem or uneven slime growth. If no movement is observed, mechanical problems or extreme excess of slime growth are indicated.
- *Slime color and appearance*—Gray, shaggy slime growth on the RBC indicates normal operation. Reddish-brown or golden-brown shaggy growth indicates normal operation during nitrification. A very dark brown, shaggy growth (with worms present) indicates a very old slime. White chalky growth indicates high influent sulfur/sulfide levels. No visible slime growth on the RBC indicates a severe pH or temperature change.

7.4.5 RBC Process Control Sampling and Testing

For process control, the RBC process does not require large amounts of sampling and testing to provide the necessary information. The frequency for performing suggested testing depends on available resources and variability of process. Frequency may be lower during normal operation and higher during abnormal conditions. The following routine sampling points and types of tests will permit the operator to identify normal and abnormal operating conditions.

RBC train influent tests

- Dissolved oxygen
- pH
- Temperature
- Settleable solids
- BOD_5
- Suspended solids
- Metals

RBC test

- Speed of rotation

RBC train effluent tests

- Dissolved oxygen
- pH
- Jar tests

Process effluent tests

- Dissolved oxygen
- pH
- Settleable solids
- BOD_5
- Suspended solids

7.4.6 Troubleshooting Operational Problems[*]

The following sections are not all inclusive; that is, they do not cover all of the operational problems associated with the rotating biological contactor process. They do, however, provide information on the most common operational problems.

7.4.6.1 White Slime

Symptom

- White slime on most of the disk area

Causal factors

- High hydrogen sulfide in influent
- Septic influent
- First stage overloaded

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[*] Much of the information in this section is based on Culp, G.L. and Heim, N.F., *Field Manual for Performance Evaluation and Troubleshooting at Municipal Wastewater Treatment Facilities*, U.S. Environmental Protection Agency, Washington, D.C., 1978.

Corrective actions

- Aerate RBC or plant influent.
- Add sodium nitrate or hydrogen peroxide to influent.
- Adjust baffles between stages 1 and 2 to increase fraction of total surface area in first stage.

7.4.6.2 Excessive Sloughing

Symptom

- Loss of slime

Causal factors

- Excessive pH variance
- Toxic influent

Corrective actions

- Implement or enforce pretreatment program.
- Install pH control equipment.
- Equalize flow to acclimate organisms.

7.4.6.3 RBC Rotation

Symptom

- Uneven RBC rotation

Causal factors

- Mechanical growth
- Uneven growth

Corrective actions

- Repair mechanical problem.
- Increase rotational speed.
- Adjust baffles to decrease loading.
- Increase sloughing.

7.4.6.4 Solids

Symptom

- Solids accumulating in reactors

Causal factor

- Inadequate pretreatment

Corrective actions

- Identify and correct grit removal problem.
- Identify and correct primary settling problem.

7.4.6.5 Shaft Bearings

Symptom

- Shaft bearings running hot or failing

Causal factor

- Inadequate maintenance

Corrective action

- Follow manufacturer's recommendations.

7.4.6.6 Drive Motor

Symptom

- Drive motor running hot

Causal factors

- Inadequate maintenance
- Improper chain drive alignment

Corrective actions

- Follow manufacturer's recommendations.
- Adjust alignment.

7.4.7 RBC Process Control Calculations

Several process control calculations may be useful in the operation of a 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.

7.4.7.1 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 in a laboratory. The K factor for domestic wastes is normally in the range of 0.5 to 0.7.

$$\text{Soluble BOD}_5 = \text{Total BOD}_5 - (K \text{ factor} \times \text{Total Suspended Solids}) \qquad (7.11)$$

■ ***Example 7.6***

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: The 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 7.7***

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:

$$\text{Total BOD} = \text{Particulate BOD} + \text{Soluble BOD}$$

$$170 \text{ mg/L} = (140 \text{ mg/L} \times 0.7) + x \text{ mg/L}$$

$$170 \text{ mg/L} = 98 \text{ mg/L} + x \text{ mg/L}$$

$$170 \text{ mg/L} - 98 \text{ mg/L} = x = 72 \text{ mg/L soluble BOD}$$

Now, we can determine the lb/day soluble BOD:

$$\begin{aligned}\text{Soluble BOD (lb/day)} &= \text{Soluble BOD (mg/L)} \times \text{Flow (MGD)} \times 8.34 \text{ lb/gal} \\ &= 72 \text{ mg/L} \times 2.2 \text{ MGD} \times 8.34 \text{ lb/gal} = 1321 \text{ lb/day}\end{aligned}$$

7.4.7.2 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.

$$\text{Total Area} = \text{1st Stage Area} + \text{2nd Stage Area} + \ldots + n\text{th Stage Area} \quad (7.12)$$

7.4.7.3 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 vary from 3 to 4 lb/day/1000 ft^2.

■ ***Example 7.8***

Problem: An RBC has a total media surface area of 102,500 ft^2 and receives a primary effluent flow rate 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:

$$0.269\text{ MGD} \times 159\text{ mg/L} \times \frac{8.34\text{ lb}}{1\text{ gal}} = 356.7\text{ lb/day}$$

$$\frac{356.7\text{ lb/day}}{102{,}500\text{ ft}^2} \times \frac{1000\text{ (number)}}{1000\text{ (unit)}} = 3.48\text{ lb/day/1000 ft}^2$$

7.4.7.4 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 RBCs can range from 1 to 3 gpd/ft^2.

■ ***Example 7.9***

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:

$$\frac{233{,}000\text{ gpd}}{96{,}600\text{ ft}^2} = 2.41\text{ gpd/ft}^2$$

7.5 CHAPTER REVIEW QUESTIONS

7.1 What type of waste treatment pound is most common?

7.2 Give three classifications of ponds based on their location in the system.

7.3 Describe the processes occurring in a raw sewage stabilization pond (facultative).

7.4 How do changes in season affect the quality of the discharge from a stabilization pond?

7.5 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?

7.6 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?

7.7 Name three main parts of the trickling filter, and give the purpose or purposes of each part.

7.8 Name three categories of trickling filter based on their organic loading rate.

7.9 Which classification of trickling filter produces the highest quality effluent?

7.10 What is the purpose of recirculation?

7.11 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?

7.12 Why is a settling tank required following the trickling filter?

7.13 List three things that should be checked as part of the normal operations and maintenance procedures for a trickling filter.

7.14 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 0.366 MGD, what is the hydraulic loading rate on the trickling filter in gallons per day per square foot (gpd/ft^2)?

7.15 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?

7.16 Describe the RBC.

7.17 Describe the process occurring in the RBC process.

7.18 Can an RBC be operated without primary settling?

7.19 What does a chalky white biomass indicate?

7.20 Name two types of RBC media.

7.21 What makes the RBC similar to the trickling filter?

7.22 What makes the RBC perform at approximately the same levels of performance throughout the year?

7.23 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?

7.24 The slime in the first stages of the RBC is gray and shaggy. The slime in the last two stages of the train is reddish brown. What does this indicate?

7.25 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?

REFERENCE AND SUGGESTED READING

Culp, G.L. and Heim, N.F. (1978). *Field Manual for Performance Evaluation and Troubleshooting at Municipal Wastewater Treatment Facilities.* Washington, D.C.: U.S. Environmental Protection Agency.

CHAPTER 8

ACTIVATED SLUDGE PROCESS

The biological treatment systems discussed to this point—ponds, trickling filters, and rotating biological contactors (RBCs)—have been around for years. The trickling filter, for example, has been around and successfully used since the late 1800s. The problem with ponds, trickling filters, and RBCs is that they are temperature sensitive, remove less BOD, and cost more to build (particularly trickling filters) 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 8.1). Primary effluent is mixed with settled solids recycled from the secondary clarifier and is 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.

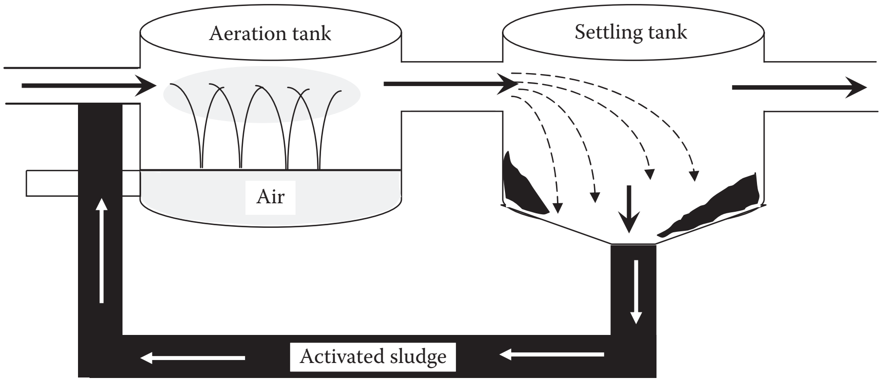

Figure 8.1 The activated sludge process.

8.1 ACTIVATED SLUDGE TERMINOLOGY

To better understand the discussion of the activated sludge process presented in the following sections, it is necessary to 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, as they are used throughout the discussion.

Absorption—Taking in or reception of one substance into the body of another by molecular or chemical actions and 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 or influent and activated sludge are 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—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 the stabilization of organic waste.

Biochemical oxygen demand (BOD)—A measure of the amount of food available to the microorganisms in a particular waste. It is measured by 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, which 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—A diffused-air-activated sludge plant takes air, compresses it, then 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 (DO)—Atmospheric oxygen dissolved in water or wastewater.

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 (MLVSS). This may be written as an F/M ratio:

$$\frac{\text{Food}}{\text{Microorganisms}} = \frac{\text{BOD (lb/day)}}{\text{MLVSS (lb)}} = \frac{\text{Flow (MGD)} \times \text{BOD (mg/L)} \times 8.34 \text{ lb/gal}}{\text{Volume (MG)} \times \text{MLVSS (mg/L)} \times 8.34 \text{ lb/gal}}$$

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 (MLSS).

Mean cell residence time (MCRT)—The average length of time particles of mixed liquor suspended solids 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 liquor.

Mixed liquor volatile suspended solids (MLVSS)—The organic matter in the mixed liquor suspended solids; 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 (SSV)—The volume (mL/L or percent) occupied by an activated sludge sample after 30 or 60 min of settling. Normally written as SSV with a subscript to indicate the time of the reading used for calculation (e.g., SSV_{30} or SSV_{60}).

Shock load—The arrival at a plant of a waste toxic to organisms, in sufficient quantity or strength 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 (SVI)—A process control calculation used to evaluate the settling quality of the activated sludge. It 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 min.

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; also known as *colloidal solids*.

Suspended—The solids that will not pass through a glass fiber filter.

Total—The solids in water, sewage, or other liquids; it includes the suspended solids and dissolved solids.

Volatile—The 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.

8.2 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.

8.2.1 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.

8.2.2 Aeration

Aeration can be mechanical or diffused. Mechanical aeration systems use agitators or mixers to mix air and mixed liquor. Some systems use *sparge rings* 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 air (5 to 10 psi), 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.

8.2.3 Settling Tank

Activated sludge systems are equipped with plain settling tanks designed to provide 2 to 4 hours of hydraulic detention time.

8.2.4 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.

8.2.5 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.

8.3 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 returned activated sludge and to supply the oxygen required 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 called 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.

8.4 FACTORS AFFECTING OPERATION OF THE ACTIVATED SLUDGE PROCESS

A number of factors affect the performance of an activated sludge system. These include the following:

- 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 oxygen (dissolved oxygen). 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.

8.5 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* (see Figure 8.2). 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 new cells. This condition is known as the *log growth phase*. As time continues, 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*. The *endogenous respiration* phase occurs as the food available becomes extremely limited and the organism mass begins to decline. Some of the microorganisms may die and break apart, thus releasing organic matter that can be consumed by the remaining population.

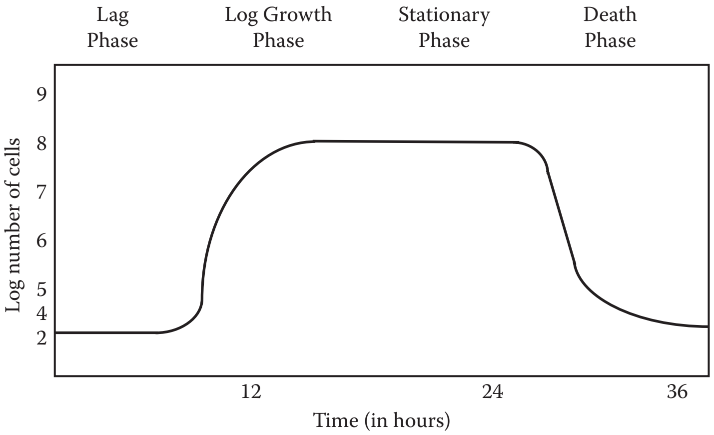

Figure 8.2 Microbe growth curve.

The actual operation of an activated sludge system is regulated by three factors: (1) the quantity of air being supplied to the aeration tank, (2) the rate of activated sludge recirculation, and (3) the amount of excess sludge being 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) biological 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.

8.6 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. The second step is the conversion of wastes to a usable form. Third is the flocculation step:

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, then absorbed through the cell wall.

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.

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*.

8.7 ACTIVATED SLUDGE PERFORMANCE-CONTROLLING FACTORS

To maintain the working organisms in the activated sludge process, the operator must be sure 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.

8.7.1 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 a loss of activated sludge.

8.7.2 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.

8.7.3 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.

8.7.4 pH

The pH of the mixed liquor should be maintained within the range of 6.5 to 9.0 (6.0 to 8.0 is ideal). Gradual fluctuations within this range will normally not upset the process. Rapid fluctuations or fluctuations outside this range can reduce organism activity.

8.7.5 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.

8.7.6 Toxicity

Sufficient concentrations of elements or compounds that enter a treatment plant that have the ability 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 that 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.

8.7.7 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, excessive return rates, or many other factors. 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.

8.7.8 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 can 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 cause 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. 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.

8.8 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 with different influent waste characteristics.

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).

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.

Complete mix

- Complete mix may or may not include primary treatment.
- It distributes the waste, return, and oxygen evenly throughout the tank.
- Aeration may be more efficient.

- It maximizes tank use.
- It allows a higher organic loading.

Note: During the complete mix, activated sludge process organisms are in the declining phase on the growth curve.

Pure oxygen

- Pure oxygen 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.

Contact stabilization

- Contact stabilization does not require primary treatment.
- During operation, 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.

Extended aeration

- Extended aeration 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.

Oxidation ditch

- The oxidation ditch does not require primary treatment.
- It is similar to the extended aeration process.

TABLE 8.1 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
DO (mg/L)	1–3	1–3	1–3	1–3
SSV_{30} (ml/L)	400–700	400–700 (contact)	400–700	400–700
Food-to-mass 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	N/A	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

Table 8.1 lists the process parameters for each of the four most commonly used activated sludge modifications.

8.9 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.

8.9.1 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.

8.9.2 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.

8.9.3 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 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.

8.9.4 Mixed Liquor Suspended Solids, Mixed Liquor Volatile Suspended Solids, 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 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.

8.9.5 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.

8.9.6 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.

8.9.7 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.

8.9.8 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 on such factors as hydraulic load, clarifier design, and sludge characteristics. 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 15- to 20-ft long clear plastic pipe marked at 6-inch intervals; the pipe is equipped with a ball valve at the bottom.

8.10 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 could maintain plant performance within the 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

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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.

- Process sidestreams
- Seasonal variations
- Required effluent quality

8.10.1 Influent Characteristics

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 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.

8.10.2 Industrial Contributors

One or more industrial contributors produce a significant portion of the plant loading (in many systems). Identifying and characterizing all industrial contributors is 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 that 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 implementation of a pretreatment program.

8.10.3 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 part of the organic or 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.

8.10.4 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.

8.10.5 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, 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, it is important to evaluate all potential process control options to determine the following:

- Sensitivity to effluent quality changes
- Seasonal variability
- Potential problems

8.11 VISUAL INDICATORS FOR INFLUENT OR AERATION TANK

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 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. Aeration tank and secondary settling tank observations are summarized in the following sections. Remember that many of these observations are very subjective and must be based on experience. Plant personnel must be properly trained on the importance of ensuring that recorded information is consistent throughout the operating period.

8.11.1 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 to air flow may be necessary, or the diffusers may require cleaning or replacement.

8.11.2 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).

8.11.3 Sludge Color and Odor

Though not as reliable an indicator of process operations as foam, sludge color 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).

8.11.4 Mixed Liquor Color

A light chocolate brown mixed liquor color indicates a well-operated activated sludge process.

8.12 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* occurs when solids are evenly distributed throughout the tank and leaving over the weir in large quantities.
- *Sludge solids washout* occurs when the sludge blanket is down but solids are flowing over the effluent weir in large quantities. Control tests indicate good-quality sludge.
- *Clumping* occurs when large clumps or masses of sludge (several inches or more) rise to the top of the settling tank.
- *Ashing* occurs when fine particles of gray to white material are flowing over the effluent weir in large quantities.
- *Straggler floc* is comprised of small, almost transparent, very fluffy, buoyant solids particles (1/8 to 1/4 inch in diameter) that rise to the surface, usually accompanied by a very clean effluent. New growth is most noted in the early morning hours. Sludge age is slightly below optimum.
- *Pin floc* is comprised of very fine solids particles, normally less than 1/32 inch in diameter, that are suspended throughout lightly turbid liquid; usually the result of an overoxidized sludge.

8.13 PROCESS CONTROL SAMPLING AND TESTING

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.

8.13.1 Aeration Tank Influent and Effluent Sampling

8.13.1.1 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 range being 6.5 to 8.5 (although a pH range of 6.5 to 9.0 is satisfactory). A pH of >9.0 may indicate toxicity from an industrial waste contributor. A pH of <6.5 may indicate loss of flocculating organisms, potential toxicity, industrial waste contributors, or acid storm flow. Keep in mind that the effluent pH may be lower because of nitrification.

8.13.1.2 Temperature

Temperature is important because it indicates 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.

8.13.1.3 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.

8.13.1.4 Settled Sludge Volume (Settleability)

Settled sludge volume (SSV) is determined at specified times during sample testing. Both the 30- and 60-minute observations are used for control. Subscripts (e.g., SSV_{30} and SSV_{60}) indicate the settling time. The test is performed on aeration tank effluent samples.

$$\text{SSV} = \frac{\text{Milliliters of Settled Sludge} \times 1000 \text{ mL/L}}{\text{Milliliters of Sample}} \tag{8.1}$$

$$\%\text{SSV} = \frac{\text{Milliliters of Settled Sludge} \times 100}{\text{Milliliters of Sample}} \tag{8.2}$$

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.

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.

8.13.1.5 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.

8.13.1.6 Alkalinity

Alkalinity is essential to biological activity. Nitrification requires 7.3-mg/L alkalinity per mg/L total Kjeldahl nitrogen.

8.13.1.7 BOD_5

Testing showing an increase in BOD_5 indicates increased organic loading; a decrease in BOD_5 indicates decreased organic loading.

8.13.1.8 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.

8.13.1.9 Total Kjeldahl Nitrogen

Total Kjeldahl nitrogen (TKN) determination is required to monitor process nitrification status and to determine alkalinity requirements.

8.13.1.10 Ammonia Nitrogen

Determination of ammonia nitrogen is required to monitor process nitrification status.

8.13.1.11 Metals

Metal contents are measured to determine toxicity levels.

8.13.2 Aeration Tank

8.13.2.1 pH

Normal pH range in the aeration tank is 6.5 to 9.0. Decreases in pH indicate the presence of process sidestreams or that insufficient alkalinity is available.

8.13.2.2 Dissolved Oxygen

The normal range of DO 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.

8.13.2.3 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.

8.13.2.4 Mixed Liquor Suspended Solids

The range of mixed liquor suspended solids is determined by the process modification used. When MLSS levels increase, more solids, organisms, and an older, more oxidized sludge are typical.

8.13.2.5 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 8.2 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.

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

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 8.2 list of indicator organisms.

Key Point: The presence of free-swimming and stalked ciliates, some flagellates, and rotifers in mixed liquor indicates a balanced, properly settling environment.

8.13.2.5.1 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.

TABLE 8.2 PROCESS CONDITION VS. ORGANISMS PRESENT

Process Condition	Organism Population
Poor BOD_5 and TSS removal No floc formation Very cloudy effluent	Predominance of amoebae and flagellates Mainly dispersed bacteria A few ciliates present
Poor-quality effluent Dispersed bacteria Some free-swimming ciliates Some floc formation Cloudy effluent	Predominance of amoebae and flagellates Some free-swimming ciliates
Satisfactory effluent Good floc formation Good settleability Good clarity	Predominance of free-swimming ciliates Few amoebae and flagellates
High-quality effluent Excellent floc formation Excellent settleability High effluent clarity	Predominance of stalked ciliates Some free-swimming ciliates A few rotifers A few flagellates
Effluent high TSS and low BOD_5 High settled sludge volume Cloudy effluent	Predominance of rotifers Large numbers of stalked ciliates A few free-swimming ciliates; no flagellates

The activated sludge process is typified by the successive development of protozoa and mature floc particles. This succession can be indicated by the presence of 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 "grows" 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 large numbers 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 a wastewater treatment plant as a “stream within a container.” 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 can see 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 causes a corresponding change in the population of microorganisms. Decreases in bacteria increase competition between protozoa and result in secession of dominant groups of protozoa.

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 available food. This is when the next group of protozoa (the free-swimming protozoa) enters 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. Secreting polysaccharides and mucoproteins that are absorbed by bacteria—which make the bacteria "sticky" through biological agglutination (biological gluing together)—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 are either 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; 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 it. 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.

8.13.2.5.2 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 utilize other organisms, as well as organic matter, as their food source. Rotifers are normally the predominant organism; the effluent will usually be cloudy (pin or ash floc) and will have very low BOD_5.

8.13.2.5.3 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.

8.13.3 Settling Tank Influent

8.13.3.1 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.

8.13.3.2 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.

8.13.3.3 Alkalinity

A lack of alkalinity in an activated sludge settling tank will prevent nitrification.

8.13.3.4 Total Suspended Solids

Mixed liquor suspended solids sampling and testing are required for determining solids loading, mass balance, and return rates.

8.13.3.5 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:

$$\text{SSV} = \frac{\text{Milliliters of Settled Sludge} \times 1000\ \text{mL}}{\text{Milliliters of Sample}} \tag{8.3}$$

$$\%\text{SSV} = \frac{\text{Milliliters of Settled Sludge} \times 100}{\text{Milliters of Sample}} \tag{8.4}$$

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.

8.13.3.6 Flow

Monitoring flow in settling tank influent is important for determination of the mass balance.

8.13.3.7 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.

8.13.4 Settling Tank

8.13.4.1 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 of the 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 can affect the test result.

