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Environmental Engineering

Applied Ecology and Environmental Management

A SERIES

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Frank R. Spellman

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Preface

Environmental engineers work to sustain human existence by balancing human needs and their impacts on the environment with the natural state of the environment as per Nature's grand design. It cannot be emphasized enough that sustaining human existence and natural processes in a state of harmony is no easy undertaking. In the face of global pollution, diminishing natural resources, increased population growth (especially in disadvantaged countries), geopolitical warfare, terrorism, global climate change, and other environmental problems, it is basic to the thesis of the *Handbook of Environmental Engineering* that we live in a world that is undergoing rapid ecological transformation. Because of these rapid changes, the role of environmental engineering has become increasingly prominent. Moreover, advances in technology have created a broad array of modern environmental issues. To mitigate these issues we must capitalize on environmental protection and remediation opportunities presented by technology.

To find and implement solutions to the problem of creating a balance between the environment and those of us who occupy this planet (who seek the so-called good life), we must have trained personnel who understand the issues and how to solve them. Common to all environmental specialists is recognition of the importance of obtaining a strong quantitative background in the environmental engineering, science, and management principles that govern environmental processes. Of course, all the training in the world will never suffice by itself unless we blend it with that uncommon trait known as common sense tempered with loads of practical on-the-job experience.

Environmental engineering students as well as practitioners in the field need to maintain an up-to-date level of knowledge and understanding of the following topics:

- The physical, chemical, and biological processes fundamental to understanding the environment fate and engineered treatment of environmental contaminants
- The sources and nature of waste materials that contribute to air, soil, and water pollution and relevant management and control technologies
- The science, mitigation techniques, and policies relevant to climate change and global environmental sustainability, energy planning, alternative energy technologies (e.g., hydraulic fracking), sustainable development, and next-generation processes
- The transport and transformation of contaminants through environmental pathways
- Pollution prevention technologies and designs associated with the treatment and disposal of waste materials
- The connection between the engineering and scientific aspects of environmental problems and decision-making processes

Developing an understanding of all of these areas can be achieved through a quantitative educational/training program and years of on-the-job experience built around the common theme of engineering and science in support of environmental decision making and management.

Currently, assorted critics are quick to point to technological advances as the culprits negatively impacting Nature's way and our environment. The fact is that environmental engineers respond to the needs of society with these same technological innovations; that is, we use technology to solve technologically driven problems. How do environmental engineers employ and put to use technology to correct or mitigate environmental problems? The simple answer first: Environmental engineers use their tools. They have a toolbox full of tools. The short list of these tools would include a knowledge of fluid mechanics, ecology, principles of toxicology, risk assessment, management principles, hydrogeology, modeling contaminant migration through multimedia systems, aquatic chemistry, environmental microbiology, applied statistical analyses, open channel hydraulics, field methods in habitat analysis and wetland delineation, principles of estuarine environment, hydrology, resources modeling, environmental sampling, sediment transport and river mechanics, geomorphic and ecological foundations of stream restoration, atmospheric chemistry, environmental chemicals, economic foundations for public decision making, business law for engineers, environmental impact assessment, geographic information systems, global environmental sustainability, water resources management, sustainable development, green engineering, energy planning, renewable energy, smart growth strategies for sustainable urban development and revitalization, and environmental safety and health, among a long list of many other specialties.

It can be seen that well-trained environmental engineers must know a little bit about a whole bunch; that is, they must be generalists. They must have a very large toolbox containing a variety of tools, and an essential one is the *Handbook of Environmental Engineering*, which is highly accessible and user friendly.

A Note to the Reader: Will It Be Milk Toast or Hardtack?

I remember the moment well. It was a few minutes before I was to enter my classroom for the first time that semester to present my opening lecture on An Introduction to Environmental Engineering to a room full of college students (a large mix of juniors, seniors, and graduate students). I was standing at my office window looking out onto the campus grounds. I just stood there, bringing on one of those thinking-too-hard headaches. Of course, because I had developed a tendency to think on two wavelengths at the same time (what I call compound thinking), the usual super headache quickly manifested itself.