8.13.4.2 Suspended Solids and Volatile Suspended Solids

Suspended solids and volatile suspended solids concentrations of the mixed liquor suspended solids (MLSS), the return activated sludge (RAS), and waste activated sludge (WAS) are routinely sampled and tested because they are critical to process control.

8.13.5 Settling Tank Effluent

8.13.5.1 BOD$_5$ and Total Suspended Solids

Testing for BOD$_5$ and total suspended solids is conducted variably (daily, weekly, or monthly). Increases indicate that treatment performance is decreasing; decreases indicate that treatment performance is increasing.

8.13.5.2 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.

8.13.5.3 Nitrate Nitrogen

Nitrate nitrogen sampling and testing are variable. Increases in nitrate nitrogen indicate increasing nitrification or an industrial contribution of nitrates. A decrease indicates reduced nitrification.

8.13.5.4 Flow

Settling tank effluent flow is sampled and tested daily. Results are required for several process control calculations.

8.13.6 Return Activated Sludge and Waste Activated Sludge

8.13.6.1 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.

8.13.6.2 Flow

The flow of return activated sludge is tested daily. Test results are required to determine the mass balance and for control of 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.

8.13.7 Process Control Adjustments

In the routine performance of their duties, wastewater operators make process control adjustments to various unit processes, including the activated sludge process. Following is a summary of the process controls available for the activated sludge process.

8.13.7.1 Process Control: Return Rate

Condition: Return rate is too high.
Result:

- Hydraulic overloading of aeration and settling tanks
- Reduced aeration time
- Reduced settling time
- Loss of solids over time

Condition: Return rate is too low.
Result:

- Septic return
- Solids buildup in settling tank
- Reduced MLSS in aeration tank
- Loss of solids over weir

8.13.7.2 Process Control: Waste Rate

Condition: Waste rate is too high.
Result:

- Reduced MLSS
- Decreased sludge density
- Increased SVI
- Decreased MCRT
- Increased F/M ratio

Condition: Waste rate is too low.
Result:

- Increased MLSS
- Increased sludge density
- Decreased SVI
- Increased MCRT
- Decreased F/M ratio

8.13.7.3 Process Control: Aeration Rate

Condition: Aeration rate is too high.
Result:

- Wasted energy
- Increased operating cost
- Rising solids
- Breakup of activated sludge

Condition: Aeration rate is too low.
Result:

- Septic aeration tank
- Poor performance
- Loss of nitrification

8.13.8 Troubleshooting Operational Problems

Without a doubt, the most important dual function performed by the wastewater operator is the identification of process control problems and implementing the appropriate actions to correct the problems. This section lists typical aeration system operational problems with their symptoms, causes, and appropriate corrective actions to restore the unit process to a normal or optimal performance level.

- **Symptom 1.** The solids blanket is flowing over the effluent weir (classic bulking). Settleability test shows no settling.

  Cause: Organic overloading

    Corrective action: Reduce organic loading.

  Cause: Low pH

    Corrective action: Add alkalinity.

  Cause: Filamentous growth

    Corrective action: Add nutrients; add chlorine or peroxide to return.

Cause: Nutrient deficiency

Corrective action: Add nutrients.

Cause: Toxicity

Corrective action: Identify source; implement pretreatment.

Cause: Overaeration

Corrective action: Reduce aeration during low flow periods.

- **Symptom 2.** Solids settled properly in settleability test but large amounts of solids lost over effluent weir.

Cause: Billowing solids due to short-circuiting

Corrective action: Identify short-circuiting cause and eliminate if possible.

- **Symptom 3.** Large amounts of small, pinhead-size solids are leaving settling tank.

Cause: Old sludge

Corrective action: Reduce sludge age (gradual change is best); increase waste rate.

Cause: Excessive turbulence

Corrective action: Decrease turbulence (adjust aeration during low flows).

- **Symptom 4.** Large amounts of light floc (low BOD_5 and high solids) are leaving the settling tank.

Cause: Extremely old sludge

Corrective action: Reduce age; increase waste.

- **Symptom 5.** Large amounts of small translucent particles (1/16 to 1/8 in.) are leaving the settling tank.

Cause: Rapid solids growth

Corrective action: Increase sludge age.

Cause: Slightly young activated sludge

Corrective action: Decrease waste.

- **Symptom 6.** Solids are settling properly but rise to the surface within a short time. Many small (1/4 in.) to large (several feet) clumps of solids are visible on the surface of the settling tank.

Cause: Denitrification

Corrective action: Increase the rate of return; adjust the sludge age to eliminate nitrification.

Cause: Overaeration

Corrective action: Reduce aeration.

- **Symptom 7.** Return activated sludge has a rotten egg odor.

  Cause: Septic return

  Corrective action: Increase the aeration rate.

  Cause: Low return rate

  Corrective action: Increase the rate of return.

- **Symptom 8.** Activated sludge organisms die during a short time.

  Cause: Toxic material in the influent

  Corrective action: Isolate the activated sludge (if possible); return all available solids; stop wasting; increase return rate; implement pretreatment program.

- **Symptom 9.** Surface of the aeration tank is covered with thick, greasy foam.

  Cause: Extremely old activated sludge

  Corrective action: Reduce activated sludge age; increase wasting; use foam control sprays.

  Cause: Excessive grease and oil in system

  Corrective action: Improve grease removal; use foam control sprays; implement pretreatment program.

  Cause: Froth-forming bacteria present

  Corrective action: Remove froth-forming bacteria.

- **Symptom 10.** Large clouds of billowing white foam are on the surface of the aeration tank.

  Cause: Young activated sludge

  Corrective action: Increase sludge age; decrease wasting; use foam control sprays.

  Cause: Low solids in aeration tank

  Corrective action: Increase sludge age; decrease wasting; use foam control sprays.

  Cause: Surfactants (detergents)

  Corrective action: Eliminate surfactants; use foam control sprays; add antifoam.

8.14 PROCESS CONTROL CALCULATIONS

As with other wastewater treatment unit processes, process control calculations are important tools used by the operator to optimize and control process operations. In this section, we review the most frequently used activated sludge calculations.

8.14.1 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:

$$\text{Settled Sludge Volume (mL/L)} = \frac{\text{Settled Sludge Volume (mL)}}{\text{Sample Volume (L)}} \quad (8.5)$$

Note: 1000 milliliters = 1 liter.

$$\text{Sample Volume (L)} = \frac{\text{Sample Volume (mL)}}{1000\ \text{mL/L}} \quad (8.6)$$

$$\%\ \text{Settled Sludge Volume} = \frac{\text{Settled Sludge Volume (mL)} \times 100}{\text{Sample Volume (mL)}} \quad (8.7)$$

■ ***Example 8.1***

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:

$$SSV_{30} = \frac{1800\ \text{mL}}{2.5\ \text{L}} = 720\ \text{mL/L}$$

$$\%SSV_{60} = \frac{1600\ \text{mL} \times 100}{2500\ \text{mL}} = 64\%$$

8.14.2 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 must be used.

$$\text{Estimated Return Rate (MGD)} = \begin{bmatrix} \text{Influent Flow (MGD)} \\ + \text{ Current Return Flow (MGD)} \end{bmatrix} \times \%SSV_{60}$$

- Assumes that %SSV_{60} is representative.
- Assumes that 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 8.2*

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 (MGD)?

Solution:

$$\text{Return Rate} = (4.2\text{ MGD} + 1.5\text{ MGD}) \times 0.38 = 2.2\text{ MGD}$$

8.14.3 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 settled sludge volume (mL/L) and the mixed liquor suspended solids (mg/L) are required for this calculation:

$$\text{Sludge Volume Index (SVI)} = \frac{\text{SSV (mL)} \times 1000}{\text{MLSS (mg/L)}} \tag{8.8}$$

■ *Example 8.3*

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	Expected Condition (Indicates)
Less than 100	Old sludge; possible pin floc; increasing effluent turbidity
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 (refer to the following chart):

SVI Value	Result	Adjustment
Increasing	Sludge is becoming less dense.	Decrease waste.
	Sludge is either younger or bulking.	Increase return rate.
	Sludge will settle more slowly.	
	Sludge will compact less.	
Decreasing	Sludge is becoming more dense.	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.

8.14.4 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, should know how to calculate:

$$\begin{aligned}\text{Waste (lb/day)} &= \text{WAS Concentration (mg/L)} \\ &\quad \times \text{WAS Flow (MGD)} \times 8.34\ \text{lb/MG/mg/L}\end{aligned} \tag{8.9}$$

■ ***Example 8.4***

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:

$$\text{Waste} = 5540\text{ mg/L} \times 0.44\text{ MGD} \times 8.34\text{ lb/MG/mg/L} = 20{,}329.6\text{ lb/day}$$

8.14.5 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 (COD) 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)

$$\text{F/M Ratio} = \frac{\begin{bmatrix}\text{Primary Effluent COD/BOD (mg/L)}\\ \times\text{ Flow (MGD)} \times 8.34\text{ lb/MG/mg/L}\end{bmatrix}}{\begin{bmatrix}\text{MLVSS (mg/L)} \times \text{Aerator Volume (MG)}\\ \times 8.34\text{ lb/MG/mg/L}\end{bmatrix}} \tag{8.10}$$

Typical F/M ratios for activated sludge processes are shown below:

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

■ ***Example 8.5***

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
Effluent flow = 2.2 MGD
Effluent BOD = 22 mg/L
Effluent TSS = 16 mg/L

Aeration volume = 0.65 MG
Settling volume = 0.30 MG
MLSS = 3650 mg/L
MLVSS = 2550 mg/L
% Waste VM = 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 (MLSS) is known (see Equation 8.11).

$$\text{MLVSS} = \text{MLSS} \times \%\text{VM} \tag{8.11}$$

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 the analysis of organic load is that COD is more accurate.

■ *Example 8.6*

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:

$$\text{MLVSS} = 2985\ \text{mg/L} \times 0.66 = 1970\ \text{mg/L}$$

8.14.5.1 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 for identifying the most effective range for individual plants, when the range of F/M values that produce the desired effluent quality has been established.

8.14.5.1.1 Required MLVSS Quantity

The pounds of MLVSS required in the aeration tank to achieve the optimum F/M ratio can be determined from the average influent food (BOD or COD) and the desired F/M ratio:

$$\text{MLVSS (lb)} = \frac{\text{Primary Effluent BOD or COD} \times \text{Flow (MGD)} \times 8.34}{\text{Desired F/M Ratio}} \tag{8.12}$$

The required pounds of MLVSS determined by this calculation can then be converted to a concentration value by:

$$\text{MLVSS (mg/L)} = \frac{\text{Desired MLVSS (lb)}}{\text{Aeration Volume (MG)} \times 8.34} \tag{8.13}$$

■ *Example 8.7*

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:

$$\text{MLVSS (lb)} = \frac{145\text{ mg/L} \times 4.0\text{ MGD} \times 8.34\text{ lb/gal}}{0.3\text{ lb COD/lb MLVSS}} = 16{,}124\text{ lb}$$

$$\text{MLVSS (mg/L)} = \frac{16{,}124\text{ MLVSS}}{0.65\text{ MG} \times 8.34} = 2974\text{ mg/L}$$

8.14.5.1.2 Calculating Waste Rates Using the 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.

$$\text{Waste Volatile Solids (lb/day)} = \text{Actual MLVSS (lb)} - \text{Desired MLVSS (lb)} \tag{8.14}$$

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):

$$\text{Waste (MGD)} = \frac{\text{Waste Volatile Solids (lb/day)}}{\text{Waste Volatile Concentration (mg/L)} \times 8.34} \tag{8.15}$$

Note: When the F/M ratio is used for process control, the volatile content of the waste activated sludge should be determined.

■ *Example 8.8*

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:

$$\text{Actual MLVSS} = 3.549\text{ mg/L} \times 0.75\text{ MG} \times 8.34 = 22{,}199\text{ lb}$$

$$\text{Required MLVSS} = \frac{140\text{ mg/L} \times 2.2\text{ MGD} \times 8.34}{0.17\text{ lb COD/lb MLVSS}} = 15{,}110\text{ lb}$$

$$\text{Waste (lb)} = 22{,}199\text{ lb} - 15{,}110\text{ lb} = 7089\text{ lb}$$

$$\text{Waste (MGD)} = \frac{7089\text{ lb/day}}{4440\text{ mg/L} \times 8.34} = 0.19\text{ MGD}$$

$$\text{Waste (gpm)} = \frac{0.19\text{ MGD} \times 1{,}000{,}000\text{ gpd/MGD}}{1440\text{ min/day}} = 132\text{ gpm}$$

8.14.6 Mean Cell Residence Time (MCRT)

Mean cell residence time (MCRT), sometimes referred to as *sludge retention time*, is a process control calculation used for activated sludge systems. The MCRT calculation illustrated in Example 8.9 uses the entire volume of the activated sludge system (aeration and settling).

$$\begin{array}{c}\text{MRCT}\\ \text{(days)}\end{array} = \frac{\text{MLSS (mg/L)} \times \begin{bmatrix}\text{Aeration Volume (MG)}\\ \text{+Clarifier Volume (MG)}\end{bmatrix} \times 8.34\text{ lb/MG/mg/L}}{\begin{array}{c}\left[\text{WAS (mg/L)} \times \text{WAS Flow (MGD)} \times 8.34\text{ lb/MG/mg/L}\right]\\ +\left[\text{TSS out (mg/L)} \times \text{Flow} \times 8.34\text{ lb/MG/mg/L}\right]\end{array}} \tag{8.16}$$

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 8.9***

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:

$$\text{MRCT} = \frac{3350\text{ mg/L} \times (1.2\text{ MG} + 0.6\text{ MG}) \times 8.34}{(6100\text{ mg/L} \times 0.08\text{ MGD} \times 8.34) + (10\text{ mg/L} \times 4.2\text{ MGD} \times 8.34)}$$

$$= 11.4\text{ days}$$

8.14.6.1 Mean Cell Residence Time Control

Because it provides an accurate evaluation of the process condition and considers all aspects of the solids inventory, 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. You should remember these important process control parameters and their impact on the MCRT:

- To increase F/M, decrease MCRT.
- To increase MCRT, decrease waste rate.
- If the MCRT is increased, the MLTSS and 30-minute settling volume increase.
- Return sludge rate has no impact on MCRT.
- MCRT has no impact on F/M when the number of aeration tanks in service is reduced.

8.14.6.2 Typical MCRT Values

The following chart lists the various aeration process modifications and associated MCRT values:

Process	MCRT (days)
Conventional	5–15
Step aeration	5–15
Contact stabilization	5–15
Extended aeration	20–30
Oxidation ditch	20–30
Pure oxygen	8–20

8.14.6.3 *MCRT Control Values*

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.

8.14.6.4 *Waste Quantities and Requirements*

Using the MCRT for process control requires determination of 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:

$$\begin{aligned}\text{Waste (lb/day)} &= \left[\frac{\text{MLSS} \times \left(\text{Aeration Vol. (MG)} + \text{Clarifier Vol. (MG)}\right) \times 8.34}{\text{Desired MCRT}}\right] \\ &\quad - \left(\text{TSS}_{\text{out}} \times \text{Flow} \times 8.34\right)\end{aligned} \tag{8.17}$$

■ ***Example 8.10***

$$\begin{aligned}\text{Waste} &= \frac{3400\text{ mg/L} \times (1.4\text{ MG} + 0.50\text{ MG}) \times 8.34}{8.6\text{ days}} - (10\text{ mg/L} \times 5.0\text{ MGD} \times 8.34) \\ &= 5848\text{ lb/day}\end{aligned}$$

8.14.6.5 *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, and gpm) is a function of the volume of waste to be removed and the design of the equipment.

$$\text{Waste(MGD)} = \frac{\text{Waste (lb/day)}}{\text{WAS Concentrations (mg/L)} \times 8.34} \tag{8.18}$$

$$\text{Waste (gpm)} = \frac{\text{Waste (MGD)} \times 1{,}000{,}000\text{ gpd/MGD}}{1440\text{ min/day}} \tag{8.19}$$

■ ***Example 8.11***

Problem: Given the following data, determine the required waste rate to maintain a MCRT of 8.8 days.

MLSS (mg/L) = 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:

$$\text{Waste (lb/day)} = \left[\frac{2500\text{ mg/L} \times (1.20 + 0.20) \times 8.34}{8.8\text{ days}}\right]$$

$$-(11\text{ mg/L} \times 5.0\text{ MGD} \times 8.34)$$

$$= 3317\text{ lb/day} - 459\text{ lb/day} = 2858\text{ lb/day}$$

$$\text{Waste (MGD)} = \frac{2858\text{ lb/day}}{6000\text{ mg/L} \times 8.34} = 0.057\text{ MGD}$$

$$\text{Waste (gpm)} = \frac{0.057\text{ MGD} \times 1{,}000{,}000\text{ gpd/MGD}}{1440\text{ min/day}} = 40\text{ gpm}$$

8.14.7 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: If influent values and effluent values do not correlate within 10 to 15%, it usually indicates 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.

8.14.7.1 Mass Balance for 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 operations 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.

$$\text{Total Suspended Solids In (lb)} = \text{TSS}_{in} \times \text{Flow(MGD)} \times 8.34 \qquad (8.20)$$

$$\text{Total Suspended Solids Out (lb)} = \text{TSS}_{out} \times \text{Flow (MGD)} \times 8.34 \qquad (8.21)$$

$$\text{Sludge Solids} = \text{Sludge Pumped (gal)} \times \%\text{Solids} \times 8.34 \qquad (8.22)$$

$$\begin{matrix}\%\text{ Mass}\\ \text{Balance}\end{matrix} = \frac{\left[\text{TSS}_{in}\ (\text{lb}) - \left(\text{TSS}_{out}\ (\text{lb}) + \text{Sludge Sol. (lb)}\right)\right] \times 100}{\text{TSS}_{in}\ (\text{lb})} \qquad (8.23)$$

8.14.7.2 Explanation of Results

1. If the mass balance is ±15%, the process is considered to be in balance. Sludge removal should be adequate, and the sludge blanket depth should be remaining stable. Sampling is considered to be producing representative samples that are being tested accurately.
2. If the mass balance is greater that ±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, then the mass balance may indicate that sample type, location, times, or procedures or the testing procedures are not producing representative results.
3. If the mass balance is less than ±15%, 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, or procedures or the testing procedures are not producing representative results.

■ *Example 8.12*

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:

$$\text{Total Suspended Solids In} = 2445 \text{ mg/L} \times 2.6 \text{ MGD} \times 8.34 = 53{,}017 \text{ lb/day}$$

$$\text{Total Suspended Solids Out} = 17 \text{ mg/L} \times 2.6 \text{ MGD} \times 8.34 = 369 \text{ lb/day}$$

$$\text{Sludge Solids Out} = 8470 \text{ mg/L} \times 0.5 \text{ MGD} \times 8.34 = 35{,}320 \text{ lb/day}$$

$$\text{Mass Balance} = \frac{\left[53{,}017 \text{ lb/day} - (369 \text{ lb/day} + 35{,}320 \text{ lb/day})\right] \times 100}{53{,}017 \text{ lb/day}} = 32.7\%$$

The value indicates that the sampling point, collection procedure, or laboratory procedure is producing inaccurate data upon which to make process control decisions. Or, more solids are entering the settling tank each day than are being removed. This should result in either (1) a solids buildup in the settling tank, or (2) a loss of solids over the effluent weir. Investigate further to determine the specific cause of the imbalance.

8.14.7.3 Mass Balance Biological Process

Solids are produced when biological processes are used to remove organic matter from wastewater. The mass balance for an aerobic biological process must take into account both the solids removed by 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, a series of *K* factors has been developed 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 8.3 lists average *K* factors in pounds of solids produced per pound of BOD removed for selected processes.

8.14.7.4 Conversion Factors

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 8.3).

8.14.7.5 Mass Balance Calculation

$$BOD_5 \text{ In (lb)} = \text{BOD (mg/L)} \times \text{Flow (MGD)} \times 8.34$$

$$BOD_5 \text{ Out (lb)} = \text{BOD (mg/L)} \times \text{Flow (MGD)} \times 8.34$$

$$\text{Solids Produced (lb/day)} = [BOD_{in} \text{ (lb)} - BOD_{out} \text{ (lb)}] \times K$$

$$TSS_{out} \text{ (lb/day)} = TSS_{out} \text{ (mg/L)} \times \text{Flow (MGD)} \times 8.34$$

TABLE 8.3 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 feed	0.85
Extended aeration	0.65
Oxidation ditch	0.65
Contact stabilization	1.00
Trickling filter	1.00
Rotating biological contactor	1.00

$$\text{Waste (lb/day)} = \text{Waste (mg/L)} \times \text{Flow (MGD)} \times 8.34$$

$$\text{Solids Removed (lb/day)} = \text{TSS}_{\text{out}}\text{ (lb/day)} + \text{Waste (lb/day)}$$

$$\%\text{ Mass Balance} = \frac{(\text{Solids Produced} - \text{Solids Removed}) \times 100}{\text{Solids Produced}} \quad (8.24)$$

8.14.7.6 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.

8.14.7.7 Sludge Waste Based on Mass Balance

The mass balance calculation predicts the amount of sludge that will be produced by a treatment process. This information can then be used to determine what the waste rate must be, under current operating conditions, to maintain the current solids level:

$$\text{Waste Rate (MGD)} = \frac{\text{Solids Produced (lb/day)}}{\text{Waste Concentration} \times 8.34} \quad (8.25)$$

- ***Example 8.13***

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:

$$\text{BOD}_5 \text{ In} = 220 \text{ mg/L} \times 1.1 \text{ MGD} \times 8.34 = 2018 \text{ lb/day}$$

$$\text{BOD}_5 \text{ Out} = 18 \text{ mg/L} \times 1.1 \text{ MGD} \times 8.34 = 165 \text{ lb/day}$$

$$\text{BOD}_5 \text{ Removed} = 2018 \text{ lb/day} - 165 \text{ lb/day} = 1853 \text{ lb/day}$$

$$\text{Solids Produced} = 1853 \text{ lb/day} \times 0.65 \text{ lb/lb BOD5} = 1204 \text{ lb/day}$$

$$\text{Solids Out} = 22 \text{ mg/L} \times 1.1 \text{ MGD} \times 8.34 = 202 \text{ lb/day}$$

$$\text{Sludge Out} = 8710 \text{ mg/L} \times 0.024 \text{ MGD} \times 8.34 = 1743 \text{ lb/day}$$

$$\text{Solids Removed} = (292 \text{ lb/day} + 1743 \text{ lb/day}) = 1945 \text{ lb/day}$$

$$\text{Mass Balance} = \frac{(1204 \text{ lb/day} - 1945 \text{ lb/day}) \times 100}{1204 \text{ lb/day}} = 62\%$$

The mass balance indicates either of the following:

1. The sampling points, collection methods, or laboratory testing procedures are producing nonrepresentative results.
2. 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:

$$\text{Waste (gpd)} = \frac{\text{Solids Produced (lb/day)}}{\text{Waste TSS (mg/L)} \times 8.34} \tag{8.26}$$

$$\text{Waste} = \frac{1204 \text{ lb/day} \times 1{,}000{,}000}{8710 \text{ mg/L} \times 8.34} = 16{,}575 \text{ gpd}$$

8.14.8 Solids Concentration in 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.

8.15 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, providing information on the cause of problems, providing information for making seasonal changes, and 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.

8.16 CHAPTER REVIEW QUESTIONS

8.1 Increasing the wasting rate will ________ the MLSS concentration, ________ the return concentration, ________ the MCRT and F/M ratio, and ________ the SVI.

8.2 What two purposes does the air supplied to the aeration basin serve?

Use the following data for Questions 8.3 through 8.7:

Plant influent
Flow = 2.10 MGD
BOD = 230 mg/L
TSS = 270 mg/L
Primary effluent
Flow = 2.10 MGD
Aeration tank influent
BOD = 175 mg/L
TSS = 133 mg/L
Aeration tank
Volume = 1,265,000 gal
MLSS = 2780 mg/L
MLVSS = 1860 mg/L

SSV test
Sample = 2000 mL
30-min settleability test = 1750 mL
60-min settleability test = 1050 mL
Waste activated sludge
Flow = 0.090 MGD
Solids = 6125 mg/L
Volatile solids = 4105 mg/L
Return activated sludge
Flow = 0.50 MGD
Solids = 5785 mg/L
Volatile solids = 4165 mg/L
Settling tank volume = 882,000 gal
Desired F/M ratio = 0.25 lb/lb
Desired MCRT = 6.5 days

8.3 What is the mean cell residence time (MCRT) in days?

8.4 What is the food-to-microorganism (F/M) ratio?

8.5 What is the SSV_{60} in mL/L?

8.6 Using the SSV_{60} in mL/L, what is the sludge volume index?

8.7 What must be done to decrease the SVI?

8.8 What is the liquid mixture of microorganisms and solids removed from the bottom of the settling tank called?

8.9 What is the mixture of primary effluent and return sludge called?

8.10 What are the three things that must be balanced to make the activated sludge process perform properly?

8.11 What is the major purpose of an activated sludge process?

8.12 Name two types of aeration devices used in the activated sludge process.

8.13 List three observations the operator should make as part of the daily operation of the activated sludge process.

8.14 A 2100-mL sample of activated sludge is allowed to settle for 60 min. At the end of the 60 min, the sludge has settled 1200 mL. What is the SSV_{60} of the sample?

8.15 An activated sludge sample has an MLSS concentration of 2240 mg/L. The SSV_{30} of the sample is 425 mL/L. What is the sludge volume index of the sample?

8.16 The operator wastes 0.067 MGD of activated sludge. The WAS concentration is 8180 mg/L. How many pounds of activated sludge solids have been removed from the process?

8.17 Which activated sludge process aerates the return sludge before mixing it with the influent flow?

8.18 A microscopic examination of the activated sludge reveals a predominance of rotifers. What process adjustment does this indicate is required?

8.19 Given the following data, calculate the desired pounds of mixed liquor suspended solids (MLSS) in the aeration tank:

Primary effluent suspended solids = 125 mg/L

Influent flow = 2.2 MGD

Desired sludge age = 5.0 days

Aeration tank = 100 ft × 40 ft × 12 ft

Influent BOD = 230 mg/L

Effluent suspended solids = 14 mg/L

8.20 List three observations that would indicate that the activated sludge was becoming old.

8.21 What are the major differences between the conditions known as bulking, rising, and ashing sludge?

8.22 Why is color a less reliable process indicator?

8.23 List the conditions you would expect to observe when the activated sludge system is operating normally?

8.24 Why is it important to select the same sample time and location each day?

8.25 What can cause the sludge blanket to increase?

8.26 Describe a device used to measure sludge blanket depth.

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CHAPTER 9

DISINFECTION

9.1 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 instead 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 water supply for a downstream water supply. In the treatment of water for human consumption, treated water is typically chlorinated (although ozonation is also currently being applied in many cases). Chlorination is the preferred disinfection in potable water supplies because of the unique ability of chlorine to provide a residual. This chlorine residual is important because when treated water leaves the waterworks facility and enters the distribution system the possibility of contamination is increased. The residual works to continuously disinfect water right up to the consumer's tap. This chapter discusses basic chlorination and dechlorination. In addition, it describes ultraviolet (UV) irradiation, ozonation, and bromine chlorine disinfection.

9.2 CHLORINE DISINFECTION

Chlorination for disinfection follows all of the other steps in conventional wastewater treatment. The purpose of chlorination is to reduce the population of organisms in the wastewater to levels that are 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.

9.2.1 Chlorination Terminology

Several terms are pertinent to a discussion of disinfection by chlorination. Because it is important for the operator to be familiar with these terms, we present them here:

Chlorine—A strong oxidizing agent that has strong disinfecting capability. It is a yellow–green gas that is extremely corrosive and toxic to humans in extremely low concentrations in 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. Not all of the organisms are destroyed during the process. This differentiates disinfection from *sterilization*, which is the destruction of all organisms.

Dose—The amount of chemical being added in milligrams per 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.

9.2.2 Wastewater Chlorination Facts

9.2.2.1 Chlorine Facts

- Elemental chlorine (Cl_2, gaseous) 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 the discharge of the final effluent to the receiving waters.
- 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, as a 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 (e.g., sulfide, nitrite, iron, thiosulfate) present in the 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.

9.2.2.2 Hypochlorite Facts

Hypochlorite is relatively safe to work with, although some minor hazards are associated with its use (skin irritation, 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.

9.2.3 Wastewater Chlorination Process Description

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.

A very reactive substance, chlorine is added to wastewater to satisfy all chemical demands—that is, to react with certain chemicals (such as sulfide, sulfite, or 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. This produces a combined residual, which can be measured using chlorine residual 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 normally 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. Based on water quality standards, total residual limitations on chlorine are:

- Freshwater—Less than 11 ppb total chlorine residual
- Estuaries—Less that 7.5 ppb for halogen-produced oxidants
- Endangered species—Use of chlorine is prohibited

9.2.4 Chlorination Equipment

9.2.4.1 Hypochlorite Systems

Depending on the form of hypochlorite selected for use, special equipment to control the addition of hypochlorite to the wastewater is required. Liquid forms require the use of metering pumps, which can 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. The hypochlorite solution or dry feed systems dispenses the hypochlorite, which is then mixed with the flow. The treated wastewater then enters the contact tank to provide the required contact time.

9.2.4.2 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 to the gas form. Small facilities will normally draw the gas form of chlorine from the cylinder. As the gas is withdrawn, the 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.

9.2.5 Chlorination 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 include make-up solution (solution feed systems) or adding powder or pellets to the dry chemical feeder or tablets to the tablet chlorinator.

Chlorine operations include adjustment of chlorinator feed rates, inspection of mechanical equipment, testing for leaks using ammonia swabs (white smoke indicates the presence of leaks), changing containers (which 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 chlorine residual and may also require collection and analysis of samples to determine the fecal coliform concentration in the effluent.

9.2.6 Troubleshooting Operation Problems

On occasion, operational problems with the disinfection process develop. The wastewater operator must be able to recognize these problems and correct them. For proper operation, the chlorination process requires routine observation, meter readings, process control and testing, and various process control calculations. Comparison of daily results with expected normal ranges is the key to identifying problems during the troubleshooting process and to taking the appropriate corrective action (if required). In this section, we review normal operational and performance factors, point out various problems that can occur with the disinfection process, identify causes, and suggest corrective actions that should be taken.

9.2.6.1 Operator Considerations

The operator should consider the following items:

- *Flow distribution*—The operator monitors the flow to ensure that it is evenly distributed between all units in service and that the flow through each individual unit is uniform, with no indication of short-circuiting.
- *Contact tank*—The contact tanks or basins must be checked to ensure that no excessive accumulation of scum is present on the surface, that no solids are accumulating on the bottom, and that mixing appears to be adequate.
- *Chlorinator*—The operator should check to ensure that no evidence of leakage is apparent, the operating pressure and vacuum are within specified levels, the current chlorine feed settling is within expected levels, the inline cylinders have sufficient chlorine to ensure continuous feed, and the exhaust system is operating as designed.

9.2.6.2 Factors Affecting Performance

Operators must be familiar with those factors that affect chlorination performance. Any item that interferes with the chlorine reactions or increases the demand for chlorine can affect performance and, in turn, may produce nondisinfectant products. Factors affecting chlorination performance include:

- *Effluent quality*—Poor-quality effluents have higher chlorine demands, high concentrations of solids prevent chlorine–organism contact, and incomplete nitrification can cause extremely high chlorine demand.
- *Mixing*—To be effective, chlorine must be in contact with the organisms. Poor mixing results in poor chlorine distribution. Installation of baffles and using a high length-to-width ratio will improve mixing and contact.
- *Contact time*—The chlorine disinfection process is time dependent. As the contact time decreases, process effectiveness decreases. A minimum of 30 minutes of contact must be available at design flow.
- *Residual levels*—The chlorine disinfection process is dependent on the total chlorine residual. The concentration of residual must be sufficient to ensure that the desired reactions occur. At the design contact time, the required minimum total chlorine residual concentration is 1.0 mg/L.

9.2.6.3 Process Control Sampling and Testing

The process performance evaluation is based on the bacterial content (fecal coliform) of the final effluent. To ensure proper operation of the chlorination process, the operator must perform process control testing for the chlorination process. Process control testing consists of performing a total chlorine residual test on chlorine contact effluent. The frequency of the testing is specified in the plant permit. The normal expected range of results is also specified in the plant permit.

9.2.6.4 Troubleshooting

Following are common operational problems, symptoms, casual factors, and corrective actions associated with chlorination system use in wastewater treatment:

- **Symptom 1.** Coliform count fails to meet the required standards for disinfection.

  Cause: Inadequate chlorination equipment capacity

    Corrective action: Replace equipment as necessary to provide treatment based on maximum flow through the pipe.

  Cause: Inadequate chlorine residual control

    Corrective action: Use chlorine residual analyzer to monitor and control chlorine dosage automatically.

  Cause: Short-circuiting in chlorine contact chamber

    Corrective action: Install baffling in the chlorine contact chamber; install mixing device in chlorine contact chamber.

  Cause: Solids buildup in contact chamber

    Corrective action: Clean contact chamber.

Cause: Chlorine residual is too low

Corrective action: Increase contact time and/or increase chlorine feed rate.

- **Symptom 2.** Chlorinator has low chlorine gas pressure.

Cause: Insufficient number of cylinders connected to the system

Corrective action: Connect enough cylinders to the system so the feed rate does not exceed recommended withdrawal rate for cylinders.

Cause: Stoppage or restriction of flow between cylinders and chlorinator

Corrective action: Disassemble the chlorine header system at the point where cooling begins, locate the stoppage, and clean with solvent.

- **Symptom 3.** Chlorinator has no chlorine gas pressure.

Cause: Empty chlorine cylinders or cylinders not connected to the system

Corrective action: Replace the empty cylinders or connect the cylinders.

Cause: Plugged or damaged pressure-reducing valve

Corrective action: Repair reducing valve after shutting cylinder valves and decreasing gas in the header system.

- **Symptom 4.** Chlorinator will not feed any chlorine.

Cause: Dirty pressure-reducing valve in the chlorinator

Corrective action: Disassemble the chlorinator and clean the valve stem and seat; precede the valve with a filter/sediment trap.

Cause: Chlorine cylinder hotter than the chlorine control apparatus (chlorinator)

Corrective action: Reduce the temperature in the cylinder area; do not connect a new cylinder that has been sitting in the sun.

- **Symptom 5.** Chlorine gas is escaping from the pressure-reducing valve.

Cause: Ruptured pressure-reducing valve main diaphragm

Corrective action: Disassemble the valve and diaphragm; inspect the chlorine supply system for moisture intrusion.

- **Symptom 6.** Chlorine feed rate cannot be maintained without icing of the chlorine system.

Cause: Insufficient evaporator capacity

Corrective action: Reduce feed rate to 75% of evaporator capacity; if this eliminates the problem, then the main diaphragm of the pressure-reducing valve is ruptured.

Cause: The external pressure-reducing valve cartridge is clogged

Corrective action: Flush and clean the cartridge.

- **Symptom 7.** The chlorinator system is unable to maintain a sufficient water bath temperature to keep the external pressure-reducing valve open.

  Cause: Heating element malfunction

    Corrective action: Remove and replace the heating element.

- **Symptom 8.** The maximum feed rate cannot be obtained from the chlorinator.

  Cause: Inadequate chlorine gas pressure

    Corrective action: Increase pressure; replace empty or low cylinders.

  Cause: Water pump injector clogged with deposits

    Corrective action: Clean injector parts using muriatic acid; rinse parts with freshwater and place back in service.

  Cause: Leak in vacuum-relief valve

    Corrective action: Disassemble the vacuum-relief valve and replace all springs.

  Cause: Vacuum leak in joints, gaskets, tubing, etc. in chlorinator system

    Corrective action: Repair all vacuum leaks by tightening joints, replacing gaskets, or replacing tubing or compression nuts.

- **Symptom 9.** An adequate chlorine feed rate cannot be maintained.

  Cause: Malfunction or deterioration of chlorine water supply pump

    Corrective action: Overhaul the pump (if a turbine pump is used, try closing the valve to maintain the proper discharge pressure).

- **Symptom 10.** The chlorine residual is too high in plant effluent to meet requirements.

  Cause: Chlorine residual too high

    Corrective action: Install dechlorination facilities.

- **Symptom 11.** The chlorine residual produced in the effluent varies widely.

  Cause: Inadequate chlorine flow proportioning meter capacity to meet plant flow rates

    Corrective action: Replace with higher capacity chlorinator meter.

  Cause: Malfunctioning controls

    Corrective action: Call manufacturer’s technical representative.

  Cause: Solids settled in chlorine contact chamber

    Corrective action: Clean the chlorine contact tank.

Cause: Flow proportioning control device not zeroed or spanned correctly

Corrective action: Re-zero and span the device in accordance with the manufacturer's instructions.

- **Symptom 12.** Chlorine residual cannot be obtained.

Cause: High chemical demand

Corrective action: Locate and correct the source of the high demand.

Cause: Test interference

Corrective action: Add sulfuric acid to samples to reduce interference.

- **Symptom 13.** Chlorine residual analyzer, recorder, and controller do not control chlorine residual properly.

Cause: Fouled electrodes

Corrective action: Clean electrodes.

Cause: Loop time too long

Corrective action: Reduce the control loop time by: (1) moving the injector closer to the point of application, (2) increasing the velocity in the sample line to the analyzer, (3) moving the cell closer to the sample point, and (4) moving the sample point closer to the point of application.

Cause: Insufficient potassium iodide being added for the amount of residual being measured

Corrective action: Adjust the potassium iodide feed to correspond with the chlorine residual being measured.

Cause: Malfunctioning buffer additive system

Corrective action: Repair buffer additive system.

Cause: Malfunctioning analyzer cell

Corrective action: Call authorized service personnel to repair the electrical components.

Cause: Poor mixing of chlorine at the point of application

Corrective action: Install a mixing device to cause turbulence at the point of application.

Cause: Improperly set rotameter tube range

Corrective action: Set a proper feed rate range.

9.2.6.5 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.

9.2.7 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 chlorine residual 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 forced many treatment facilities to add an additional process to remove the chlorine prior to discharge. 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 with potentially fatal hazards associated with it. 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.

9.2.7.1 Safe Work Practices for Chlorine

Because of the inherent dangers involved with handling chlorine, each facility using chlorine (for any reason) should be sure to have a written safe work practice in place and followed by plant operators. A sample safe work practice for handling chlorine is 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 1-ton chlorine cylinders in a cool dry place away from direct sunlight or heating units. Railroad tank cars compensate for direct sunlight.
8. Store 1-ton chlorine 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 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 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 by gently expelling 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 that are 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 people 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: The Occupational Safety and Health Administration (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; follow the two-person rule.
28. Use supplied-air breathing equipment when entering a chlorine atmosphere. *Never* use canister-type gas masks when entering a chlorine atmosphere.
29. Be sure that the supplied-air breathing apparatus has been properly maintained in accordance with the plant's self-contained breathing apparatus 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 from the shipper (bill of lading has been signed by plant personnel); 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 a 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 the 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.

9.2.8 Chlorination Process Calculations

Several calculations are useful in operating a chlorination system. Many of these calculations are discussed and illustrated in this section.

9.2.8.1 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:

$$\text{Chlorine Demand} = \text{Chlorine Dose (mg/L)} - \text{Chlorine Residual (mg/L)} \tag{9.1}$$

■ ***Example 9.1***

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:

$$\text{Chlorine Demand} = 7.1\text{ mg/L} - 1.0\text{ mg/L} = 6.1\text{ mg/L}$$

9.2.8.2 Chlorine Feed Rate

The chlorine feed rate is the amount of chlorine added to the wastewater in pounds per day:

$$\text{Chlorine Feed Rate} = \text{Dose (mg/L)} \times \text{Flow (MGD)} \times 8.34\text{ lb/MG/mg/L} \tag{9.2}$$

■ ***Example 9.2***

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:

$$\text{Feed} = 5.55\text{ mg/L} \times 22.89\text{ MGD} \times 8.34\text{ lb/MG/mg/L} = 1060\text{ lb/day}$$

9.2.8.3 Chlorine Dose

Chlorine dose is the concentration of chlorine being added to the wastewater. It is expressed in milligrams per liter:

$$\text{Dose (mg/L)} = \frac{\text{Chlorine Feed Rate (lb/day)}}{\text{Flow (MGD)} \times 8.34\text{ lb/MG/mg/L}} \tag{9.3}$$

■ ***Example 9.3***

Problem: Each day, 320 lb of chlorine are added to a wastewater flow of 5.60 MGD. What is the chlorine does in milligrams per liter?

Solution:

$$\text{Dose} = \frac{320\text{ lb/day}}{5.60\text{ MGD} \times 8.34\text{ lb/MG/mg/L}} = 6.9\text{ mg/L}$$

9.2.8.4 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:

$$\text{Available Chlorine} = \text{Amount of Hypochlorite} \times \%\ \text{Available Chlorine} \tag{9.4}$$

■ ***Example 9.4***

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:

$$\text{Quantity of Chlorine} = 30\ \text{lb} \times 0.625 = 18.75\ \text{lb}$$

9.2.8.5 Required Quantity of Dry Hypochlorite

This calculation is used to determine the amount of hypochlorite required to achieve the desired dose of chlorine:

$$\text{Hypochlorite (lb/day)} = \frac{\left[\begin{array}{l}\text{Required Chlorine Dose (mg/L)}\\ \times\ \text{Flow (MGD)} \times 8.34\ \text{lb/MG/mg/L}\end{array}\right]}{\%\ \text{Available Chlorine}} \tag{9.5}$$

■ ***Example 9.5***

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:

$$\text{Hypochlorite} = \frac{8.5\ \text{mg/L} \times 3.25\ \text{MGD} \times 8.34\ \text{lb/MG/mg/L}}{0.70} = 329\ \text{lb/day}$$

9.2.8.6 Required Quantity of Liquid Hypochlorite

$$\text{Hypochlorite (gpd)} = \frac{\left[\begin{array}{l}\text{Required Chlorine Dose (mg/L)}\\ \times\ \text{Flow (MGD)} \times 8.34\ \text{lb/MG/mg/L}\end{array}\right]}{\left[\begin{array}{l}\%\ \text{Available Chlorine} \times 8.34\ \text{lb/gal}\\ \times\ \text{Hypochlorite Solution Specific Gravity}\end{array}\right]} \tag{9.6}$$

■ ***Example 9.6***

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:

$$\text{Hypochlorite} = \frac{8.8\text{ mg/L} \times 3.28\text{ MGD} \times 8.34\text{ lb/MG/mg/L}}{0.71 \times 8.34\text{ lb/gal} \times 1.25} = 32.5\text{ gpd}$$

9.2.8.7 Ordering Chlorine

Because disinfection must be continuous, the supply of chlorine must never be allowed to run out. The process consists of three steps, and the following calculation provides a simple method for determining when additional supplies must be ordered:

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 the projected flow and dose:

$$\text{Projected Flow} = \text{Current Flow (MGD)} \times (1.0 + \%\text{ Change}) \tag{9.7a}$$

$$\text{Projected Dose} = \text{Current Dose (mg/L)} \times (1.0 + \%\text{ Change}) \tag{9.7b}$$

■ ***Example 9.7***

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:

$$\text{Projected Flow} = 4.5\text{ MGD} \times (1.0 + 0.075) = 4.84\text{ MGD}$$

To determine the amount of chlorine required for a given period:

$$\text{Chlorine Required} = \text{Feed Rate (lb/day)} \times \text{No. of Days Required}$$

■ ***Example 9.8***

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:

Chlorine Required = 90 lb/day × 124 days = 11,160 lb

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. A safety factor as a specific quantity can be expressed as follows:

$$\text{Total Required } Cl_2 = \text{Chlorine Required (lb)} + \text{Safety Factor}$$

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, round all decimal parts of a cylinder up to the next highest number of full cylinders.

9.3 ULTRAVIOLET IRRADIATION

Although ultraviolet (UV) disinfection was recognized as a method for achieving disinfection in the late 19th century, its application virtually disappeared with the evolution of chlorination technologies. In recent years, however, there has been resurgence in its use in the wastewater field, largely as a consequence of concern about the discharge of toxic chlorine residual. Even more recently, UV disinfection has gained more attention because of tough new regulations on chlorine use imposed by both OSHA and the U.S. Environmental Protection Agency. Because of this relatively recent increased regulatory pressure, many facilities are actively engaged in seeking alternatives to chlorine for other disinfection, and improvements in UV technology have made it an attractive candidate. Ultraviolet light has very good germicidal qualities and is effective in destroying microorganisms. It is used in hospitals, biological testing facilities, and many other similar locations. In wastewater treatment, the plant effluent is exposed to ultraviolet light of a specified wavelength and intensity for a specified contact period. The effectiveness of the process is dependent on:

- UV light intensity
- Contact time
- Wastewater quality (turbidity)

The Achilles' heel of UV for disinfecting wastewater is turbidity. If the wastewater quality is poor, the ultraviolet light will be unable to penetrate the solids, and the effectiveness of the process decreases dramatically. For this reason, many states limit the use of UV disinfection to facilities that can reasonably be expected to produce an effluent containing 30 mg/L or less of BOD_5 and total suspended solids.