On one wavelength I was thinking about my pending lecture presentation. More specifically, I was thinking about how to grab the students' attention—that is, how to hook them and reel them in. To actually deliver the message, I had to, needed to, keep the students' attention; otherwise, I would lose them to one of those annoying Twitter tweets, or songs, or daydreams, but boredom was not an option in my classroom. I could choose to take the milk toast approach by pointing out that the environment is in trouble. Yes, they should be careful about that glass of water they might drink. Yes, they should think about the air they are breathing. Yes, they should think about the ozone hole. Yes, they should think about the Arctic ice melt. Yes, they should think about being members of the world's foremost "throw-away society." No, it is not hopeless. No, we are not doomed. No, we are not headed toward the so-called Sixth Extinction.

The fact is I knew I could present all this, but the truth is I do not believe that environmental professionals should focus on only reactionary actions to mitigate any of these problems. That type of presentation would have been a milk toast presentation, with no body or substance, a timid, unassertive, spineless approach lacking in boldness and vigor. One thing is certain—if you set out to save the world from human-derived destruction, you'd best leave the milk toast approach at home. Why would anyone think it is better to fix a problem after it occurs than to prevent it in the first place?

I remember rubbing that throbbing forehead of mine as I looked out over what should have been a glorious, early Fall campus panorama; instead, I was presented with a disgusting trash-laden vista featuring a large tree whose fully leafed branches were loaded with candy wrappers and other fluttering banners of our throw-away society: discarded plastic bags, scraps of newspaper, the rings of six packs. My glance shifted down to a flower bed and the beauty of its blooms, interrupted here and there by various types of trash and, of course, those trail-marker beer cans and bottles … here, there, and everywhere. The debris served as clear markers of campus pathways often taken. It was funny that the cars and trucks in a nearby parking lot did not register in my brains cells, just the amazing assortment of discarded trash.

My thought process then shifted gears to my preferred hardtack approach; that is, I would scare the bejesus out of my bright-eyed students. More specifically, I would present the obvious and that which was not so obvious. Simply, I would point out the need for environmental studies because of a litany of environmental issues, the harm that human activity was inflicting on the biophysical environment, the many anthropogenic effects on the natural environment that are combining to kill us all off, eventually. I planned to loosely categorize causes, effects, and mitigation, pointing out that effects are interconnected and that they can cause new effects. To accomplish all this, I initially decided to assemble, in one form or another, a semester's worth of presentations that would include the following causes and effects of environmental problems:

- *Causes*
  Human overpopulation
  Hydrological issues
  Intensive farming
  Land use
  Nanotechnology
  Nuclear issues
  Biodiversity issues
  Ecophagy
- *Effects*
  Climate change (which I consider to be a natural phenomenon exacerbated by humans)
  Environmental degradation
  Environmental health
  Environmental issues with energy
  Environmental issues with war
  Overpopulation
  Genetic engineering
  Pollution (air, water, and soil)
  Resource depletion
  Toxicants
  Waste

Of course, I also planned to point out that all of the above causes and effects were about to become their focus in life, both their burden and their passion. The prospective environmental professionals were in this class not only to learn about the causes and effects of environmental issues but also to learn how to mitigate them, to comply with environmental laws, and, more importantly, to put into place practices to prevent the causes and thus prevent environmental damage in the first place. Simply, at least in my view, it was important to me to point out the environmental issues and imprint them on those young minds while expressing the importance of engineering out a potential problem before it manifests itself. Prevention is always better than mitigation (e.g., recycling, treatment, disposal). Being proactive is better than being reactive. Building one's own box to think outside of makes better sense than thinking outside someone else's creation.

So, on that day I was faced with that same never-ending dilemma of how to harness the students' attention and apply it to the cause of preserving our environment? How was I to make the lasting point that our environment is in trouble? Intuitively, I knew that scaring them was an easy way to make them tune into my lectures but I also realized that words only carry so much weight, scary or not. I rubbed my head and indirectly the headache, and then I had a eureka moment. The answer was right in front of me. You know the old saying that a picture is worth a thousand words? Well, pictures often provide the cement necessary to imprint a memory. The view out my window was all I needed to show my students. So I did. I ushered them into my office and single-filed them to the window to glance out onto the campus grounds and then sent them back to their desks in the classroom. I also directed to them to write a 150-word description of what they had observed through the window. (I always make my students write, write, and write some more. Knowing environmental engineering without knowing how to write is like knowing dentistry without knowing how to pull teeth.) The students were instructed to email their papers to me, because I have found that if I can put students on a computer then I have my foot in the door to capturing their attention span and turning on their learning mechanism. By the way, 77 out of 79 of the digital responses I received described exactly what I wanted them to observe outside that window. And what they saw is really what this handbook is—a ready reference and guidebook providing information and instruction on how to engineer out a problem before it occurs.