In the operation of UV systems, UV lamps must be readily available when replacements are required. The best lamps are those with a stated operating life of at least 7500 hours and those that do not produce significant amounts of ozone or hydrogen peroxide. The lamps must also meet technical specifications for intensity, output, and arc length. If the UV light tubes are submerged in the wastestream, they must be contained within quartz tubes, which not only protect the lights but also make cleaning and replacement easier.

Contact tanks must be used with UV disinfection. They are designed with the banks of UV lights in a horizontal position, either parallel or perpendicular to the flow, or with banks of lights placed in a vertical position perpendicular to the flow.

Note: The contact tank must provide, at a minimum, a 10-second exposure time.

Key Point: Ultraviolet light is extremely hazardous to the eyes. Never look directly into the ultraviolet light, and never enter an area without proper eye protection where UV lights are in operation.

We stated earlier that turbidity has been a problem for UV wastewater treatment; however, if turbidity is its Achilles' heel, then the need for increased maintenance (as compared to other disinfection alternatives) is the toe of the same foot. UV maintenance requires that the tubes be cleaned on a regular basis or as needed. In addition, periodic acid washing is also required to remove chemical buildup. Routine monitoring of UV disinfection systems is required. Checking for bulb burnout, buildup of solids on quartz tubes, and UV light intensity is required.

9.4 OZONATION

Ozone is a strong oxidizing gas that reacts with most organic and many inorganic molecules. It is produced when oxygen molecules separate, collide with other oxygen atoms, and form a molecule consisting of three oxygen atoms. For high-quality effluents, ozone is a very effective disinfectant. Current regulations for domestic treatment systems limit the use of ozonation to filtered effluents unless the effectiveness of the system can be demonstrated prior to installation.

Note: Effluent quality is the key performance factor for ozonation.

Key Point: Ozone is an extremely toxic substance. Concentrations in air should not exceed 0.1 ppm. It also has the potential to create an explosive atmosphere. Sufficient ventilation and purging capabilities should be provided.

For ozonation of wastewater, the facility must have the capability to generate pure oxygen along with an ozone generator. A contact tank with ≥10-minute contact time at design average daily flow is required. Off-gas monitoring for process control is also required. In addition, safety equipment capable of monitoring ozone in the atmosphere and a ventilation system to prevent ozone levels exceeding 0.1 ppm are necessary. The actual operation of the ozonation process consists of monitoring and adjusting the ozone generator and monitoring the control system to maintain the required ozone concentration in the off-gas. The process must also be evaluated periodically using biological testing to assess its effectiveness.

Note: Ozone has certain advantages over chlorine for the disinfection of wastewater: (1) ozone increases dissolved oxygen in the effluent, (2) ozone has a briefer contact time, (3) ozone has no undesirable effects on marine organisms, and (4) ozone decreases turbidity and odor.

9.5 BROMINE CHLORIDE

Bromine chloride is a mixture of bromine and chlorine. It forms hydrocarbons and hydrochloric acid when mixed with water. Bromine chloride is an excellent disinfectant that reacts quickly and normally does not produce any long-term residuals.

Note: Bromine chloride is an extremely corrosive compound in the presence of low concentrations of moisture.

The reactions occurring when bromine chloride is added to the wastewater are similar to those occurring when chlorine is added. The major difference is the production of bromamine compounds rather than chloramines. The bromamine compounds are excellent disinfectants but are less stable and dissipate quickly. In most cases, the bromamines decay into other, less toxic compounds rapidly and are undetectable in the plant effluent. The factors that affect performance are similar to those affecting the performance of the chlorine disinfection process. Effluent quality, contact time, etc. have a direct impact on the performance of the process.

9.6 NO DISINFECTION

In a very limited number of cases, treated wastewater discharges without disinfection are permitted. These are approved on a case-by-case basis. Each request must be evaluated based on the point of discharge, the quality of the discharge, the potential for human contact, and many other factors.

9.7 CHAPTER REVIEW QUESTIONS

9.1 Name one factor that affects the performance of the ultraviolet irradiation process.

9.2 Explain the difference between disinfection and sterilization.

9.3 To be effective enough, chlorine must be added to satisfy the ________ and produce a ________ mg/L ________ for at least ________ minutes at design flow rates.

9.4 Elemental chlorine is ________ in color and is ________ times heavier than air.

9.5 Why must you take safety precautions when working with chlorine?

9.6 What problems are created when chlorine is used for disinfection?

9.7 Describe the ultraviolet irradiation process for disinfection.

9.8 Describe the ozonation disinfection process.

9.9 What are the safety hazards associated with the ultraviolet irradiation and ozonation processes?

9.10 What is the major advantage of bromine chloride when compared with chlorine for disinfection?

9.11 You are currently adding 450 lb of chlorine per day to a wastewater flow of 6.55 MGD. What is the chlorine dose in mg/L?

9.12 The chlorine dose is 8.22 mg/L. If the residual is 1.10 mg/L, the chlorine demand is ______________.

9.13 Why is dechlorination required to be installed (in many facilities) following chlorination for disinfection?

9.14 The plant adds 350 lb per day of dry hypochlorite powder to the plant effluent. The hypochlorite powder is 40% available chlorine. What is the chlorine feed rate in pounds per day?

9.15 The plant uses liquid hypochlorite, which is 69% available chlorine and has a specific gravity of 1.28. The required feed rate to comply with the plant's discharge permit total residual chorine limit is 280 lb/day. What is the required flow rate for the hypochlorite solution in gallons per day?

9.16 The plant currently uses 45.8 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)?

9.17 Why are chlorine additions to critical waters, such as natural trout steams, prohibited?

CHAPTER 10

SOLIDS HANDLING

10.1 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 because 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 be as much as 97% water content and because the cost of disposal will be related to the volume of sludge being processed, one of the primary purposes or goals of sludge treatment (along with stabilizing it so it is no longer objectionable or environmentally damaging) is to separate as much of the water from the solids as possible. 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 (heat treatment, vacuum filtration, and incineration, among others).

10.1.1 Sludge vs. Biosolids

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 of, 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.

10.1.2 A Note About Sludge Treatment

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 chapter, 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 a plant's overall performance capabilities. 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.

10.2 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 sludge from a typical domestic facility is quite objectionable and has a high percentage of water, two characteristics that make handling difficult.

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 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.

10.3 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 changes. The main component of all sludges is *water.* Prior to treatment, most sludge contain 95 to 99% water (see Table 10.1). 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 cost and 50% of the operation cost 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 sludge treatment processes, thus allowing the same flexibility in choosing the optimum sludge treatment and disposal method. The various forms of water and their approximate percentages for a typical activated sludge are shown in Table 10.2. The forms of water associated with sludges include:

TABLE 10.1 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.

- *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.

From a public health view, the second and probably more important component of sludge is the *solids matter.* Representing from 1 to 8% 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 that will burn or volatilize at 550°C after 15 minutes in a muffle furnace. The percent organic solids within a 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 aerobic or anaerobic environments. 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, we must first cover sludge pumping calculations. It is difficult (if not impossible) to treat the sludge unless it is pumped to the specific sludge treatment process.

TABLE 10.2 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.

10.4 SLUDGE PUMPING PROCESS CONTROL CALCULATIONS

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 know for licensure examinations) are covered in this section.

10.4.1 Estimated Daily Sludge Production

The calculation for estimating the required sludge pumping rate establishes an initial pumping rate and helps us to evaluate the adequacy of the current withdrawal rate:

$$\text{Estimated Pump Rate (gpm)} = \frac{\begin{bmatrix}\text{(Influent TSS Conc.} - \text{Effluent TSS Conc.)} \\ \times \text{Flow (MGD)} \times 8.34 \text{ lb/gal}\end{bmatrix}}{\text{\% Solids in Sludge} \times 8.34 \text{ lb/gal} \times 1440 \text{ min/day}} \tag{10.1}$$

■ ***Example 10.1***

Problem: The sludge withdrawn from the primary settling tank contains 1.4% solids. The unit influent contains 285 mg/L 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:

$$\begin{aligned}\text{Sludge Withdrawal Rate} &= \frac{(285 \text{ mg/L} - 140 \text{ mg/L}) \times 5.55 \text{ MGD} \times 8.34 \text{ lb/day}}{0.014 \times 8.34 \text{ lb/gal} \times 1440 \text{ min/day}} \\ &= 40 \text{ gpm}\end{aligned}$$

Note: Use the following information for Example 10.2 through Example 10.7:

Operating time = 15 min/cycle

Frequency = 24 cycles/day

Pump rate = 120 gpm

Solids = 3.70%

Volatile matter = 66%

10.4.2 Sludge Pumping Time

The sludge pumping time is the total time (in minutes) that the pump operates during a 24-hr period.

$$\text{Pump Operating Time} = \text{Time/Cycle (min)} \times \text{Frequency (cycles/day)} \tag{10.2}$$

■ ***Example 10.2***

Problem: Using the data given above, what is the pump operating time?

Solution:

$$\text{Pump Operating Time} = 15\text{ min/hr} \times 24\text{ cycles/day} = 360\text{ min/day}$$

10.4.3 Gallons Sludge Pumped per Day

$$\text{Sludge (gpd)} = \text{Operating Time (min/day)} \times \text{Pump Rate (gpm)} \tag{10.3}$$

■ ***Example 10.3***

Problem: What is the sludge pumped in gallons per day?

Solution:

$$\text{Sludge} = 360\text{ min/day} \times 120\text{ gpm} = 43{,}200\text{ gpd}$$

10.4.4 Pounds Sludge Pumped per Day

$$\text{Sludge (lb/day)} = \text{Sludge Pumped (gal)} \times 8.34\text{ lb/gal} \tag{10.4}$$

■ ***Example 10.4***

Problem: What is the sludge pumped in pounds per day?

Solution:

$$\text{Sludge} = 43{,}200 \text{ gal/day} \times 8.34 \text{ lb/gal} = 360{,}300 \text{ lb/day}$$

10.4.5 Pounds Solids Pumped per Day

$$\text{Solids Pumped (lb/day)} = \text{Sludge Pumped (gpd)} \times \%\ \text{Solids} \tag{10.5}$$

■ ***Example 10.5***

Problem: What are the solids pumped in pounds per day?

Solution:

$$\text{Solids Pumped} = 360{,}300 \text{ lb/day} \times 0.0370 = 13{,}331 \text{ lb/day}$$

10.4.6 Pounds Volatile Matter Pumped per Day

$$\text{Volatile Matter (lb/day)} = \text{Solids Pumped (lb/day)} \times \%\text{VM} \tag{10.6}$$

■ ***Example 10.6***

Problem: What is the volatile matter pumped 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:

$$\begin{aligned}\text{Solids (lb/day)} &= \text{Pump Time (min/cycle)} \times \text{Frequency (cycles/day)} \\ &\quad \times \text{Rate (gpm)} \times 8.34 \text{ lb/gal} \times \text{Solids}\end{aligned} \tag{10.7a}$$

$$\begin{aligned}\text{Volatile Matter (lb/day)} &= \text{Time (min/cycle)} \times \text{Frequency (cycles/day)} \\ &\quad \times \text{Rate (gpm)} \times 8.34 \text{ lb/gal} \times \%\ \text{Solids} \times \%\text{VM}\end{aligned} \tag{10.7b}$$

■ ***Example 10.7***

$$\begin{aligned}\text{Solids} &= 15 \text{ min/cycle} \times 24 \text{ cycles/day} \times 120 \text{ gpm} \times 8.34 \text{ lb/gal} \times 0.0370 \\ &= 13{,}331 \text{ lb/day} \\ \text{VM} &= 15 \text{ min/cycle} \times 24 \text{ cycles/day} \times 120 \text{ gpm} \times 8.34 \text{ lb/gal} \times 0.0370 \times .66 \\ &= 8798 \text{ lb/day}\end{aligned}$$

10.4.7 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:

$$\text{Sludge (lb/MG)} = \frac{\text{Total Sludge Production (lb)}}{\text{Total Wastewater Flow (MG)}} \tag{10.8}$$

■ ***Example 10.8***

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 plant's sludge production in pounds per million gallons?

Solution:

$$\text{Sludge} = \frac{85{,}000\text{ gal} \times 8.34\text{ lb/gal}}{1.2\text{ MGD} \times 30\text{ days}} = 19{,}692\text{ lb/MG}$$

10.4.8 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:

$$\begin{matrix}\text{Sludge Production} \\ \text{(wet tons/yr)}\end{matrix} = \frac{\left[\begin{matrix}\text{Sludge Production (lb/MG)} \\ \times\text{ Avg. Daily Flow (MGD)} \times 365\text{ days/yr}\end{matrix}\right]}{2000\text{ lb/ton}} \tag{10.9}$$

■ ***Example 10.9***

Problem: The 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 in wet tons per year?

Solution:

$$\begin{matrix}\text{Sludge} \\ \text{Production}\end{matrix} = \frac{16{,}500\text{ lb/MG} \times 1.5\text{ MGD} \times 365\text{ days/yr}}{2000\text{ lb/ton}} = 4517\text{ wet tons/yr}$$

10.5 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.

10.5.1 Sludge Thickening Processes

Sludge thickening processes include gravity thickeners, flotation thickeners, and solids concentrators.

10.5.1.1 Gravity Thickening

Gravity thickening is most effective on primary sludge. In operation, solids are withdrawn from primary treatment (and sometimes secondary treatment) and 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 that 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

10.5.1.2 Flotation Thickening

Flotation thickening is used most efficiently for waste sludges from suspended-growth biological treatment process, such as the activated sludge process. Recycled water from the flotation thickener is aerated under pressure, and the water absorbs more air than it would under normal pressure. The recycled flow together with chemical additives (if used) are mixed with the 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 called 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 in which the flotation process can occur, 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. Because the process normally requires chemicals to be added to improve separation, chemical mixing equipment, storage tanks, and metering equipment to dispense the chemicals at the desired dose are required. The performance of the dissolved air-thickening process depends on various factors:

- Bubble size
- Solids loading
- Sludge characteristics
- Chemical selection
- Chemical dose

10.5.1.3 Solids Concentrators

Solids concentrators (belt thickeners) usually consist of a mixing tank, chemical storage and metering equipment, and a moving porous belt. 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.

10.5.2 Operational Considerations

As with other unit treatment processes, proper operation of sludge thickeners depends on operator observation. The operator must make routine adjustment of sludge addition and withdrawal rates to achieve the desired blanket thickness. Sampling and analysis of influent sludge, supernatant, and thickened sludge are also required. Sludge addition and withdrawal should be continuous if possible to achieve optimum performance. Mechanical maintenance is also required. Expected performance ranges for gravity and dissolved air flotation thickeners are:

- Primary sludge, 8–19% solids
- Waste activated sludge, 2–4% solids
- Trickling-filter sludge, 7–9% solids
- Combined sludges, 4–9% solids

Typical operational problems with sludge thickeners include odors, rising sludge, thickened sludge below desired solids concentration, dissolved air concentration that is too low, effluent flow containing excessive solids, and torque alarm conditions.

10.5.3 Symptoms, Causes, and Corrective Actions for Solids Concentrations Problems

10.5.3.1 Gravity Thickener

- **Symptom 1.** Odors and rising sludge are present.

  Causal factors: Sludge withdrawal rate is too low; overflow rate is too low; thickener is septic.

  > *Corrective actions:* Increase sludge withdrawal rate; increase influent flow rate; add chlorine, permanganate, or peroxide to influent.

- **Symptom 2.** The thickened sludge is below the desired solids concentration.

  Causal factors: Overflow rate is too high; sludge withdrawal rate is too high; short-circuiting is occurring.

  > *Corrective actions:* Decrease influent sludge flow rate; decrease pump rate for sludge withdrawal; identify cause and correct.

- **Symptom 3.** The torque alarm is activated.

  Causal factors: There is a heavy sludge accumulation; collector mechanism is jammed.

  > *Corrective actions:* Agitate sludge blanket to decrease density; increase sludge withdrawal rate; attempt to locate and remove obstacle; dewater tank and remove obstacle.

10.5.3.2 Dissolved Air Flotation Thickener

- **Symptom 1.** The float solids concentration is too low.

  Causal factors: Skimmer speed is too high; unit is overloaded; polymer dose is insufficient; air-to-solids ratio is excessive; dissolved air levels are low.

Corrective actions: Adjust skimmer speed to allow concentration to occur; stop sludge flow through the unit and purge with recycles flow; determine proper chemical dose and adjust; reduce airflow to pressurization tank; identify malfunction and correct.

- **Symptom 2.** The dissolved air concentration is too low.

  Causal factor: Mechanical malfunction has occurred.

  Corrective action: Identify cause and correct.

- **Symptom 3.** Effluent (subnatant) flow contains excessive solids.

  Causal factors: Unit is overloaded; chemical dose is too low; skimmer is not operating; solids-to-air ratio is low; solids have built up in the thickener.

  Corrective actions: Turn off sludge flow; purge unit with recycle; determine proper chemical dose and flow; turn skimmer on; adjust skimmer speed; increase airflow to pressurization system; remove sludge from the tank.

10.5.4 Sludge Thickening Process Control Calculations

Sludge thickening calculations are based on the concept that the solids in the primary of 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 and result in higher percent solids.

10.5.4.1 Estimating Daily Sludge Production

Equation 10.10 provides a method for establishing an initial pumping rate or evaluating the adequacy of the current pump rate:

$$\begin{matrix}\text{Est. Pump}\\ \text{Rate (gpm)}\end{matrix} = \frac{\begin{bmatrix}\text{(Influent TSS Conc.} - \text{Effluent TSS Conc.)}\\ \times \text{Flow (MGD)} \times 8.34\text{ lb/gal}\end{bmatrix}}{\text{\% Solids in Sludge} \times 8.34\text{ lb/gal} \times 1440\text{ min/day}} \qquad (10.10)$$

■ ***Example 10.10***

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:

$$\text{Sludge Withdrawal Rate} = \frac{(280\text{ mg/L} - 141\text{ mg/L}) \times 5.55\text{ MGD} \times 8.34\text{ lb/gal}}{0.015 \times 8.34\text{ lb/gal} \times 1440\text{ min/day}}$$

$$= 36\text{ gpm}$$

10.5.4.2 Surface Loading Rate

Surface loading rate (surface settling rate) is hydraulic loading—the amount of sludge applied per square foot of gravity thickener:

$$\text{Surf. Loading (gpd/ft}^2\text{)} = \frac{\text{Sludge Applied to the Thickener (gpd)}}{\text{Thickener Area (ft}^2\text{)}} \qquad (10.11)$$

■ ***Example 10.11***

Problem: The 70-ft-diameter gravity thickener receives 32,000 gpd of sludge. What is the surface loading in gallons per day per square foot?

Solution:

$$\text{Surface Loading} = \frac{32{,}000 \text{ gpd}}{0.785 \times 70 \text{ ft} \times 70 \text{ ft}} = 8.32 \text{ gpd/ft}^2$$

10.5.4.3 Solids Loading Rate

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:

$$\begin{array}{c}\text{Solids Loading Rate}\\ \text{(lb/day/ft)}\end{array} = \frac{\left[\begin{array}{c}\text{\% Sludge Solids} \times \text{Sludge Flow (gpd)}\\ \times\ 8.34 \text{ lb/gal}\end{array}\right]}{\text{Thickener Area (ft}^2\text{)}} \qquad (10.12)$$

■ ***Example 10.12***

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:

$$\text{Solids Loading Rate} = \frac{0.016 \times 39{,}000 \text{ gpd} \times 8.34 \text{ lb/gal}}{0.785 \times 50 \text{ ft} \times 50 \text{ ft}} = 2.7 \text{ lb/day/ft}^2$$

10.5.4.4 Concentration Factor

The concentration factor (CF) represents the increase in concentration due to the thickener:

$$\text{Concentration Factor (CF)} = \frac{\text{Thickened Sludge Concentration(\%)}}{\text{Influent Sludge Concentration (\%)}} \qquad (10.13)$$

■ ***Example 10.13***

Problem: The influent sludge contains 3.5% solids. The thickened sludge solids concentration is 7.7%. What is the concentration factor?

Solution:

$$\text{Concentration Factor} = \frac{7.7\%}{3.5\%} = 2.2$$

10.5.4.5 Air-to-Solids Ratio

The air-to-solids ratio is the ratio between the pounds of air being applied to the pounds of solids entering the thickener:

$$\text{Air-to-Solids Ratio} = \frac{\text{Air Flow (ft}^3\text{/min)} \times 0.075\ \text{lb/ft}^3}{\text{Sludge Flow (gpm)} \times \%\ \text{Solids} \times 8.34\ \text{lb/gal}} \tag{10.14}$$

■ ***Example 10.14***

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:

$$\text{Air-to-Solids Ratio} = \frac{13\ \text{cfm} \times 0.075\ \text{lb/ft}}{50\ \text{gpm} \times 0.0085 \times 8.34\ \text{lb/gal}} = 0.28$$

10.5.4.6 Recycle Flow in Percent

The amount of recycle flow is expressed as a percent:

$$\text{Recycle Flow (\%)} = \frac{\text{Recycle Flow Rate (gpm)} \times 100}{\text{Sludge Flow (gpm)}} \tag{10.15}$$

■ ***Example 10.15***

Problem: The sludge flow to the thickener is 80 gpm. The recycle flow rate is 140 gpm. What is the percent recycle?

Solution:

$$\text{Recycle Flow} = \frac{140\ \text{gpm} \times 100}{80\ \text{gpm}} = 175\%$$

10.6 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

10.6.1 Aerobic Digestion

Equipment used for aerobic digestion includes 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. In operation, 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 of 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 the solids are withdrawn for disposal.

Process control testing should include alkalinity, pH, percent solids, and percent volatile solids for influent sludge, supernatant, digested sludge, and digester contents. Normal operating levels for an aerobic digester are listed in Table 10.3. 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).

TABLE 10.3 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%

10.6.1.1 Aerobic Digester Process Control Calculations

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.

10.6.1.1.1 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:

$$\text{Volatile Solids Loading (lb/day/ft}^3\text{)} = \frac{\text{Volatile Solids Added (lb/day)}}{\text{Digester Volume (ft}^3\text{)}} \tag{10.16}$$

■ *Example 10.16*

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:

$$\text{Volatile Solids Loading} = \frac{1350\text{ lb/day}}{.78 \times 25\text{ ft} \times 25\text{ ft} \times 24\text{ ft}} = 0.11\text{ lb/day/ft}^3$$

10.6.1.1.2 Digestion Time in Days

Digestion time is the theoretical time the sludge remains in the aerobic digester:

$$\text{Digestion Time (days)} = \frac{\text{Digester Volume (gal)}}{\text{Sludge Added (gpd)}} \tag{10.17}$$

■ *Example 10.17*

Problem: The 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:

$$\text{Digestion Time} = \frac{240{,}000\text{ gal}}{13{,}500\text{ gpd}} = 17.8\text{ days}$$

10.6.1.1.3 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. Because of the changes occurring during sludge digestion, the calculation used to determine percent volatile matter reduction is more complicated:

$$\%\text{VM Reduction} = \frac{\left(\%\text{VM}_{\text{in}} - \%\text{VM}_{\text{out}}\right)\times 100}{\%\text{VM}_{\text{in}} - \left(\%\text{VM}_{\text{in}} \times \%\text{VM}_{\text{out}}\right)} \qquad (10.18)$$

■ *Example 10.18*

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:

$$\%\text{VM Reduction} = \frac{(0.71 - 0.53)\times 100}{0.71 - (0.71 \times 0.53)} = 53.9\text{, or } 54\%$$

Now we can determine the percent moisture reduction:

$$\begin{array}{c}\%\text{ Moisture}\\ \text{Reduction}\end{array} = \frac{\left(\%\text{ Moisture}_{\text{in}} - \%\text{ Moisture}_{\text{out}}\right)\times 100}{\%\text{ Moisture}_{\text{in}} - \left(\%\text{ Moisture}_{\text{in}} \times \%\text{ Moisture}_{\text{out}}\right)} \qquad (10.19)$$

■ *Example 10.19*

Problem: Using the digester data provided below, determine the percent moisture reduction for the digester.

Note: % Moisture = 100% – percent solids.

Raw sludge
  Percent solids = 6%
  Percent moisture = 100% – 6% = 94%
Digested sludge
  Percent solids = 15%
  Percent moisture = 100% – 15% = 85%

Solution:

$$\%\text{ Moisture Reduction} = \frac{(0.94 - 0.85)\times 100}{0.94 - (0.94 \times 0.85)} = 64\%$$

10.6.1.1.4 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 must then be converted to the actual quantity of chemical (usually lime) required by the digester.

$$\begin{matrix}\text{Chemical} \\ \text{Required (lb)}\end{matrix} = \frac{\text{Chemical Used (mg)} \times \text{Digester Vol. (MG)} \times 3.785\ \text{L/gal}}{\text{Sample Vol. (L)} \times 454\ \text{g/lb} \times 1000\ \text{mg/g}} \tag{10.20}$$

■ ***Example 10.20***

Problem: The lab reports that 225 mg of lime were required 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:

$$\text{Chemical Required} = \frac{225\ \text{mg} \times 240{,}000\ \text{gal} \times 3.785\ \text{L/gal}}{1\ \text{L} \times 454\ \text{g/lb} \times 1000\ \text{mg/g}} = 450\ \text{lb}$$

10.6.2 Anaerobic Digestion

Anaerobic digestion is the traditional method of sludge stabilization that 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 is converted into new bacterial cells. Instead, most of the organics are converted into carbon dioxide and methane gas. In operation, 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.

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,

TABLE 10.4 ANAEROBIC DIGESTER SLUDGE PARAMETERS

Raw Sludge Solids	Impact
<4% solids	Loss of alkalinity Decreased sludge retention time Increased heating requirements Decreased volatile acids-to-alkalinity ratio
4–8% solids	Normal operation
>8% solids	Poor mixing Organic overloading Decreased volatile acids-to-alkalinity ratio

and safety equipment (e.g., vacuum relief, pressure relief, flame traps, explosion proof electrical equipment). Various performance factors affect the operation of the anaerobic digester; for example, the percent volatile matter 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.

Key Point: In an anaerobic digester, the entrance of air should be prevented because of the potential for an explosive mixture resulting from air mixing with gas produced in the digester.

Note: The primary purpose of a secondary digester is to allow for solids separation.

Along with being able to recognize normal and 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 10.4.

10.6.2.1 Sludge Additions

Sludge must be pumped (in small amounts) several times each day to achieve the desired organic loading and optimum performance.

Note: Keep in mind that in fixed-cover operations additions must be balanced by withdrawals; if not, structural damage occurs.

10.6.2.2 Sludge Withdrawal

Digested sludge is withdrawn only when necessary—always leave at least 25% seed.

10.6.2.3 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.

10.6.2.4 pH Control

pH should be adjusted to maintain a range of 6.8 to 7.2 by adjusting the feed rate, sludge withdrawal, or alkalinity additions.

Note: The buffer capacity of an anaerobic digester is indicated by the volatile acids-to-alkalinity relationship. Decreases in alkalinity cause a corresponding increase in the ratio.

10.6.2.5 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.

10.6.2.6 Mixing

If the digester is equipped with mixers, mixing should be accomplished to ensure that organisms are exposed to food materials.

10.6.2.7 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 is necessary. It is important that these critical safety devices be checked and maintained for proper operation.

Note: Because of the inherent dangers 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 OSHA's confined space entry standard.

10.6.2.8 Process Control Monitoring, Testing, and Troubleshooting

During operation, anaerobic digesters must be monitored and tested to ensure proper operation. Testing should be accomplished to determine supernatant pH, volatile acids, alkalinity, BOD or COD, total solids, and temperature. Sludge (in and out) should be routinely tested for percent solids and percent volatile matter. Normal operating parameters are listed in Table 10.5. As with all other unit processes, the wastewater operator is expected to recognize problematic symptoms with anaerobic digesters and take the appropriate corrective actions. Symptoms, causes, and corrective actions are discussed below:

TABLE 10.5 NORMAL OPERATING RANGES FOR ANAEROBIC DIGESTERS

Parameter	Normal Range
Sludge retention time	
Heated	30–60 days
Unheated	180+ days
Volatile solids loading	0.04–0.1 lb VM/day/ft^3
Operating temperature	
Heated	90–95°F
Unheated	Varies with season
Mixing	
Heated, primary	Yes
Unheated, secondary	No
% Methane in gas	60–72%
% Carbon dioxide in gas	28–40%
pH	6.8–7.2
Volatile acids-to-alkalinity ratio	≤0.1
Volatile solids reduction	40–60%
Moisture reduction	40–60%

- **Symptom 1.** Digester gas production is reduced, pH drops below 6.8, or the volatile acids-to-alkalinity ratio increases.

  Causal factors: Digester souring; organic overloading; inadequate mixing; low alkalinity; hydraulic overloading; toxicity; loss of digestion capacity

  > *Corrective actions:* Add alkalinity (e.g., digested sludge, lime); improve temperature control; improve mixing; eliminate toxicity; clean the digester.

- **Symptom 2.** Gray foam is oozing from the digester.

  Causal factors: Rapid gasification; foam-producing organisms; foam-producing chemical

  > *Corrective actions:* Reduce mixing; reduce feed rate; mix slowly by hand; clean all contaminated equipment.

10.6.2.9 Anaerobic Digester Process Control Calculations

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.

10.6.2.9.1 Required Seed Volume in Gallons

$$\text{Seed Volume (gal)} = \text{Digester Volume} \times \text{\% Seed} \tag{10.21}$$

■ *Example 10.21*

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:

$$\text{Seed Volume} = 266{,}000 \text{ gal} \times 0.25 = 66{,}500 \text{ gal}$$

10.6.2.9.2 Volatile Acids-to-Alkalinity Ratio

The volatile acids-to-alkalinity ratio can be used to control operation of an anaerobic digester:

$$\text{Volatile Acids-to-Alkalinity Ratio} = \frac{\text{Volatile Acids Concentration}}{\text{Alkalinity Concentration}} \tag{10.22}$$

■ *Example 10.22*

Problem: The digester contains 240 mg/L volatile acids and 1860 mg/L alkalinity. What is the volatile acids-to-alkalinity ratio?

Solution:

$$\text{Ratio} = \frac{240 \text{ mg/L}}{1860 \text{ mg/L}} = 0.13$$

Note: Increases in the ratio normally indicate a potential change in the operation condition of the digester as shown in Table 10.6.

10.6.2.9.3 Sludge Retention Time

Sludge retention time (SRT) is the length of time the sludge remains in the digester:

$$\text{SRT (days)} = \frac{\text{Digester Volume (gal)}}{\text{Sludge Volume Added per Day (gpd)}} \tag{10.23}$$

■ *Example 10.23*

Problem: Sludge is added to a 525,000-gal digester at the rate of 12,250 gpd. What is the sludge retention time?

TABLE 10.6 VOLATILE ACIDS-TO-ALKALINITY RATIOS

Operating Condition	Volatile Acids-to-Alkalinity Ratio
Optimum	≤0.1
Acceptable range	0.1–0.3
Increase in % carbon dioxide in gas	≥0.5
Decrease in pH	≥0.8

Solution:

$$\text{SRT} = \frac{525{,}000 \text{ gal}}{12{,}250 \text{ gpd}} = 42.9 \text{ days}$$

10.6.2.9.4 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:

$$\begin{aligned}\text{Gas Production } (\text{ft}^3) = \text{VM}_{\text{in}}\ (\text{lb/day}) \times \%\text{VM Reduction}\\ \times \text{Production Rate } (\text{ft}^3/\text{lb})\end{aligned} \tag{10.24}$$

■ ***Example 10.24***

Problem: A 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 cubic feet of gas per pound of volatile matter destroyed. What is the estimated gas production in cubic feet per day?

Solution:

$$\text{Est. Gas Production} = 11{,}450 \text{ lb/day} \times 0.52 \times 11.2 \text{ ft}^3/\text{lb} = 66{,}685 \text{ ft}^3/\text{day}$$

10.6.2.9.5 Percent Volatile Matter Reduction

Because of the changes occurring during sludge digestion, the calculation used to determine percent volatile matter reduction is more complicated:

$$\%\text{VM Reduction} = \frac{\left(\%\text{VM}_{\text{in}} - \%\text{VM}_{\text{out}}\right) \times 100}{\%\text{VM}_{\text{in}} - \left(\%\text{VM}_{\text{in}} \times \%\text{VM}_{\text{out}}\right)} \tag{10.25}$$

■ ***Example 10.25***

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:

$$\%\text{VM Reduction} = \frac{(0.74 - 0.55) \times 100}{0.74 - (0.74 \times 0.55)} = 57\%$$

10.6.2.9.6 Percent Moisture Reduction in Digested Sludge

$$\begin{matrix}\%\text{ Moisture}\\ \text{Reduction}\end{matrix} = \frac{\left(\%\text{ Moisture}_{\text{in}} - \%\text{ Moisture}_{\text{out}}\right) \times 100}{\%\text{ Moisture}_{\text{in}} - \left(\%\text{ Moisture}_{\text{in}} \times \%\text{ Moisture}_{\text{out}}\right)} \tag{10.26}$$

■ ***Example 10.26***

Problem: Using the digester 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:

$$\%\text{ Moisture Reduction} = \frac{(0.94 - 0.86) \times 100}{0.94 - (0.94 \times 0.86)} = 61\%$$

10.6.3 Composting

The purpose of composting sludge is to stabilize the organic matter, reduce volume, and eliminate pathogenic organisms. In a composting operation, dewatered solids are usually mixed with a bulking agent (e.g., 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 60%.

10.6.4 Lime Stabilization

In the lime stabilization process, residuals are mixed with lime to achieve a pH of 12. This pH is maintained for at least 2 hr. The treated solids can then be dewatered for disposal or directly land applied.

10.6.5 Thermal Treatment

Thermal treatment (or wet air oxidation) subjects sludge to a high temperature and pressure in a closed reactor vessel. The high temperature and pressure rupture the cell walls of any microorganisms present in the solids, causing 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.

10.6.6 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.

10.6.7 Stabilization Operation and Performance

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.

10.7 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.

10.7.1 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), drying beds include 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 first 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. The downside, however, is 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.

10.7.1.1 Performance Factors

In sludge drying beds, various factors affect the length of time required to achieve the desired solids concentrations. The major factors and their impact on drying bed performance include the following:

- *Climate*—Drying beds in cold or moist climates will require significantly longer drying times to achieve an adequate level of percent solids concentrations in the dewatered sludge.
- *Depth of applied sludge*—The depth of the sludge drawn onto the bed has a major impact on the required drying time. Deeper sludge layers require longer drying times. Under ideal conditions, a well-digested sludge drawn to a depth of approximately 8 inches will require approximately 3 weeks to reach the desired 40 to 60% solids.
- *Type of sludge applied*—The quality and solids concentration of the drying media will affect the time requirements.
- *Bed cover*—Covered drying beds prevent rewetting of the sludge during storm events. In most cases, this reduces the average drying time required to reach the desired solids levels.

10.7.1.2 Operational Considerations

Although drying beds involve two natural processes—drainage and evaporation—that normally work well enough on their own, a certain amount of preparation and operator attention are still required to maintain optimum drying performance. In the preparation stage, for example, all debris is removed from the raked and leveled media surface, then all openings to the bed are sealed. After the bed is prepared properly, the sludge lines are opened, and sludge is allowed to flow slowly onto the media. The bed is filled to the desired operating level (8 to 12 inches). The sludge line is closed and flushed, and the bed drain is opened. Water begins to drain. The sludge remains on the media until the desired percent solids (40 to 60%) is achieved. Later, the sludge is removed. In most operations, manual removal is required to prevent damage to the underdrain system. The sludge is disposed of in an approved landfill or by land application as a soil conditioner. In the operation of a sludge drying bed, the operator observes the operations, looks for various indicators of operational problems, and makes process adjustments as required. Following are some examples:

- **Symptom 1.** Sludge takes a long time to dewater.

  Causal factors: Sludge applied too deep; sludge applied to a dirty bed; plugged or broken drain system; insufficient design capacity; inclement weather; poor drying conditions

Corrective actions: Use the procedure described below to determine the appropriate sludge depth:

- Clean bed and apply smaller depth of sludge (e.g., 6 to 8 in.).
- Measure the decrease in depth (drawdown) at the end of 3 days of drying.
- Use a sludge depth equal to twice the 3-day drawdown depth for future applications.

Allow the sludge to dry to the minimum allowable percent solids and remove. After the sludge has dried, remove the sludge and 0.5 to 1.0 in. of sand and add clean sand. Use an external water source (with backflow prevention) to slowly flush underdrains; repair or replace underdrains as required. Prevent damage to the underdrains by draining during freezing weather. Use polymer to increase bed performance, and cover or enclose the beds.

- **Symptom 2.** Influent sludge is very thin.

  Causal factor: Coning in the digester

  Corrective action: Reduce rate of sludge withdrawal.

- **Symptom 3.** Sludge feed lines plug frequently.

  Causal factor: Solids or grit accumulating in the lines

  Corrective actions: Open lines fully at the start of each withdrawal cycle; flush lines at the end of each withdrawal cycle.

- **Symptom 4.** Flies are breeding in the drying sludge.

  Causal factors: Inadequately digested sludge; natural insect reproduction

  Corrective actions: Break sludge crust, and apply a larvicide (borax); use insecticide (if approved) to eliminate adult insects; remove sludge as soon as possible.

- **Symptom 5.** Objectionable odors are detected when sludge is applied to the bed.

  Causal factor: Raw or partially digested sludge applied to the bed

  Corrective actions: Add lime to the sludge to control odors and potential insect and rodent problems; remove the sludge as quickly as possible; identify and correct the digester problem.

10.7.2 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.

10.7.2.1 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* 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 is discharged from the upper layer. The coils are then washed and reapplied to the drum. The coil filter is 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.

10.7.2.1.1 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. Installation of a blanket takes several days. With proper care, the cloth will last several hundred to several thousand hours. The life of the blanket depends on the cloth selected, conditioning chemical, backwash frequency, and cleaning (e.g., acid bath) frequency.

10.7.2.1.2 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.

10.7.2.1.3 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, conditional sludge must be filtered as quickly as possible after chemical addition to obtain these desirable results.

10.7.2.2 Operational Considerations

The rotating drum picks up chemically treated sludge. A vacuum is applied to the inside of the drum to draw the sludge onto the outside of the drum cover. This porous outside cover or filter medium allows the filtrate or liquid to pass through into the drum and the filter cake (dewatered sludge) to stay on the medium. In the cake release/discharge mode, slight air pressure is applied to the drum interior. Dewatered solids are lifted from the medium and scraped off by a scraper blade. Solids drop onto a conveyor for transport for further treatment or disposal. The filtrate water is returned to the plant for treatment. The operator observes drum speed, sludge pickup, filter cake thickness and appearance, chemical feed rates, sludge depth in vat, and overall equipment operation. Sampling and testing are routinely performed on influent sludge solids concentration, filtrate BOD and solids, and sludge cake solids concentration. Several vacuum filter operational problems and causal factors, along with recommended corrective actions are listed below:

- **Symptom 1.** Filtrate has a high level of solids.

  Causal factors: Improper coagulant dosage; filter media binding

  > *Corrective actions:* Adjust coagulant dosage; recalibrate the coagulant feeder; clean synthetic cloth with steam and detergent; clean steel coil with acid bath; clean cloth with water or replace cloth.

- **Symptom 2.** Filter cake is thin with poor dewatering.

  Causal factors: Filter media binding; improper chemical dosage; inadequate vacuum; drum speed too high or drum submergence too low

  > *Corrective actions:* Clean synthetic cloth with steam and detergent; clean steel cloth with acid bath; clean cloth with water or replace cloth; adjust coagulant dosage; recalibrate coagulant feeder; repair vacuum system; reduce drum speed; increase drum submergence.

- **Symptom 3.** Vacuum pump stops.

  Causal factors: No power to drive motor; lack of seal water; broken drive belt

  > *Corrective action:* Reset heater, breaker, etc.; restart seal water flow; replace drive belt.

- **Symptom 4.** Drum stops rotating.

  Causal factor: No power to drive motor

  > *Corrective action:* Reset heater, breaker, etc.; restart.

- **Symptom 5.** Receiver is vibrating.

  Causal factors: Clogged filtrate pump; loose bolts and gasket around inspection plate; worn ball check valve in filtrate pump; air leaks in suction line; dirty drum face; missing seal strips

  > *Corrective actions:* Clean pump; tighten bolts and gasket; replace ball check; seal leaks; clean face with pressure hose; replace missing seal strips.

- **Symptom 6.** Vat level is high.

  Causal factors: Improper chemical conditioning; feed rate too high; drum speed too slow; clogged or off filtrate pump; plugged drain line; vacuum pump stopped; missing seal strips

  > *Corrective actions:* Change coagulant dosage; reduce feed rate; increase drum speed; turn on or clean pump; clean drain line; replace seal strips.

- **Symptom 7.** Vat level is low.

  Causal factors: Feed rate too low; vat drain valve open

  > *Corrective actions:* Increase feed rate; close vat drain valve.

- **Symptom 8.** Vacuum pump is drawing high amperage.

  Causal factors: Clogged filtrate pump; improper chemical conditioning; high vat level; cooling water flow to vacuum pump too high

  > *Corrective actions:* Clear pump clog; adjust coagulant dosage; decrease cooling water flow rate.

- **Symptom 9.** Scale buildup occurring on vacuum pump seals.

  Causal factor: Hard, unstable water

  > *Corrective action:* Add sequestering agent.

10.7.2.3 Process Control Calculation: Vacuum Filter Yield

Probably the most frequent calculation vacuum filter operators have to make is determining filter yield. Example 10.27 illustrates how this calculation is made.

■ ***Example 10.27***

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:

$$\frac{3002.4\text{ lb/hr}}{369.3\text{ ft}^2} = 8.13\text{ lb/hr/ft}^2$$

10.7.3 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 plate-and-frame presses and belt 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 the plates together, and related handling systems for chemical makeup and feed, as well as supernatant and solids collection and transport. 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; 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.

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.

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.

10.7.3.1 Operational Considerations

Most plate and filter press operations are partially or fully automated. Operation consists of observation, maintenance, and sampling and testing. Operation of belt filter presses consists of preparation of conditioning chemicals, chemical feed rate adjustments, sludge feed rate adjustments, belt alignment, belt speed and belt tension adjustments, sampling and testing, and maintenance. Common operation problems, causal factors, and recommended corrective actions for the plate press and belt filter press are provided below:

- **Symptom 1.** Plate press plates fail to seal.

  Causal factors: Poor alignment; inadequate shimming

    Corrective actions: Realign parts; adjust shimming of stay bosses.

- **Symptom 2.** Plate press cake discharge is difficult.

  Causal factors: Inadequate precoat; improper conditioning

    Corrective actions: Increase precoat and feed at 25 to 40 psig; change conditioner type or dosage (use filter leaf test to determine).

- **Symptom 3.** Plate press filter cycle times are excessive.

  Causal factors: Improper conditioning; low feed solids

    Corrective actions: Change chemical dosage; improve thickening operation.

- **Symptom 4.** Plate press filter cake sticks to conveyors.

  Causal factor: Improper conditioning chemical or dosage

    Corrective action: Increase inorganic conditioner dose.

- **Symptom 5.** Plate press precoat pressures gradually increase.

  Causal factors: Improper sludge conditioning; improper precoat feed; plugged filter media; calcium buildup in media

Corrective actions: Change chemical dosage; decrease feed for a few cycles, then optimize; wash filter media; wash media with inhibited hydrochloric acid.

- **Symptom 6.** Plate press experiencing frequent media binding.

  Causal factors: Inadequate precoat; initial feed rate too high (no precoat)

  Corrective actions: Increase precoat; reduce feed rate and develop initial cake slowly.

- **Symptom 7.** Plate press is experiencing excessive moisture in the cake.

  Causal factors: Improper conditioning; filter cycle too short

  Corrective actions: Change chemical dosage; lengthen filter cycle.

- **Symptom 8.** Sludge is blowing out of plate press.

  Causal factor: Obstruction between plates

  Corrective action: Shut down feed pump, hit press closure drive, restart feed pump, and clean after cycle.

- **Symptom 9.** Plate press is experiencing leaks around lower faces of the plates.

  Causal factor: Wet cake soiling media on lower faces

  Corrective action: See "Plate press is experiencing excessive moisture in the cake" entry above (Symptom 7).

- **Symptom 10.** Filter cake discharge in belt press is difficult.

  Causal factors: Wrong conditioning chemical; improper chemical dosage; changing sludge characteristics; wrong application point

  Corrective actions: Change conditioning chemical; adjust chemical dosage; change chemical or sludge; adjust application point.

- **Symptom 11.** Sludge is leaking from belt edges in belt press.

  Causal factors: Excessive belt tension; belt speed too low; excessive sludge feed rate

  Corrective actions: Reduce belt tension; increase belt speed; reduce sludge feed rate.

- **Symptom 12.** Belt press filter cake has excessive moisture.