A final word about this handbook: This is not your grandfather's handbook. This handbook presents the facts, as it must, but it is also opinionated and peppered with statements based on the author's observations, experiences, mistakes, misjudgments, and a few triumphs along the way. Readers who do not agree with the opinions stated within will at least be thinking on their own. And this is what I consider to be my hardtack approach, to make you think. Is there any other way? By the way, if my students do not learn a thing from me other than the following statement, then mission still accomplished!

> If a builder constructs a house for a person and does not make it firm and the house collapses and causes the death of the owner, the builder shall be put to death.
>
> **Hammurabi's Code, 1750 BC**

Author

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1 Introduction

> One of the penalties of an ecological education is that one lives alone in a world of wounds. Much of the damage inflicted on the land is quite invisible to laymen. An ecologist must either harden his shell and make believe the consequences of science are none of his business or he must be the doctor who sees the marks of death in a community that believes itself well and does not want to be told otherwise.
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> The government tells us we need flood control and comes to straighten the creek in our pasture. The engineer on the job tells us the creek is now able to carry off more flood water, but in the process we lost our old willows where the cows switched flies in the noon shade, and where the owl hooted on a winter night. We lost the little marshy spot where our fringed gentians bloomed.
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> Some engineers are beginning to have a feeling in their bones that the meanderings of a creek not only improve the landscape but are a necessary part of hydrologic functioning. The ecologist sees clearly that for similar reasons we can get along with less channel improvement on Round River.
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> **Leopold (1993, p. 165)**

> The best advice I give to any rookie environmental engineer is that which already has been rendered by wiser and a lot more far-seeing people than me: "*primum non nocere*."
>
> **— Frank R. Spellman**

ENVIRONMENT

When we say the "environment," what do we mean exactly? Think about it. The term can mean many different things to many different people. From the individual point of view, the environment can be defined as his or her environment. From the environmental professional's point of view, the environment he or she works with requires a more specific definition. To the environmental professional, the term may take on global dimensions (i.e., the atmosphere, hydrosphere, lithosphere, and biosphere), may refer to a very localized area in which a specific problem must be addressed, or may, in the case of contained environments, refer to a small volume of liquid, gaseous, or solid materials within a treatment plant unit process. In the current digital era, some may consider "environment" to be an office environment, a creative environment, a learning environment, a corporate environment, a virtual environment, an aquatic environment, a tropical environment, a social environment, a conservation environment, or even a desktop environment, an integrated development environment, or a runtime environment. Obviously, when we use the term we need to be specific. In this text, then, we define *environment* as the natural environment, which includes all living things (all life forms) and all nonliving things that influence life. That is, our environment is that 10-mile-thick layer on the 200-million-square-mile surface of this planet. Remember, without that 10-mile-thick layer, which contains air, soil, and water (the environment), Earth would be a sterile hunk of orbiting rock. Without air, water, and soil, there is nothing we can—or could—relate to (Spellman and Stoudt, 2013).

ENVIRONMENTAL EQUILIBRIUM AND THE FLY IN THE OINTMENT

We had not walked any part of the Appalachian Trail, with its nearly 50 mountains spanning 14 states and 8 national forests, for more than several years. Though we had never walked its entire 2160-mile length, from Springer Mountain in Georgia to Katahdin, Maine, at once, over the course of several years a long time ago we had in piecemeal fashion covered most of it, and hiked many of the several hundred trails that parallel and join it as well. But we had moved out of easy reach of the Trail, and for years had only our memories of it.