  Causal factors: Improper belt speed or drainage time; wrong conditioning chemical; improper chemical dosage; inadequate belt washing; wrong belt weave or material

Corrective actions: Adjust belt speed; change conditioning chemical; adjust chemical dosage; clear spray nozzles and adjust sprays; replace belt.

- **Symptom 13.** Belt wear along the edges in belt press is excessive.

  Causal factors: Roller misalignment; improper belt tension; tension or alignment system control malfunction

  Corrective actions: Correct roller alignment; correct tension; repair tracking and alignment system controls.

- **Symptom 14.** Belt shifts or seizes in belt press.

  Causal factors: Uneven sludge distribution; inadequate or uneven belt washing

  Corrective actions: Adjust feed for uniform sludge distribution; clean and adjust belt-washing sprays.

10.7.3.2 Filter Press Process Control Calculations

As part of the operating routine for filter presses, operators are called upon to make certain process control calculations. The process control calculation most commonly used in operating the belt filter press determines the hydraulic loading rate on the unit. The most commonly used process control calculation used in the operation of plate-and-filter presses determines the pounds of solids pressed per hour. Both of these calculations are demonstrated below.

10.7.3.2.1 Belt Filter Press Hydraulic Loading Rate

■ ***Example 10.28***

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:

$$\frac{0.30\text{ MG}}{1\text{ day}} \times \frac{1{,}000{,}000\text{ gal}}{1\text{ MG}} \times \frac{1\text{ day}}{1440\text{ min}} = \frac{208.3\text{ gal}}{1\text{ min}}; \quad 60\text{ in.} \times \frac{1\text{ ft}}{12\text{ in.}} = 5\text{ ft}$$

$$\frac{208.3\text{ gal}}{5\text{ ft}} = 41.7\text{ gpm/ft}$$

10.7.3.2.2 Pounds of Solids Pressed Per Hour in Plate-and-Frame Press

■ ***Example 10.29***

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:

$$850\text{ gal}\times\frac{3.7\%}{100\%}\times\frac{8.34\text{ lb}}{1\text{ gal}}=262.3\text{ lb}$$

$$\frac{262.3\text{ lb}}{120\text{ min}}\times\frac{60\text{ min}}{1\text{ hr}}=131.2\text{ lb/hr}$$

$$\frac{131.2\text{ lb/hr}}{140\text{ ft}^2}=0.94\text{ lb/hr/ft}^2$$

10.7.4 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.

10.7.4.1 Operational Considerations

The centrifuge spins at a very high speed. The centrifugal force it creates throws the solids out of the water. Chemically conditioned solids are pumped into the centrifuge. The spinning action throws the solids to the outer wall of the centrifuge. The centrate (water) flows inside the unit to a discharge point. The solids held against the outer wall are scraped to a discharge point by an internal scroll moving slightly faster or slower than the centrifuge speed of rotation. In the operation of the continuous-feed, solid-bowl, conveyor-type centrifuge (this is the most common type currently used), as well as in other commonly used centrifuges, solids/liquid separation occurs as a result of rotating the liquid at high speeds to cause separation by gravity.

The solid-bowl centrifuge is a rotating unit with a bowl and a conveyor. The unit has a conical section at one end that acts as a drainage device. The screw conveyor pushes the sludge solids to outlet ports and the cake to a discharge hopper. The sludge slurry enters the rotating bowl through a feed pipe leading into the hollow shaft of the rotating screw conveyor. The sludge is distributed through ports into a pool inside the rotating bowl. As the liquid sludge flows through the hollow shaft toward the overflow device, the fine solids settle to the wall of the rotating bowl. The screw conveyor pushes the solids to the conical section, where the solids are forced out of the water and the water drains back in the pool. Expected percent solids for centrifuge dewatered sludge are in the range of 10 to 15%. The expected performance is dependent on the type of sludge being dewatered, as shown in Table 10.7. Centrifuge operation is dependent on various performance factors:

- Bowl design (length/diameter ratio, flow pattern)
- Bowl speed
- Pool volume

TABLE 10.7 EXPECTED PERCENT SOLIDS FOR CENTRIFUGE DEWATERED SLUDGES

Type of Sludge	Percent Solids
Raw sludge	25–35%
Anaerobic digestion	15–30%
Activated sludge	8–10%
Heat treated	30–50%

- Conveyor design
- Relative conveyor speed
- Type and condition of sludge
- Type and amount of chemical conditioning
- Operating pool depth
- Relative conveyor speed (if adjustable)

Centrifuge operators often find that the operation of centrifuges can be simple, clean, and efficient. In most cases, chemical conditioning is required to achieve optimum concentrations. Operators soon discover that centrifuges are noise makers; units run at very high speed and produce high-level noise that can cause loss of hearing with prolonged exposure. When working in an area where a centrifuge is in operation, special care must be taken to provide hearing protection.

Actual operation of a centrifugation unit requires the operator to control and adjust chemical feed rates, to observe unit operation and performance, to control and monitor centrate returned to treatment system, and to perform required maintenance as outlined in the manufacturer's technical manual. The centrifuge operator must be trained to observe and recognize (as with other unit processes) operational problems that may occur with centrifuge operation. Several typical centrifuge problems, causal factors, and suggested corrective actions are provided below:

- **Symptom 1.** Centrate clarity is poor.

  Causal factors: Feed rate too high; wrong plate dam position; worn conveyor flights; speed too high; high feed sludge solids concentration; improper chemical conditioning

  > *Corrective actions:* Adjust sludge feed rate; increase pool depth; repair or replace conveyor; change pulley setting to obtain lower speed; dilute sludge feed; adjust chemical dosage.

- **Symptom 2.** Solids cake is not dry enough.

  Causal factors: Feed rate too high; wrong plate dam position; speed too low; excessive chemical conditioning; influent too warm

  > *Corrective actions:* Reduce sludge feed rate; decrease pool depth to increase dryness; change pulley setting to obtain higher speed; adjust chemical dosage; reduce influent temperature.

- **Symptom 3.** Torque control keeps tripping.

  Causal factors: Feed rate too high; feed solids concentration too high; foreign material (e.g., tramp iron) in machine; misaligned gear unit; gear unit mechanical problem

    Corrective actions: Reduce flows; dilute flows; remove conveyor and clear foreign materials; correct gear unit alignment; repair gear unit.

- **Symptom 4.** Vibration is excessive.

  Causal factors: Improper lubrication; improper adjustment of vibration isolators; discharge funnels contacting centrifuge; plugged portions of conveyor flights (causing an imbalance); improperly aligned gear box; damaged pillow box bearings; bowl out of balance; parts not tightly assembled; uneven wear on conveyor

    Corrective actions: Lubricate according to manufacturer's instructions; adjust isolators; reposition slip joints at funnels; flush centrifuge; align gearbox; replace bearings; return rotating parts to factory for rebalancing; tighten parts; resurface and rebalance.

- **Symptom 5.** Power consumption suddenly increases.

  Causal factors: Contact between bowl exterior and accumulated solids in case; effluent pipe plugged

    Corrective actions: Apply hard surfacing to areas with wear; clear solids discharge.

- **Symptom 6.** Power consumption gradually increases.

  Causal factor: Conveyor blade wear

    Corrective action: Replace blades.

- **Symptom 7.** Solids discharge is surging spasmodically.

  Causal factors: Pool depth too low; rough conveyor helix; feed pipe too near drainage deck; excessive vibration

    Corrective actions: Increase pool depth; refinish conveyor blade area; move feed pipe to effluent end (if applicable).

- **Symptom 8.** Centrifuge shuts down or will not start.

  Causal factors: Blown fuses; tripped overload relay; motor overheated/thermal protectors tripped; torque control tripped; vibration switch tripped

    Corrective actions: Replace fuses; flush centrifuge and reset relay; flush centrifuge; reset thermal protectors.

10.7.5 Sludge Incineration

Not surprisingly, 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 ignition temperature, a solids feed system, and ash handling equipment. It is important to note that the system must also include all required equipment (e.g., scrubbers) to achieve compliance with air pollution control requirements. 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 of disposal.

10.7.5.1 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.

10.7.5.2 Incineration Processes

10.7.5.2.1 Multiple Hearth Furnace

The multiple hearth furnace consists of a circular steel shell surrounding a number of hearths. Scrappers (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. 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 are used to 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.

10.7.5.2.2 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 super-heated 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 necessary 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: These systems retain a high amount of heat in the sand, so they can be operated as little as 4 hours per day with little or no reheating.

10.7.5.3 Operational Considerations

The operator of an incinerator monitors various performance factors to ensure optimal operation. These performance factors include feed sludge volatile solids content, feed sludge moisture content, operating temperature, sludge feed rate, fuel feed rate, and air feed rate.

Note: To ensure that the volatile material is ignited, the sludge must be heated between 1400 and 1700°F.

To be sure that operating parameters are in the correct range, the operator monitors and adjusts sludge feed rate, airflow, and auxiliary fuel feed rate. All maintenance conducted on an incinerator should be in accordance with the manufacturer's recommendations. The operator of a multiple hearth or fluidized bed incinerator must be able to recognize operational problems using various indicators or through observation. Such observations, causal factors, and recommended corrective actions are provided below:

- **Symptom 1.** Multiple hearth incinerator temperature is too high.

  Causal factors: Excessive fuel feed rate; greasy solids; thermocouple burned out

  > *Corrective actions:* Decrease fuel feed rate; reduce sludge feed rate; increase air feed rate; replace thermocouple.

- **Symptom 2.** Multiple hearth furnace temperature is too low.

  Causal factors: Increase in moisture content of the sludge; fuel system malfunction; excessive air feed rate; flame out

  > *Corrective actions:* Increase fuel feed rate until dewatering operation improves; establish proper fuel feed rate; decrease air feed rate; increase sludge feed rate; relight furnace.

- **Symptom 3.** Oxygen content of the multiple hearth furnace stack gas is too high.

  Causal factors: Sludge feed rate too low; sludge feed system blockage; air feed rate too high

  > *Corrective actions:* Increase sludge feed rate; clear any feed system blockages; decrease air feed rate.

- **Symptom 4.** Oxygen content of multiple hearth furnace stack gas is too low.

  Causal factors: Increase in volatile solids or grease content of the sludge; air feed rate too low

    Corrective actions: Increase air feed rate; decrease sludge feed rate.

- **Symptom 5.** Multiple hearth furnace refractories are deteriorated.

  Causal factor: Rapid startup/shutdown of furnace

    Corrective actions: Repair furnace refractories; follow specified startup/shutdown procedures.

- **Symptom 6.** Unusually high cooling effect is observed in the multiple hearth furnace.

  Causal factor: Air leak

    Corrective action: Locate and repair leak.

- **Symptom 7.** The multiple hearth furnace has a short hearth life.

  Causal factor: Uneven firing

    Corrective action: Fire hearths equally on both sides.

- **Symptom 8.** Center shaft shear pin in the multiple hearth furnace has failed.

  Causal factors: Rabble arm dragging on hearth; debris caught under the arm

    Corrective actions: Adjust rabble arm to eliminate rubbing; remove debris.

- **Symptom 9.** Scrubber temperature in the multiple hearth furnace is too high.

  Causal factor: Low water flow to scrubber

    Corrective action: Adjust water flow to proper level.

- **Symptom 10.** Stack gas temperature in the multiple hearth furnace is too low.

  Causal factors: Inadequate fuel feed supply; excessive sludge feed rate

    Corrective actions: Increase fuel feed rate; decrease sludge feed rate.

- **Symptom 11.** Stack gas temperature in the multiple hearth furnace is too high.

  Causal factors: Increased volatile solids content (heat value) in sludge; excessive fuel feed rate

    Corrective actions: Increase air feed rate; decrease sludge feed rate; decrease fuel feed rate.

- **Symptom 12.** Furnace burners are slagging up in the multiple hearth furnace.

  Causal factor: Burner design

    Corrective action: Replace burners with newer designs that reduce slagging.

- **Symptom 13.** Rabble arms are dropping in the multiple hearth furnace.

  Causal factors: Excessive hearth temperatures; loss of cooling air

    Corrective actions: Maintain temperatures within proper range; discontinue injection of scum into the hearth; repair cooling air system immediately.

- **Symptom 14.** Excessive air pollutants are found in the multiple hearth furnace stack gas.

  Causal factors: Incomplete combustion (insufficient air); air pollution control malfunction

    Corrective actions: Raise air-to-fuel ratio; repair or replace broken equipment.

- **Symptom 15.** Flashes or explosions are occurring in the multiple hearth furnace.

  Causal factor: Scum or grease accumulation

    Corrective action: Remove scum or grease before incineration.

- **Symptom 16.** Fluidized bed temperature is falling.

  Causal factors: Inadequate fuel supply; excessive sludge feed rate; excessive sludge moisture levels; excessive air flow

    Corrective actions: Increase fuel supply; repair fuel system malfunction; decrease sludge feed rate; correct sludge dewatering process problem; decrease airflow rate.

- **Symptom 17.** Oxygen level is low (<3%) in fluidized bed exhaust gas.

  Causal factors: Low airflow rate; fuel feed rate too high

    Corrective actions: Increase blower air feed rate; reduce fuel feed rate.

- **Symptom 18.** Oxygen level is high (>6%) in fluidized bed exhaust gas.

  Causal factor: Sludge feed rate too low

    Corrective actions: Increase sludge feed rate; adjust fuel feed rate to maintain steady bed temperature.

- **Symptom 19.** Fluidized bed control panel shows erratic bed depth.

  Causal factor: Bed pressure taps plugged with solids

Corrective actions: Tap a metal rod into pressure tap pipe when the unit is not in operation; apply compressed air to pressure tap while the unit is in operation (follow the manufacturer's safety guidelines).

- **Symptom 20.** Preheat burner in fluidized bed fails and alarm sounds.

  Causal factors: Pilot flame not receiving fuel or spark; defective pressure regulators; pilot flame igniting but flame scanner is malfunctioning

  Corrective actions: Correct fuel system problem; replace defective part; replace defective regulators; clear scanner sight glass; replace defective scanner.

- **Symptom 21.** Bed temperature in fluidized bed is too high.

  Causal factors: Bed gun fuel feed rate too high; grease or high organic content in sludge (high heat value)

  Corrective actions: Reduce bed gun fuel feed rate; increase airflow rate; decrease sludge fuel rate.

- **Symptom 22.** Bed temperature in fluidized bed reads off scale.

  Causal factor: Thermocouple burned out

  Corrective action: Replace thermocouple.

- **Symptom 23.** Scrubber inlet in the fluidized bed shows high temperature.

  Causal factors: No water flowing in scrubber; plugged spray nozzles; ash water not recirculating

  Corrective actions: Open valves to provide water; correct system malfunction to provide required pressure; clear nozzles and strainers; repair or replace recirculation pump; unclog scrubber discharge line.

- **Symptom 24.** Fluidization in fluidized bed is poor.

  Causal factor: Sand leakage through support plate during shut down

  Corrective actions: Clear wind box; clean wind box at least once per month.

10.8 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., toxins, pathogenic organisms) or dangerous to the environment (e.g., toxins, pesticides, heavy metals). Treated biosolids are land applied by either direct injection or application and plowing in (incorporation).

10.8.1 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, such as determination of percent solids, heavy metals, organic pesticides and herbicides, alkalinity, total organic carbon (TOC), organic nitrogen, and ammonia nitrogen.

10.8.2 Process Control Calculations

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.

10.8.2.1 Disposal Cost

The cost of disposal of biosolids can be determined by:

$$\text{Cost} = \text{Biosolids (wet tons/yr)} \times \%\ \text{Solids} \times \text{Cost per dry ton} \qquad (10.27)$$

■ ***Example 10.30***

Problem: The 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 per dry ton. What is the annual cost for sludge disposal?

Solution:

$$\text{Cost} = 1925\ \text{wet tons/yr} \times 0.18 \times \$28/\text{dry ton} = \$9702$$

10.8.2.2 Plant Available Nitrogen

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. We provide volatilization rates based on this example below:

$$\underset{\text{(lb/dry ton)}}{\text{PAN}} = \begin{bmatrix} \text{(Organic Nitrogen (mg/kg)} \times f_1) \\ + \text{(Ammonia Nitrogen (mg/kg)} \times V_1) \end{bmatrix} \times 0.002 \text{ lb/dry ton} \quad (10.28)$$

where:

f_1 = Mineral rate for organic nitrogen (assume 0.20).

V_1 = Volatilization rate 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 10.31***

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:

$$\text{PAN} = \left[(21{,}000 \text{ mg/kg} \times 0.20) + (10{,}500 \times 0.85)\right] \times 0.002 = 26.3 \text{ lb/dry ton}$$

10.8.2.3 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:

$$\underset{\text{Rate (dry tons/ac)}}{\text{Biosolids Application}} = \frac{\text{Plant Nitrogen Requirement (lb/ac)}}{\text{Plant Available Nitrogen (lb/dry ton)}} \quad (10.29)$$

■ ***Example 10.32***

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:

$$\text{Biosolids Application Rate} = \frac{150 \text{ lb/ac}}{30 \text{ lb/dry ton}} = 5 \text{ dry tons/ac}$$

10.8.2.4 Metals Loading

When biosolids are land applied, metals concentrations are closely monitored and their loading on land application sites is calculated.

$$\text{Loading (lb/ac)} = \text{Metal Concentration (mg/kg)} \times 0.002\ \text{lb/dry ton} \times \text{Application Rate (dry tons/ac)} \tag{10.30}$$

■ ***Example 10.33***

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:

$$\text{Loading Rate} = 14\ \text{mg/kg} \times 0.002\ \text{lb/dry ton} \times 11\ \text{dry tons} = 0.31\ \text{lb/ac}$$

10.8.2.5 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:

$$\text{Applications} = \frac{\text{Maximum Allowable Cumulative Load (lb/ac)}}{\text{Metal Loading (lb/ac/application)}} \tag{10.31}$$

■ ***Example 10.34***

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:

$$\text{Applications} = \frac{48.0\ \text{lb/ac}}{0.35\ \text{lb/ac}} = 137$$

10.8.2.6 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:

$$\text{Site Life (yr)} = \frac{\text{Maximum Allowable Applications}}{\text{Number of Applications Planned per Year}} \tag{10.32}$$

■ ***Example 10.35***

Problem: Biosolids are 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:

$$\text{Site Life} = \frac{135 \text{ applications}}{2 \text{ applications per year}} = 68 \text{ years}$$

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.

10.9 CHAPTER REVIEW QUESTIONS

10.1 What is the advantage of thickening biosolids before they move on in the treatment process?

10.2 Which thickening process is best for thickening process residuals from primary treatment?

10.3 Which thickening process is best for thickening process residuals from secondary treatment?

10.4 Name three devices that can be used to thicken waste activated sludge.

10.5 Name three factors that affect the performance of the gravity thickener.

10.6 Name three processes that use biological activity to stabilize wastewater solids.

10.7 When operating an aerobic digester, the dissolved oxygen level should be maintained at ______________ mg/L or higher.

10.8 What is the normal operating temperature of a heated anaerobic digester?

10.9 Any daily temperature change of more than ______________°F will cause the anaerobic digester production of methane gas to decrease.

10.10 The supernatant contains 340 mg/L volatile acids and 1830 mg/L of alkalinity. What is the volatile acids-to-alkalinity ratio? Based on the ratio, is the digester operating properly?

10.11 The digester is 40 ft in diameter and has a depth of 25 ft. Solids are pumped to the digester at the rate of 5000 gpd. What is the digestion time based on flow?

10.12 The primary treatment residual solids pumped to the digester contain 70% volatile matter. The digested biosolids removed from the digester contain 48% volatile matter. What is the percent volatile matter reduction?

10.13 When sludge is pumped from primary settling directly to the anaerobic digester, pumping should be controlled to produce a sludge with ______________ solids.

10.14 To oxidize biosolids using lime stabilization, what is required?

10.15 Can sludge be added to a floating cover anaerobic digester without withdrawing an equal amount of supernatant or sludge?

10.16 What do the digestion rate and the volatile matter reductions achieved by an anaerobic digester depend on?

10.17 What is the volatile acids-to-alkalinity ratio when the anaerobic digester contains 387 mg/L of volatile acids and 5805 mg/L of alkalinity?

10.18 The biosolids pump operates 30 min every 3 hr. The pump delivers 65 gpm. If the biosolids are 5.1% solids and have a volatile matter content of 64%, how many pounds of volatile solids are removed from the settling tank each day?

10.19 Name three general ways that biosolids can be dewatered.

10.20 What two actions take place in a biosolids drying bed?

10.21 Thickened thermally conditioned biosolids are 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 biosolids concentration is 11%, what is the filter yield in lb/hr/ft^2? Assume the sludge weight is 8.34 lb/gal.

CHAPTER 11

PERMITS, RECORDS, AND REPORTS

11.1 INTRODUCTION

Permits, records, and reports play a significant role in wastewater treatment operations. In fact, with regard to the permit, 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 guidance on requirements for your specific locality, contact the state's water control board or other authorized state agency for information. In this handbook, the term *board* signifies the state-reporting agency.

11.1.1 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 the 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 used to report 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.

11.2 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 that covers a specified class of dischargers. It is developed to allow dischargers in a specific 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.

11.2.1 Monitoring

- Date, time, and exact place of sampling or measurements
- Names of individuals performing the 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

Note: All records must be kept at least 3 years (longer at the request of the state board).

11.2.2 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 dates, times, and duration
- Steps planned or taken to reduce or eliminate the problem
- Steps planned or taken to prevent a 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 day of the next month.

11.3 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.

11.3.1 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)
- Average hourly concentration (mg/L)
- Daily quantity (kg/day)
- Daily concentration (mg/L)
- Instantaneous minimum concentration (mg/L)
- Instantaneous maximum concentration (mg/L)

11.3.2 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.

11.3.3 Special Conditions

Any special requirements or conditions set for approval of the discharge will be contained in this section. Special conditions may include:

- Monitoring required to determine effluent toxicity
- Pretreatment program requirements

11.3.4 Licensed Operator Requirements

The permit will specify, based on the treatment system complexity and the volume of flow treated, the minimum license classification required for someone to be the designated responsible charge operator.

11.3.5 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.

11.3.6 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.

11.3.6.1 Average Monthly Concentration

The average monthly concentration (AMC) is the average of the results of all tests performed during the month:

$$\text{AMC (mg/L)} = \frac{\sum \text{Test}_1 + \text{Test}_2 + \text{Test}_3 + \ldots + \text{Test}_n}{n \text{ (tests during month)}} \tag{11.1}$$

11.3.6.2 Average Weekly Concentration

The average weekly concentration (AWC) is the average of the results 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.

$$\text{AWC (mg/L)} = \frac{\sum \text{Test}_1 + \text{Test}_2 + \text{Test}_3 + \ldots + \text{Test}_n}{n \text{ (tests during calendar week)}} \tag{11.2}$$

11.3.6.3 Average Hourly Concentration

The average hourly concentration (AHC) is the average of all of the test results collected during a 60-minute period:

$$\text{AHC (mg/L)} = \frac{\sum \text{Test}_1 + \text{Test}_2 + \text{Test}_3 + \ldots + \text{Test}_n}{n \text{ (tests during 60-minute period)}} \tag{11.3}$$

11.3.6.4 Daily Quantity

Daily quantity is the quantity of a pollutant in kilograms per day discharged during a 24-hour period:

$$\begin{aligned}\text{Daily Quantity (kg/day)} = \text{Concentration (mg/L)} \times \text{Flow (MGD)} \\ \times 3.785 \text{ kg/mg/L/MG}\end{aligned} \tag{11.4}$$

11.3.6.5 Average Monthly Quantity

Average monthly quantity (AMQ) is the average of all the individual daily quantities determined during the month:

$$\text{AMQ (kg/day)} = \frac{\sum DQ_1 + DQ_2 + DQ_3 + \ldots + DQ_n}{n \text{ (tests during month)}} \tag{11.5}$$

11.3.6.6 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.

$$\text{AWQ (kg/day)} = \frac{\sum DQ_1 + DQ_2 + DQ_3 + \ldots + DQ_n}{n \text{ (tests during calendar week)}} \tag{11.6}$$

11.3.6.7 Minimum Concentration

The minimum concentration is the lowest instantaneous value recorded during the reporting period.

11.3.6.8 Maximum Concentration

The maximum concentration is the highest instantaneous value recorded during the reporting period.

11.3.6.9 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 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:

$$\text{Geometric Mean} = \text{Antilog}\left[\frac{\log X_1 + \log X_2 + \log X_3 + \ldots \log X_n}{n \text{ (number of tests)}}\right] \tag{11.7}$$

or

$$\text{Geometric Mean} = \sqrt[n]{X_1 \times X_2 \times \ldots \times X_n}$$

REFERENCES AND RECOMMENDED READING

Metcalf & Eddy. (1991). *Wastewater Engineering: Treatment, Disposal, Reuse*, 3rd ed. New York: McGraw-Hill.

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Spellman, F.R. (2007). *The Science of Water*, 2nd ed. Boca Raton, FL: CRC Press.

USEPA. (2007). *Advanced Wastewater Treatment to Achieve Low Concentration of Phosphorus*. Washington, D.C.: U.S. Environmental Protection Agency.

CHAPTER 12

FINAL REVIEW EXAM

Now that you have reviewed each lesson and completed the chapter review questions, where provided, you may test your overall knowledge of the material contained in Volume 1 and Volume 2 of this handbook by completing this final review exam. Although most of the questions that follow can be answered by referring to the topics covered in Volume 2, keep in mind that licensure exams at the higher levels also require knowledge gained at the lower levels of licensure; that is, each higher level exam is comprehensive, covering materials that were also presented in lower level exams.

For the questions you have difficulty answering or that you answer incorrectly, review the pertinent sections containing the applicable subject matter. A thorough understanding of all of the material presented in Volume 1 and Volume 2 of the handbook should prepare you for the Class III/II or Grade II/III licensing examinations and set the stage for successful completion of the Class I or Grade III/IV examinations. Operators preparing for the Class I or Grade III/IV licensing exams should be familiar with the topics covered in Volume 3.

Unlike the actual state licensure examinations, which contain an assortment of different types of questions (e.g., multiple choice, true or false, essay, completion questions), the final review exam presented here requires a written response to each question. The questions have been formatted in this way because experience has shown that, when studying for an exam (any exam), it is always best to write out the answer for better retention. Moreover, when studying for an exam, it is best to consider only the correct answer instead of several different choices (e.g., multiple choice questions) that could possibly be the correct answer, which can lead to the test taker selecting the wrong answer on the licensure exam. Upon completion of the final review exam, check your answers with those given in Appendix B.

FINAL REVIEW EXAM

12.1 What is the purpose of the sludge recirculation system?

12.2 Give three reasons for treating wastewater.

12.3 The trickling filter is 100 ft in diameter and 5.5 ft deep. The influent flow rate is 2.25 MGD, and the recirculation ratio is 0.5:1. What is the hydraulic loading for the trickling filter in gallons per day per square foot (gpd/ft^2)?

12.4 Name two types of solids based on physical characteristics.

12.5 The trickling filter is 80 ft in diameter and 3.5 ft deep. The influent flow rate is 3.40 MGD, and the recirculation ratio is 0.25:1. What is the organic loading in pounds of BOD per day per 1000 ft^3 if the primary effluent BOD is 112 mg/L?

12.6 Define *organic* and *inorganic*.

12.7 The highest organic loading in a rotating biological contactor (RBC) train usually occurs ________.

12.8 Name four types of microorganisms that may be present in wastewater.

12.9 Microscopic examination of activated sludge is a useful tool. What should the operator be trying to identify?

12.10 When organic matter is decomposed aerobically, what materials are produced?

12.11 Define *flocculation*.

12.12 Name three materials or pollutants that are not removed by the natural purification process.

12.13 What do we call the used water and solids from a community that flow to a treatment plant?

12.14 Where do disease-causing bacteria in wastewater come from?

12.15 What does the term *pathogenic* mean?

12.16 What is wastewater called that comes from the household?

12.17 What is wastewater called that comes from industrial complexes?

Use the following information for Questions 12.18 through 12.21:

Primary settling tank
Number = 2
Length = 190 ft
Width = 120 ft
Water depth = 12 ft
Aeration tank
Number = 4
Length = 200 ft

Width = 80 ft

Water depth = 12 ft

Secondary settling tank

Number = 4

Diameter = 100 ft

Water depth = 18 ft

12.18 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?

12.19 What is the surface area (in square feet) of each of the primary settling tanks?

12.20 What is the volume (in cubic feet) of each of the aeration tanks?

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

12.22 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?

12.23 The depth of water in a grit channel is 28 in. What is the depth in feet?

12.24 A fecal coliform sample preserved at 4°C can be held up to how many hours before beginning the test?

12.25 Mixing biosolids with a filler material and allowing it to stand in piles (windrows) to allow natural oxidation to occur is known as ____________.

12.26 The operator withdraws 5350 gal of solids from the digester. How many pounds of solids have been removed?

12.27 Sludge added to the digester causes a 1900-ft^3 change in the volume of sludge in the digester. How many gallons of sludge have been added?

12.28 What is the purpose of heating and mixing a primary anaerobic digester?

12.29 A composite sample will give a(n) ____________.

12.30 The main action of a mixed media filter is ____________.

12.31 The plant effluent contains 32 mg/L solids. The effluent flow rate is 3.10 MGD. How many pounds per day of solids are discharged?

12.32 The plant effluent contains 25 mg/L BOD$_5$. The effluent flow rate is 7 MGD. How many kilograms per day of BOD$_5$ are being discharged?

12.33 The operator wishes to remove 3000 lb/day of solids from the activated sludge process. The waste activated sludge concentration is 3050 mg/L. What is the required flow rate in million gallons per day?

12.34 The plant influent includes an industrial flow that contains 220 mg/L BOD. The industrial flow is 0.70 MGD. What is the population equivalent for the industrial contribution in people per day?

12.35 The label of hypochlorite solution states that the specific gravity of the solution is 1.1588. What is the weight of 1 gallon of the hypochlorite solution?

Use the following information for Questions 12.36 through 12.39:

Plant influent

Flow = 8.40 MGD

Suspended solids = 360 mg/L

BOD = 240 mg/L

Primary effluent

Flow = 8.40 MGD

Suspended solids = 130 mg/L

BOD = 160 mg/L

Activated sludge effluent

Flow = 8.34 mg/L

Suspended solids = 17 mg/L

BOD = 20 mg/L

Anaerobic digester

Solids in = 6.6%

Solids out = 13.5%

Volatile matter in = 65.5%

Volatile matter out = 47.9%

12.36 What is the plant percent removal for BOD_5?

12.37 What is the plant percent removal for TSS?

12.38 What is the primary treatment percent removal of BOD_5?

12.39 What is the percent volatile matter reduction in the digestion percent?

Use the following information for Questions 12.40 through 12.42:

Plant influent

Flow = 8.40 MGD

Suspended solids = 360 mg/L

BOD = 240 mg/L

Primary effluent

Flow = 8.40 MGD

Suspended solids = 130 mg/L

BOD = 160 mg/L

Activated sludge effluent

Flow = 8.34 mg/L

Suspended solids = 17 mg/L

BOD = 20 mg/L

Anaerobic digester

Solids in = 6.6%

Solids out = 13.5%

Volatile matter in = 65.5%

Volatile matter out = 47.9%

Plant influent

Flow = 8.45 MGD

Grit channel

Number of channels = 2

Channel length = 45 ft

Channel width = 3 ft

Water depth = 3.5 ft

12.40 What is the hydraulic detention time (in hours) for primary settling when both tanks are in service?

12.41 What is the hydraulic detention time (in minutes) in the grit channel when both channels are in service?

12.42 What is the hydraulic detention time (in days) of the anaerobic digester?

12.43 Appreciable quantities of septic sludge "burping" to the surface of primary settling tanks could indicate ________________.

12.44 When a high organic waste load reaches an activated sludge plant, the operator's first indicator is a decrease in ________________.

12.45 What is the purpose of the bar screen?

12.46 What two methods are available for cleaning a bar screen?

12.47 Name two ways to dispose of screenings.

12.48 Turbidity in wastewater is caused by ________________.

12.49 What must be done to the cutters in a comminutor to ensure proper operation?

12.50 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 action should you recommend to identify the specific cause?

12.51 The reaction of chlorine and ammonia in wastewater produces what compound?

12.52 What is the most critical criterion for determining when a mixed media filter should be backwashed?

12.53 What is grit? Give three examples of materials that are considered to be grit.

12.54 The plant has three channels in service. Each channel is 2 ft wide and has a water depth of 4 ft. What is the velocity in the channel when the flow rate is 9.0 MGD?

12.55 What is the concentration of hydrogen ions at a pH of 7?

12.56 How are the results of a membrane filter test reported?

12.57 A membrane filter test for fecal coliform reveals blue, green, black, and yellow dots. Which ones should be counted?

12.58 Where should chlorine vents be placed?

12.59 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?

12.60 What is the purpose of primary treatment?

12.61 What is the purpose of the settling tank in the secondary or biological treatment process?

12.62 Belt filter presses are operated as a ______________ process.

12.63 An incubator for the BOD test should be controlled at a temperature of ______________°C.

12.64 The circular settling tank is 80 ft in diameter and has a depth of 12 ft. The effluent weir extends around the circumference of the tank. The flow rate is 2.20 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 information for Questions 12.65 through 12.68:

Plant effluent
Flow = 0.40 MGD
Suspended solids = 370 mg/L
BOD = 380 mg/L
Town population = 2850 people
Industrial construction
Flow = 0.039 MGD
Suspended solids = 650 mg/L
BOD = 970 mg/L
Pond
Length = 1400 ft
Width = 1100 ft
Operating depth = 4.1 ft

12.65 What is the pond area in acres?

12.66 What is the pond volume in acre-feet?

12.67 What is the influent flow rate in acre-feet per day?

12.68 What is the influent flow rate in acre-inches per day?

12.69 Give three classifications of ponds based on their location in the treatment system.

12.70 What kind of odors can scrubbers be effectively used for?

12.71 What is the optimum velocity through a bar screen?

12.72 About how much (percentage) of an RBC is submerged?

12.73 At what depth should the sludge blanket be maintained?

12.74 What is *disinfection*?

12.75 Describe the processes occurring in a raw sewage stabilization pond (facultative).

12.76 How do seasonal changes affect the quality of the discharge from a stabilization pond?

12.77 What are the two most common sources of oxygen for lagoons?

12.78 What is the normal depth range of a facultative pond?

12.79 What is the advantage of using mechanical or diffused aeration equipment to provide oxygen?

12.80 Describe how the dissolved oxygen level of a pond changes during the day.

12.81 What is the purpose of the polishing pond?

Use the following information for Questions 12.82 through 12.86 (in all cases, assume that the flow is equally split between the two filters):

Plant effluent
Flow = 2.10 MGD
Suspended solids = 2.05 mg/L
BOD_5 = 190 mg/L
Trickling filters
Number = 2
Diameter = 90 ft
Media depth = 8 ft
Recirculation ratio = 1.5:1.0

12.82 What is the total flow (in MGD) to each filter?

12.83 What will the total flow to each filter be (in MGD) if the operator changes the recirculation ratio to 0.70:1.0?

12.84 What is the hydraulic loading (in gpd/ft^2) for each filter at a 1.5:1.0 recirculation ratio?

12.85 What is the hydraulic loading (in gpd/ft^2) for each filter at a 0.75:1.0 recirculation ratio?

12.86 What is the organic loading (in lb BOD per 1000 ft^3) for each filter at a 0.80:1.0 recirculation ratio?

12.87 What chemical is commonly added to a lagoon to increase available nitrate?

12.88 What chemical is normally required in the operation of a gravity belt thickener?

12.89 What two chemicals can be added to anaerobic digesters to increase alkalinity?

12.90 Name three main parts of the trickling filter, and give the purposes of each part.

12.91 Name three classifications of trickling filters, and identify the classification that produces the highest quality effluent.

Use the following information for Questions 12.92 through 12.94:

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 = 240,000 ft^2
Media area, stage 2 = 210,000 ft^2
Media area, stages 3–8 = 160,000 ft^2 (each)
K factor = 0.55
Hydraulic loading = 7.1 gpd/ft^2
Soluble BOD organic loading = 6.5 lb BOD/1000 ft^2

12.92 What is the hydraulic loading in gpd/ft^2?

12.93 What is the total organic loading (in lb BOD/day/1000 ft^2 of media)?

12.94 What is the soluble BOD organic loading (in lb BOD/day/1000 ft^2 of media)?

12.95 Name the two chemicals responsible for the majority of inorganic odors in wastewater treatment.

12.96 Describe the process occurring in the rotating biological contactor process.

12.97 What makes the RBC process similar to the trickling filter?

12.98 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?

12.99 What do we call the slime that grows on a trickling filter?

APPENDIX **A**

ANSWERS TO CHAPTER REVIEW QUESTIONS

CHAPTER 1

1.1 Developing a policy statement
1.2 2, 1, 3
1.3 Written and enforced lockout/tagout program
1.4 Correct the conditions that caused the accident.
1.5 False
1.6 Protecting emergency response personnel

CHAPTER 2

2.1 26 ft
2.2 77 ft
2.3 Eccentric, segmental
2.4 Flow nozzle
2.5 Ultrasonic flowmeter
2.6 4937 gal
2.7 4.57
2.8 213,904 ft^3

2.9 103 ft

2.10 8064 lb

2.11 Always constant

2.12 Pressure due to the depth of water

2.13 The line that connects the piezometric surface along a pipeline

2.14 0.28 ft

2.15 254.1 ft

2.16 6.2×10^{-8}

2.17 0.86 ft

2.18 Pressure energy due to the velocity of the water

2.19 A pumping condition where the center of the pump impeller is above the surface of the water being pumped

2.20 The slope of the specific energy line

CHAPTER 3

3.1 Positive-displacement

3.2 High-viscosity

3.3 Positive-displacement

3.4 High

3.5 High

3.6 Eye

3.7 Static, dynamic

3.8 Shut off

3.9 $V^2/2g$

3.10 Total head

3.11 Head capacity, efficiency, horsepower demand

3.12 Water

3.13 Suction lift

3.14 Elevation head

3.15 Water horsepower and pump efficiency

3.16 Centrifugal force

3.17 Stuffing box

3.18 Impeller

3.19 Rings, impeller

3.20 Casing

CHAPTER 4

4.1 A flexible piping component that absorbs thermal or terminal movement

4.2 Fluid

4.3 Fluid

4.4 Connected

4.5 Flow

4.6 Pressure loss

4.7 Increases

4.8 Automatically

4.9 Insulation

4.10 Leakage

4.11 Four times

4.12 Routine preventive maintenance

4.13 12

4.14 Schedule, thickness

4.15 Increases

4.16 Ferrous

4.17 Increases

4.18 Iron oxide

4.19 Cast iron

4.20 Iron

4.21 Corrosion

4.22 Decreases

4.23 Clay, concrete, plastic, glass, or wood

4.24 Corrosion proof

4.25 Cement

4.26 Pressed

4.27 Turbulent, lower

4.28 Steel

4.29 Fusion

4.30 Flexible

4.31 Aluminum

4.32 Annealed

4.33 Fusion

4.34 Metals, plastics
4.35 Laminar flow
4.36 Reinforced nonmetallic
4.37 Wire-reinforced
4.38 Dacron®
4.39 Diameter
4.40 Flexibility
4.41 E.E.
4.42 Reinforced, pressure
4.43 Flexible
4.44 Expansion joint
4.45 Vibration dampener
4.46 Plain
4.47 Bends
4.48 Pressure
4.49 Plug
4.50 Long-radius elbow
4.51 Valves
4.52 Throttle; start; stop
4.53 Globe
4.54 Butterfly
4.55 Pressure; preset
4.56 Solid particles
4.57 Shut off
4.58 Lubricate

CHAPTER 5

5.1 Hydrogen sulfide is present.
5.2 To protect plant equipment and remove materials that are not affected by treatment
5.3 To remove large solids (rags, ticks, rocks, etc.)
5.4 Manual, mechanical
5.5 Burial, incineration, grinding, and return to flow
5.6 Measure flow
5.7 Sharpen and align.

5.8 Rate of flow, depth of the wastewater in the channel, width of the channel, and number of channels in service

5.9 $$\text{Velocity (fps)} = \frac{9.0\ \text{MGD} \times 1.55\ \text{cfs/MGD}}{3\ \text{channels} \times 2.5\ \text{ft} \times 3\ \text{ft}} = 0.62\ \text{fps}$$

5.10 Try to start the machine to ensure that you have all energy sources off and de-energized.

5.11 Reduce odors, freshen septic wastes, reduce BOD, prevent corrosion, and improve settling and flotation.

5.12 To prevent excessive wear on the pump caused by grit and to prevent grit from taking up valuable space in downstream units

5.13 1 ft/s

5.14 1 ft/s

5.15 $$\frac{4.0\ \text{MG}}{1\ \text{day}} \times \frac{1\ \text{day}}{24\ \text{hr}} \times \frac{64\ \text{hr}}{1} = 10.7\ \text{MG}$$

$$\text{Flow Rate} = \frac{4\ \text{ft} \times 6\ \text{ft} \times 2\ \text{ft}}{10.7\ \text{MG}} = 4.5\ \text{ft}^3/\text{MG}$$

5.16 Anaerobic

5.17 Flow rate in open channels

5.18 Decrease slowly, then return to saturation slowly.

5.19 Slow the wastewater so the heavy inorganic material will settle out.

5.20 Remove settleable solids.

5.21 Reduce odors, neutralize acids and bases, reduce corrosion, reduce BOD, improve solids and grease removal, and reduce loadings on plant.

5.22 Weir Loading Rate = Q/Weir Length = 4.5 MGD/500 ft = 9000 gpd/ft

CHAPTER 6

6.1 To reduce settleable and floatable solids

6.2 $$\text{VM} = 70\ \text{gpm} \times \frac{20\ \text{min}}{3\ \text{hr}} \times \frac{24\ \text{hr}}{\text{day}} \times \frac{5.0\%}{100} \times \frac{64\%}{100} \times \frac{8.34\ \text{lb}}{\text{gal}} = 2989\ \text{lb/day}$$

6.3 $$\text{Detention Time} = \frac{\begin{array}{c}0.785 \times 90\ \text{ft} \times 90\ \text{ft} \times 10\ \text{ft}\\ \times 7.48\ \text{gal/ft}^3 \times 24\ \text{hr/day}\end{array}}{2.5\ \text{MGD} \times 1{,}000{,}000\ \text{gal/MG}} = 4.6\ \text{hr}$$

$$\text{Surface Loading Rate} = \frac{2.5\ \text{MGD} \times 1{,}000{,}000\ \text{gal/MG}}{0.785 \times 90\ \text{ft} \times 90\ \text{ft}} = 393.2\ \text{gpd/ft}^2$$

$$\text{Weir Overflow Rate} = \frac{2.5\ \text{MGD} \times 1{,}000{,}000\ \text{gal/MG}}{3.14 \times 90\ \text{ft}} = 8846\ \text{gpd/ft}$$

6.4 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%.

6.5 To prevent floatable solids (scum) from leaving the tanks

6.6 90 to 95% of the settleable solids

6.7 1.5 to 2.5 hr

6.8 Surface Area = 90 ft×25 ft = 2250 ft²

$$\text{Surface Overflow Rate} = \frac{1{,}600{,}000 \text{ gal}}{2250 \text{ ft}^2} = 711.1 \text{ gpd}$$

6.9 $$\text{Weir Overflow Rate} = \frac{1{,}350{,}000 \text{ gal}}{90 \text{ ft}} = 15{,}000 \text{ gpd/ft}$$

6.10 $$\text{Tank Volume} = 90 \text{ ft} \times 15 \text{ ft} \times 10 \text{ ft} \times 7.48 \text{ gal/ft}^3 = 100{,}980 \text{ gal}$$

$$\begin{aligned}\text{Detention Time} &= 3 \times 100{,}900 \text{ gal} \times 1 \text{ day/6,000,000} \\ &\quad \times 24 \text{ hr/1 day} \times 60 \text{ min/1 hr} \\ &= 72.7 \text{ min}\end{aligned}$$

$$\text{Surface Overflow Rate} = \frac{6{,}000{,}000 \text{ gpd}}{3 \times 90 \text{ ft} \times 15 \text{ ft}} = 1481 \text{ gpd/ft}$$

$$\text{Weir Overflow Rate} = \frac{6{,}000{,}000 \text{ gpd}}{3 \times 80 \text{ ft}} = 25{,}000 \text{ gpd/ft}$$

6.11 Detention Time = 2.8 hr

6.12 $$\text{Detention Time} = \frac{0.785 \times 90 \text{ ft} \times 90 \text{ ft} \times 10 \text{ ft} \times 7.48 \text{ gal/ft}^3 \times 24 \text{ hr/day}}{3.7 \text{ MGD} \times 1{,}000{,}000 \text{ gal/MG}} = 3.1 \text{ hr}$$

$$\text{Surface Loading Rate} = \frac{3.7 \text{ MGD} \times 1{,}000{,}000 \text{ gal/MG}}{0.785 \times 90 \text{ ft} \times 90 \text{ ft}} = 581.9 \text{ gpd/ft}^2$$

$$\text{Weir Overflow Rate} = \frac{3.7 \text{ MGD} \times 1{,}000{,}000 \text{ gal/MG}}{3.14 \times 90 \text{ ft}} = 13{,}093 \text{ gpd/ft}$$

6.13 $$\text{VM} = 80 \text{ gpm} \times \frac{30 \text{ min}}{3 \text{ hr}} \times \frac{24 \text{ hr}}{\text{day}} \times \frac{5.0\%}{100} \times \frac{66\%}{100} \times 8.34 \text{ lb/gal} = 5284 \text{ hr}$$

6.14 $$\text{Detention Time} = \frac{0.785 \times 80 \text{ ft} \times 80 \text{ ft} \times 9 \text{ ft} \times 7.5 \text{ gal/ft}^3 \times 24 \text{ hr/day}}{2.60 \text{ MGD} \times 1{,}000{,}000 \text{ gpd/MGD}} = 3.1 \text{ hr}$$

$$\text{Surface Loading Rate} = \frac{2.60 \text{ MGD} \times 1{,}000{,}000 \text{ gpd/MGD}}{0.785 \times 80 \text{ ft} \times 80 \text{ ft}} = 518 \text{ gpd/ft}^2$$

$$\text{Water Overload Rate} = \frac{2.6 \text{ MGD} \times 1{,}000{,}000 \text{ gpd/MGD}}{3.14 \times 80 \text{ ft}} = 10{,}350 \text{ gpd/ft}$$

6.15 It is most likely that the pump rate has resulted in a hole in the solids blanket (coning); the operator should reduce the pump rate and increase the frequency of pumping.