For us, the lure of sojourning the Appalachian Trail had always been more than just an excuse to get away from it all—whatever "it" happened to be at the time. The draw, the magnetism of the Trail was more—much more—to us than that, though we have always found its magic difficult to define. Maybe it was a combination of elements—recollections, pleasant memories, ephemeral surprises found and never forgotten. Memories waking from the miles-deep sleep of earned exhaustion to the awareness of peace … inhaling deep draughts of cool, clean mountain air; breathing through nostrils tickled with the pungency of pure, sweet pine … eardrums soothed by the light tattoo of fresh rain pattering against taut nylon … watching darkness lifted, then suddenly replaced with cloud-filtered daylight, spellbound by the sudden, ordinary miracle of a new morning … anticipating our expected adventure and realizing the pure, unadulterated treasure of pristine wilderness we momentarily owned, with minds not weighed down by the mundane, everyday existence. That is what we took away from our Trail experiences years ago, what we remembered about living on the Trail, on our untroubled sojourn through one of the last pure wilderness areas left in the United States. Those memories were magnets. They drew us inexorably to the Trail—back again and again.

But, of course, the Trail had another drawing card—the natural world and all its glory. The Trail defined that for us. The flora that surrounds you on the Trail literally encapsulates you, as it does in any dense forest, and brings you fully into its own world, shutting out all the other worlds of your life. For a brief span of time, along the Trail, the office was gone; cities, traffic, the buzz and grind of work melted away into forest. But this forest was different, and its floral inhabitants created the difference. Not only the thickets of rhododendrons and azaleas (in memory, always in full bloom) but also the other forest growths drew us there: the magnificent trees—that wild assortment of incomparable beauty that stood as if for forever—that was the Trail.

This was how it had been no more than 25 years ago, but now things were different; things had changed for the worse. To say that we were shocked at what we found recently along the Trail—along most of its length—is true, and we can only describe it as wounding heartache, as achingly sad to us as the discovery of the physical debilitation of a long-beloved friend. Even though still lined (and in some places densely packed) with Fraser fir, red spruce, sugar maples, shagbark hickory, northern red oak, quaking aspens, tulip poplars, white basswood, yellow buckeyes, black gums, old-growth beech, mountain laurel, and those incomparable dogwoods whose creamy-white bracts light up the woods in early spring, the world along the Trail was different. Let us paint you a picture of the differences. Walking various segments of the trail and its arteries in North Carolina, Virginia, and Maryland, we observed:

- Standing dead Fraser fir and red spruce
- Stands of pollution-killed trees where fallen gray tree trunks criss-crossed each other in a horrible game of giant jackstraws
- Standing dead red spruce silhouetted by polluted fog
- Understories of brambles looking up at dead sugar maples
- Foliage areas bleached by ozone
- Trees of all varieties starved to death, the necessary soil nutrients leached away by decades of acid deposition and the trees weakened until they were no longer capable of withstanding the assaults of even ordinary disease and bad weather
- Logged wasteland areas
- Branch dieback on northern red oak
- Premature leaf drop on quaking aspens
- Thinning crowns on sugar maples
- Tipped-over tulip poplars with rotted roots
- Chemically green ponds in areas where active strip mining occurs
- An orange waterfall next to an abandoned mine
- An overview, where 25 years earlier we viewed the surrounding landscape for 50 miles, now veiled in thick, stagnant, polluted fog with visibility reduced to 2 or 3 miles

When asked to describe pollution—the fly in the ointment of what should be a pristine environment—most people have little trouble doing so, having witnessed some form of it firsthand. They usually come up with an answer that is a description of its obvious effects. But pollution is complicated, and although it can be easily described it cannot be easily defined, because what pollution is and is not is a judgment call. In nature, however, even the most minute elements are intimately connected with every other element, and so too are pollution's effects. In this chapter, we describe pollution more fully and explain the difficulty involved with defining it, beginning a process that will allow readers to create their own definition of pollution, although each reader's definition will vary.

POLLUTION DEFINED

When we need a definition for any environmental term, the first place we look is in pertinent U.S. Environmental Protection Agency (USEPA) publications. For the term *pollution*, however, we did not find the USEPA definition particularly helpful nor complete. The USEPA (1989) defined pollution as: "Generally, … the presence of matter or energy whose nature, location, or quantity has undesired environmental effects … impurities producing an undesirable change in an ecosystem." Under the Clean Water Act (CWA), for example, the term is defined as "the man-made or man-induced alteration of the physical, biological, and radioactive integrity of water" (USEPA, 1989). Although their definition is not inaccurate, it leaves out too much to suit our needs. The USEPA does, however, provide an adequate definition of the term *pollutant*, defining it as "any substance introduced into the environment that adversely affects the usefulness of a resource." Pollution is often classed as point-source or nonpoint-source pollution; however, the USEPA's definition of pollution seems so general as to be useless, perhaps because it fails to add material on what such a broadly inclusive term may cover. Definitions from other sources present similar problems. One of the problems with defining pollution is that it has many manifestations (Figure 1.1).

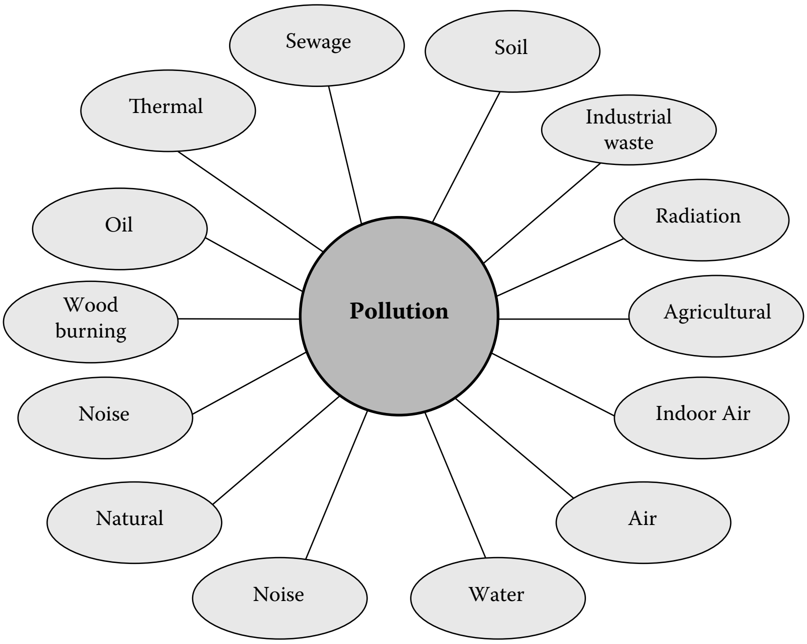

FIGURE 1.1 Manifestations of pollution.

TABLE 1.1
Categories and Types of Pollution

Pollution Categories	Type of Pollution	
Air pollution	Acid rain Chlorofluorocarbon Global warming Global dimming	Global distillation Particulates Smog Ozone depletion
Water pollution	Eutrophication Hypoxia Marine pollution Marine debris Ocean acidification Oil spills Ship pollution	Surface runoff Thermal pollution Wastewater Waterborne diseases Water quality Water stagnation
Soil contamination	Bioremediation Electrical resistance heating Herbicides	Pesticides Soil guideline values (SGVs)
Radioactive contamination	Actinides in the environment Environmental radioactivity Fission products Nuclear fallout	Plutonium in the environment Radiation poisoning Radium in the environment Uranium in the environment
Others	Invasive species Light pollution Noise pollution	Radio spectrum pollution Visual pollution

Figure 1.1 attempts to illustrate what pollution is but also works to confound the difficulty. The main problem with the manifestations of pollution is that it they are too general. Beyond its many manifestations, why is pollution so difficult to define? The element of personal judgment mentioned earlier contributes to the difficulty. Anyone who seriously studies pollution quickly learns that there are five major categories of pollution, each with its own accompanying subsets; these are shown in Table 1.1 (the types of pollution listed are defined later in the chapter). The categories and types of pollution listed in Table 1.1 can also be typed or classified as to whether the pollutants are *biodegradable* (subject to decay by microorganisms) or *nonbiodegradable* (cannot be decomposed by microorganisms). Moreover, nonbiodegradable pollutants can also be classified as *primary pollutants* (emitted directly into the environment) or *secondary pollutants* (result of some action of a primary pollutant).

POLLUTION VOCABULARY

To understand the basic concepts of environmental pollution, it is necessary to learn the core vocabulary. Remember what Voltaire said: “If you wish to converse with me, please define your terms.”

Scientists gather information and draw conclusions about the workings of the environment by applying the *scientific method*, a way of gathering and evaluating information. It involves observation, speculation (hypothesis formation), and reasoning. The science of pollution may be divided among the study of air pollution (atmosphere), water pollution (hydrosphere), soil pollution (geosphere), and life (biosphere). Again, the emphasis in this text is on the first three—air, water, and soil—because without any of these, life as we know it is impossible.