6.16 There is most likely a short-circuit in the clarifier flow pattern. Clarifier short circuits can be caused by unlevel effluent weirs or damaged/missing inlet baffles. Corrective action should include adjusting weir level, reaping, or installing baffles at the head of the clarifiers.

6.17 DT = 2.2 hr

CHAPTER 7

7.1 Facultative ponds

7.2 Stabilization pond, oxidation pond, polishing pond

7.3 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

7.4 Summer effluent is high in solids (algae) and low in BOD_5. Winter effluent is low in solids and high in BOD_5.

7.5

$$\text{Volume} = 609\text{ ft} \times 425\text{ ft} \times 6\text{ ft} \times \frac{7.48\text{ gal}}{1\text{ ft}^3} = 13{,}161{,}060\text{ gal}$$

$$\text{Detention Time} = 13{,}161{,}060\text{ gal} \times \frac{1\text{ day}}{300{,}000\text{ gal}} = 43.9\text{ days}$$

7.6

$$\text{Area} = 730\text{ ft} \times 410\text{ ft} \times \frac{1\text{ ac}}{43{,}560\text{ ft}^2} = 6.87\text{ ac}$$

$$\text{Hydraulic Loading Rate} = \frac{0.66\text{ ac-ft/day}}{6.87\text{ ac}} = 0.096\text{ in./day}$$

7.7 (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.

7.8 Standard-rate, high-rate, roughing

7.9 Standard-rate

7.10 To provide additional oxygen, reduce organic loading, improve sloughing, reduce odors, eliminate filter flies

7.11 Total = 2.3 MGD × (1.0 + 0.80) = 4.1 MGD

7.12 To remove sloughings from the wastewater prior to discharge

7.13 Arm movement, distribution orifice clogging, odors, operational problem indications

7.14 0.288 MGD + 0.366 MGD = 0.654 MGD

Surface Area = 0.785 × (90 ft)^2 = 6359 ft^2

$$\text{Hydraulic Loading Rate} = \frac{654{,}000}{6359\ \text{ft}^2} = 103\ \text{gpd/ft}^2$$

7.15 $$\text{Recirculation Ratio} = \frac{4.30\ \text{MGD}}{3.0\ \text{MGD}} = 1.43$$

7.16 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.

7.17 Slime on the 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.

7.18 No. An RBC must follow primary settling in order to remove the settleable solids. An RBC is designed to treat only soluble material.

7.19 White biomass indicates filamentous bacteria growth.

7.20 Standard density and high density

7.21 The biological growth is attached to the media.

7.22 The units are normally covered and maintain the same temperature throughout the year.

7.23 Gray, shaggy, translucent is normal. Sulfur will cause slime to become white and chalky in appearance.

7.24 Nitrification is occurring in the later stages of the process.

7.25 $$\text{Hydraulic Loading} = \frac{450{,}000\ \text{gpd}}{200{,}000\ \text{ft}^2} = 2.25\ \text{gpd/ft}^2$$

CHAPTER 8

8.1 Decrease, decrease, decrease, increase, increase

8.2 Provides the oxygen necessary for the microorganisms and the required mixing to put the food and microorganisms together

8.3 $$\text{MCRT} = \frac{2780\ \text{mg/L} \times (1.27\ \text{MG} + 0.88\ \text{MG}) \times 8.34}{(6125\ \text{mg/L} \times 0.09\ \text{MGD} \times 8.34) + (18\ \text{mg/L} \times 2.10\ \text{MGD} \times 8.34)} = 10.1\ \text{days}$$

8.4 $$\text{F/M Ratio} = \frac{175\ \text{mg/L} \times 2.10\ \text{MGD} \times 8.34}{1860\ \text{mg/L} \times 1.27\ \text{MG} \times 8.34} = 0.16\ \text{BOD}_5/\text{lb MLSS}$$

8.5 $\text{SSV}_{60} = \dfrac{1050 \text{ mL}}{2\text{L}} = 525 \text{ mL/L}$

8.6 $\text{SVI} = \dfrac{525 \times 1000 \text{ mL}}{2780 \text{ L}} = 189 \text{ mL/L}$

8.7 Decrease the waste rate.

8.8 Activated sludge

8.9 Mixed liquor

8.10 Food, oxygen, and organisms

8.11 To remove BOD

8.12 Mechanical and diffused

8.13 Aeration tank foam color, odors, settling tank capacity, solids loss, aeration rates process control tests, etc.

8.14 $\text{SSV}_{60} = \dfrac{1200 \text{ mL} \times 1000}{2100 \text{ mL}} = 571$

8.15 $\text{SVI} = \dfrac{425 \times 1000}{2240 \text{ mg/L}} = 190$

8.16 Waste = 8180 mg/L × 0.067 MGD × 8.34 = 4571 lb/day

8.17 Contact stabilization

8.18 Waste rate should be increased slightly.

8.19 MLSS under aeration = Q (MGD) × Primary Effluent Suspended Solids (mg/L) × 8.34 × Sludge Age (days) = 2.2 MGD × 125 mg/L × 8.34 × 5 days = 11,468 lb

8.20 Thick, greasy, brown or tan foam; dark brown sludge color; ash or pin floc in effluent; possibly rising sludge in settling tank

8.21 (1) Bulking occurs when solids do not settle; (2) rising sludge occurs when the solids settle but rise back into the flow quickly; (3) ashing results from excessively old sludge with discrete settling.

8.22 Color could be the result of outside factors, such as stormwater or industrial waste.

8.23 Chocolate brown sludge color; musty odor; uniform blanket settling; light, crisp white foam; low solids in effluent; very clear effluent

8.24 This helps eliminate variations that are not the result of changes in the sludge settling characteristics.

8.25 Increased flow, increased temperature, sludge bulking, decreased sludge age, increased organic loading

8.26 The most widely used unit consists of a 15- to 20-ft-long clear plastic pipe marked at 6-in. intervals; the pipe is equipped with a ball valve at the bottom.

CHAPTER 9

9.1 Turbidity, maintenance, intensity of bulbs, contact time, age of bulbs

9.2 Disinfection destroys pathogenic organism; sterilization destroys all organisms.

9.3 Demand, 1; residual, 30

9.4 Yellow green, 2.5

9.5 Chlorine is a toxic substance.

9.6 Toxic to aquatic organisms, reduces fish population, retards shellfish reproduction and growth

9.7 Wastewater is exposed to UV irradiation of a specified intensity for at least 10 seconds.

9.8 Ozone is produced onsite at the treatment plant. It is added to the wastewater to achieve specified ozone concentration in the off-gas. Use is limited to filtered effluents. It may be used for other effluents only if proven to be effective.

9.9 Direct exposure to UV light can cause severe eye injury; ozone is a highly toxic gas that is capable of creating flammable and explosive atmospheres.

9.10 Bromine chloride requires less contact time and produces bromamines that remain in the wastewater for shorter periods of time. The amount of toxic material still present when the flow is released to the environment is significantly reduced.

9.11 $$\text{Dose} = \frac{450\text{ lb/day}}{6.55\text{ MGD} \times 8.34} = 8.24\text{ mg/L}$$

9.12 7.1 mg/L

9.13 May be required by plant's permit because chlorine is very toxic to aquatic organisms and must be removed to prevent stream damage

9.14 350 HTH per day × 0.40 available chlorine = 140 lb chlorine per day

9.15 $$\text{Flow Rate} = \frac{280\text{ lb Chlorine per day}}{0.69\%\text{ Available Chlorine} \times 8.34\text{ lb/gal} \times 1.28} = 48.7\text{ gpd}$$

9.16 $$\text{No. of Containers} = \frac{45.8\text{ lb/day} \times 1.10 \times 365\text{ days}}{2000\text{ lb/container}} = 9.2\text{, or }10$$

9.17 Chlorine and its byproducts (e.g., chloramines) are very toxic.

CHAPTER 10

10.1 Removes water from biosolids; reduces the volume of biosolids; better results and lower costs

10.2 Gravity thickener

10.3 Gravity thickener

10.4 Gravity thickener, flotation thickener, belt thickener

10.5 Age of solids, blanket depth, hydraulic detention time, temperature, solids detention time

10.6 Aerobic digestion, anaerobic digestion, composting

10.7 1.0

10.8 95–98°F

10.9 1°F

10.10 $$\text{Volatile Acids-to-Alkalinity Ratio} = \frac{340 \text{ mg/L}}{1830 \text{ mg/L}} = 0.19 \text{ (acceptable)}$$

10.11 $$\text{Detention Time} = \frac{0.785 \times 40 \text{ ft} \times 40 \text{ ft} \times 25 \text{ ft} \times 7.48 \text{ gal/ft}^3}{5000 \text{ gpd}} = 47.0 \text{ days}$$

10.12 $$\%\text{VM Reduction} = \frac{(0.70 - 0.48) \times 100}{0.70 - (0.70 \times 0.48)} = 60.4\%$$

10.13 4 to 8%

10.14 pH adjustment

10.15 Yes

10.16 Degree of mixing provided, temperature of the digester, volatile matter concentration of the raw sludge

10.17 0.07

10.18 $$\begin{aligned}\text{Volatile Solids Removed} &= 30 \text{ min/cycle} \times \frac{24 \text{ hr}}{3 \text{ hr/cycle}} \times 65 \text{ gpm} \\ &\quad \times 8.34 \text{ lb/gal} \times 0.051 \times .64 \\ &= 4247 \text{ lb/day}\end{aligned}$$

10.19 Drying beds, vacuum and pressure filtration and centrifugation

10.20 Drainage and evaporation

10.21 $$\text{Area} = 3.14 \times 10 \text{ ft} \times 8.34 \text{ ft} = 263.8 \text{ ft}^2$$

$$\begin{aligned}\text{Filter Yield} &= \frac{30 \text{ gpm}}{1 \text{ min}} \times \frac{60 \text{ min}}{1 \text{ hr}} \times \frac{8.34 \text{ lb}}{1 \text{ gal}} \times \frac{11\%}{100} \\ &= \frac{1651.3 \text{ lb/hr}}{263.8 \text{ ft}^2} = 6.26 \text{ lb/hr/ft}^2\end{aligned}$$

APPENDIX **B**

ANSWERS TO FINAL REVIEW EXAM (CHAPTER 12)

12.1 Maintain control of the digester at the proper temperature.

12.2 Prevent disease; protect aquatic organisms; protect water quality.

12.3 430 gpd/ft^2

12.4 Dissolved and suspended

12.5 181 lb BOD_5/day/1000 ft^3

12.6 *Organic* indicates matter that is made up primarily of carbon, hydrogen, and oxygen and will decompose into mainly carbon dioxide and water at 550°C. *Inorganic* indicates "without carbon."

12.7 On the first stage

12.8 Algae, bacteria protozoa, rotifers, virus

12.9 The predominant groups of organisms

12.10 Carbon dioxide, water, more organisms, stable solids

12.11 Grows fine solids into larger more settleable solids

12.12 Toxic matter, inorganic dissolved solids, pathogenic organisms

12.13 Effluent

12.14 From body wastes of humans who have diseases

12.15 Disease-causing

12.16 Domestic waste

12.17 Industrial waste

12.18 Weir Length = 3.14 × 110 ft = 345 ft.

12.19 Surface Area = 190 ft × 120 ft = 22,800 ft^2

12.20 Volume = 200 ft × 80 ft × 12 ft = 192,000 ft^3

12.21 $[(2 \times 200\text{ ft}) + (2 \times 80\text{ ft})] \times 4 = 2240\text{ ft of fence}$

12.22 $\%\text{ Solids} = \dfrac{22\text{ g} \times 100}{500\text{ g}} = 4.4\%$

12.23 2.33 ft

12.24 6 hr

12.25 Composting

12.26 Solids Removed = 5350 gal × 8.34 lb/gal = 44,619 lb

12.27 Sludge Added = 1900 ft^3 × 7.48 gal/ft^3 = 14,212 gal

12.28 To increase the digestion rate

12.29 Representative long-term sample

12.30 Straining

12.31 32 mg/L × 3.20 MGD × 8.34 lb/MG/mg/L = 827.3 lb/day

12.32 25 mg/L × 7.00 MGD × 3.785 KG/MG/mg/L = 662.3 kg/day

12.33 $\text{Flow Rate} = \dfrac{3000\text{ lb/day}}{3050\text{ mg/L} \times 8.34\text{ lb/MG/mg/L}} = 0.118\text{ MGD}$

12.34 $$\text{Population Equivalent} = \frac{220\text{ mg/L} \times 0.70\text{ MGD} \times 8.34\text{ lb/MG/mg/L}}{0.17\text{ lb BOD}_5\text{/person/day}}$$
$$= 7555\text{ people}$$

12.35 8.34 lb/gal × 1.1588 = 9.66 lb/gal

12.36 $\%\text{BOD}_5\text{ Removal} = \dfrac{(240\text{ mg/L} - 20\text{ mg/L}) \times 100}{240\text{ mg/L}} = 91.6\%$

12.37 $\%\text{TSS Removal} = \dfrac{(360\text{ mg/L} - 17\text{ mg/L}) \times 100}{360\text{ mg/L}} = 95.3\%$

12.38 $\%\text{BOD}_5\text{ Removal} = \dfrac{(240\text{ mg/L} - 160\text{ mg/L}) \times 100}{240\text{ mg/L}} = 33\%$

12.39 $\%\text{VM Reduction} = \dfrac{(0.655 - 0.479) \times 100}{0.655 - (0.655 \times 0.479)} = 52\%$

12.40 $$\text{Detention Time} = \frac{\begin{array}{c}150\text{ ft} \times 110\text{ ft} \times 10\text{ ft} \times 2\text{ tanks}\\ \times 7.48\text{ gal/ft}^3 \times 24\text{ hr/day}\end{array}}{8.45\text{ MGD} \times 1{,}000{,}000\text{ MGD}} = 7.0\text{ hr}$$

12.41 $$\text{Detention Time} = \frac{\begin{array}{c}45\text{ ft} \times 3\text{ ft} \times 3.5\text{ ft} \times 2\text{ channels}\\ \times 7.48\text{ gal/ft}^3 \times 1440\text{ min/day}\end{array}}{8.45\text{ MGD} \times 1{,}000{,}000\text{ gal/MG}} = 1.2\text{ min}$$

12.42 $\text{Detention Time} = \dfrac{110{,}000 \times 7.48\text{ gal/ft}^3}{18{,}000\text{ gpd}} = 45.7\text{ days}$

12.43 Sludge is not being pumped in sufficient quantities.

12.44 Dissolved oxygen residual in the aeration tank

12.45 To remove large objects

12.46 Manual and mechanical cleaners

12.47 Burial in an approved landfill; incineration

12.48 Finely divided suspended material

12.49 Cutter must be sharpened and/or replaced when needed; cutter alignment must be adjusted as needed.

12.50 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.

12.51 Chloramine

12.52 Filter effluent quality

12.53 Grit is heavy inorganic matter (e.g., sand, gravel, metal filings, egg shells, coffee grounds).

12.54 $$\text{Velocity} = \frac{9.0\text{ MGD} \times 1.55\text{ cfs/MGD}}{3\text{ channels} \times 2\text{ ft} \times 4\text{ ft}} = 0.6\text{ fps}$$

12.55 0.1 µg/L

12.56 As count per 100 mL

12.57 Blue dots only

12.58 Near or at floor level because chlorine is heavier than air

12.59 There is a large amount of organic matter in the grit; the aeration rate must be increased to prevent settling of the organic solids.

12.60 To remove settleable and floatable solids

12.61 To remove the settleable solids formed by the biological activity

12.62 Continuous

12.63 20°C

12.64 $$\text{Detention Time} = \frac{\begin{array}{c}0.785 \times 80\text{ ft} \times 80\text{ ft} \times 12\text{ ft}\\ \times\, 7.48\text{ gal/ft}^3 \times 24\text{ hr/day}\end{array}}{2.20\text{ MGD} \times 1{,}000{,}000\text{ gal/MG}} = 4.9\text{ hr}$$

$$\text{Surface Loading Rate} = \frac{2.20\text{ MGD} \times 1{,}000{,}000\text{ gal/MG}}{0.785 \times 80\text{ ft} \times 80\text{ ft}} = 438\text{ gpd/ft}^2$$

$$\text{Weir Overflow Rate} = \frac{2.20\text{ MGD} \times 1{,}000{,}000\text{ gal/MG}}{3.14 \times 80\text{ ft}} = 8758\text{ gpd/ft}$$

12.65 $$\text{Pond Area} = \frac{1400\text{ ft} \times 1000\text{ ft}}{43{,}500\text{ ft}^3\text{/ac-ft}} = 32.1\text{ ac}$$

12.66 $$\text{Pond Volume} = \frac{1400\text{ ft} \times 1000\text{ ft} \times 4.1\text{ ft}}{43{,}560\text{ ft}^3\text{/ac-ft}} = 132\text{ ac-ft}$$

12.67 Influent Flow Rate = 0.40 MGD × 3.069 ac-ft/MG = 1.23 ac-ft

12.68 Influent Flow Rate = 0.40 MGD × 36.8 ac-in./MG = 14.7 ac-in./day

12.69 Stabilization pond, oxidation pond, polishing pond

12.70 Inorganic odors, because inorganics dissolve better in water

12.71 1.5 ft/s

12.72 40%

12.73 2 ft (secondary settling tank)

12.74 Refers to the process in which certain carbon users will break down nitrate for its oxygen if no DO is in the water

12.75 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

12.76 Summer effluent is high in solids (algae) and low in BOD_5. Winter effluent is low in solids and high in BOD_5.

12.77 Algae and surface aerators

12.78 Between 3 and 6 ft

12.79 Eliminates wide diurnal and seasonal variation in pond DO

12.80 Increases during the daylight hours and decreases during darkness

12.81 Reduces fecal coliform BOD_5, total suspended solids, and nutrient levels.

12.82 $$\text{Total Flow} = \frac{2.10\text{ MGD} \times (1.0 + 1.5)}{2} = 2.6\text{ MGD}$$

12.83 $$\text{Total Flow} = \frac{2.10\text{ MGD} \times (1.0 + 0.70)}{2} = 1.8\text{ MGD}$$

12.84 $$\text{Hydraulic Loading} = \frac{2.10\text{ MGD} \times (1.0 + 1.5) \times 1{,}000{,}000\text{ gal/MG}}{0.785 \times 90\text{ ft} \times 90\text{ ft} \times 2}$$

$$= 412.8\text{ gpd/ft}^2$$

12.85 $$\text{Hydraulic Loading} = \frac{2.10\text{ MGD} \times (1.0+0.75) \times 1{,}000{,}000\text{ gal/MG}}{0.785 \times 90\text{ ft} \times 90\text{ ft} \times 2}$$

$$= 289\text{ gpd/ft}^2$$

12.86 $$\text{Organic Loading} = \frac{190\text{ mg/L} \times 2.10\text{ MGD} \times 8.34\text{ lb/MG/mg/L} \times 1000}{2\text{ filters} \times 0.785 \times 90\text{ ft} \times 90\text{ ft} \times 8\text{ ft}}$$

$$= 32.7\text{ lb/BOD}_5\text{/1000 ft}^3$$

12.87 Sodium nitrate

12.88 Polymer

12.89 Lime and bicarbonate

12.90 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

12.91 Standard rate (best effluent quality), high rate, and roughing

12.92 $240{,}000 \text{ ft}^2 + 210{,}000 \text{ ft}^2 + (6 \times 160{,}000 \text{ ft}^2) = 1{,}410{,}000 \text{ ft}^2$

$$\text{Hydraulic Loading} = \frac{8.40 \text{ MGD} \times 1{,}000{,}000 \text{ gal/MG}}{1,410,000 \text{ ft}^2} = 6.0 \text{ gpd/ft}^2$$

12.93

$$\text{Organic Loading} = \frac{190 \text{ mg/L} \times 8.40 \text{ MGD} \times 8.34 \text{ lb/MG/mg/L} \times 1000}{1{,}410{,}000 \text{ ft}^2}$$

$$= 9.44 \text{ lb BOD}_5/1000 \text{ ft}^2$$

12.94 $190 \text{ mg/L} - (150 \text{ mg/L} \times 0.55) = 107 \text{ mg/L}$

$$\text{Organic Loading} = \frac{107 \text{ mg/L} \times .40 \text{ MGD} \times 8.34 \text{ lb/MG/mg/L} \times 1000}{1{,}410{,}000 \text{ ft}^2}$$

$$= 5.3 \text{ lb BOD}_5/\text{day}/1000 \text{ ft}^3$$

12.95 Hydrogen sulfide and ammonia

12.96 Disks covered with biological growth rotate in wastewater. Organisms collect food during submergence. Oxygen is transferred during exposure to air. Organisms oxidize the organic matter. Waste products and sloughings are discharged to the wastewater flow for removal in the settling tank.

12.97 The use of fixed-film biological organisms

12.98 Normal, gray and shaggy; high sulfur, chalky and white

12.99 Zoogleal mass

APPENDIX C

FORMULAE

AREA (FT^2)

Rectangular Tank

$$A = L \times W$$

Circular Tank

$$A = \pi r^2 \text{ or } A = 0.785\ D^2$$

VOLUME (FT^3)

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

$$\text{Surface Settling Rate} = \frac{\text{Total gallons per day}}{\text{Surface area of tank}}$$

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