The *atmosphere* is the envelope of thin air around the Earth. The role of the atmosphere is multifaceted: (1) it serves as a reservoir of gases, (2) it moderates the Earth’s temperature, (3) it absorbs energy and damaging ultraviolet (UV) radiation from the sun, (4) it transports energy away from equatorial regions, and (5) it serves as a pathway for vapor-phase movement of water in the hydrologic cycle. *Air*, the mixture of gases that constitutes the Earth's atmosphere, is by volume at sea level 78.0% nitrogen, 21.0% oxygen, 0.93% argon, and 0.03% carbon dioxide, together with very small amounts of numerous other constituents.

The *hydrosphere* is the water component of the Earth, encompassing the oceans, seas, rivers, streams, swamps, lakes, groundwater, and atmospheric water vapor. *Water* (H_2O) is a liquid that when pure is without color, taste, or odor. It covers 70% of the Earth's surface and occurs as standing (oceans, lakes) and running (rivers, streams) water, rain, and vapor. It supports all forms of Earth's life.

The *geosphere* consists of the solid portion of Earth, including *soil*; the *lithosphere* is the topmost layer of decomposed rock and organic matter that usually contains air, moisture, and nutrients and can therefore support life. The *biosphere* is the region of the Earth and its atmosphere in which life exists, an envelope extending from up to 6000 meters above to 10,000 meters below sea level. Living organisms and the aspects of the environment pertaining directly to them are *biotic* (biota); the other, nonliving part of the physical environment is considered to be *abiotic*.

The series of biological, chemical, and geological processes by which materials cycle through ecosystems are called *biogeochemical cycles*. We are concerned with two types: the *gaseous* and the *sedimentary*. Gaseous cycles include the carbon and nitrogen cycles. The main *sinks*—the main receiving areas for material (e.g., plants are sinks for carbon dioxide)—of nutrients in the gaseous cycle are the atmosphere and the ocean. The sedimentary cycles include sulfur and phosphorus cycles. The main sink for sedimentary cycles is the soil and rocks of the Earth's crust.

Formerly known as natural science, *ecology*, as it is commonly called today, is critical to the study of environmental science, as it is the study of the structure, function, and behavior of the natural systems that comprise the biosphere. The terms *ecology* and *interrelationship* are interchangeable; they mean the same thing. In fact, ecology is the scientific study of the interrelationships among organisms and between organisms and all aspects, living and nonliving, of their environment.

Ecology is normally approached from two viewpoints: (1) the environment and the demands it places on the organisms in it, or (2) organisms and how they adapt to their environmental conditions. An *ecosystem*, a cyclic mechanism, describes the interdependence of species in the living world (the biome or community) with one another and with their nonliving (abiotic) environment. An ecosystem has physical, chemical, and biological components, as well as energy sources and pathways.

An ecosystem can be analyzed from a functional viewpoint in terms of several factors. The factors important in this discussion include *biogeochemical cycles*, *energy*, and *food chains*. Each ecosystem is bound together by biogeochemical cycles through which living organisms use energy from the sun to obtain or "fix" nonliving inorganic elements such as carbon, oxygen, and hydrogen from the environment and transform them into vital food, which is then used and recycled. The environment in which a particular organism lives is a *habitat*. The role of an organism in a habitat is its *niche*.

Obviously, in a standard handbook on a major profession such as environmental engineering, we need to define the niche that environmental engineers play in their particular habitat—that is, the role that environmental engineers play in their profession. Environmental engineers use the principles of engineering, biology, and chemistry to develop solutions to environmental problems. They are involved in efforts to improve recycling, waste disposal, public health, and water, soil, and air pollution control. More specifically, as is made clear in Figure 1.2, they integrate science and engineering principles to improve the natural environment. Further, also as shown in Figure 1.2, the goal of environmental engineers is to provide healthy water, air, and land for human habitation and for other organisms. Although this text takes the proactive approach of engineering out the problem of a pollution event before it occurs, the reality is that environmental engineers also work to clean up pollution sites (the reactive mode, for sure). Notice that Figure 1.2 includes environmental law and sustainability. These two specialties not only are buzzwords in today's environmental world but are also absolutely necessary skills sets in the toolbox of any successful environmental engineer. The well-rounded environmental engineering practitioner must understand environmental law and resource sustainability.

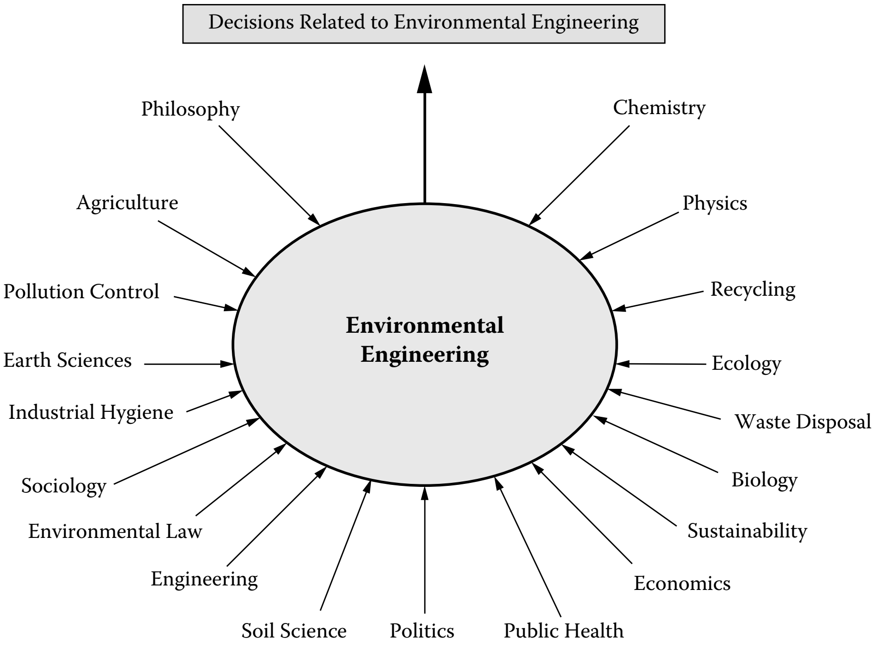

FIGURE 1.2 Components of environmental engineering.

Environmental engineers are also concerned with finding plausible solutions to problems in the field of public health such as vectorborne diseases and implementing laws that promote adequate sanitation in urban, rural, and recreational areas. Example 1.1 provides just one hypothetical example of environmental professionals at work in the real world.

■ EXAMPLE 1.1. SALMON AND THE RACHEL RIVER

The Rachel River, a hypothetical river system in the northwestern United States, courses its way through an area that includes a Native American reservation. The river system outfalls to the Pacific Ocean, and the headwaters begin deep and high within the Cascade Range in the state of Washington. For untold centuries, this river system provided a natural spawning area for salmon. The salmon fry thrived in the river and eventually grew the characteristic dark blotches on their bodies and transformed from fry to parr. When the time came to make their way to the sea, their bodies larger and covered with silver pigment, the salmon, now called smolt, inexorably migrated to the ocean, where they thrived until time to return to the river and spawn, about 4 years later. In spawning season, the salmon instinctively headed toward the odor generated by the Rachel River (their homing signal) and up the river to their home waters, as their life-cycle instincts demanded.

Before non-Native American settlers arrived in this pristine wilderness region, nature, humans, and salmon lived in harmony and provided for each other. Nature gave the salmon the perfect habitat; the salmon provided Native Americans with sustenance, and the Native Americans gave both their natural world and the salmon the respect they deserved.

After the settlers came to the Rachel River Valley, changes began to take place. The salmon still ran the river and humans still fed on the salmon, but the circumstances quickly changed. The settlers wanted more land, and Native Americans were forced to give way; they were either killed or forcibly moved to other places, such as reservations, while the settlers did all they could to erase Native American beliefs and cultural inheritance.

The salmon still ran.

After the settlers drove out the Native Americans, the salmon continued to run for a while, but more non-Native Americans continued to pour into the area. As the area became more crowded, the salmon still ran, but by now their home, their habitat, the Rachel River, had begun to show the effects of modern civilization. The prevailing philosophy was, "If we don't want it any more, we can just throw it away." The river provided a seemingly endless dump—out of the way, out of sight, out of mind. And they threw their trash, all the mountains of trash they could manufacture, into the river.

The salmon still ran.

More time passed. More people moved in, and the more people that came into the area, the bigger their demands. In its natural course, sometimes the river flooded, creating problems for the settler populations. Also, everyone wanted power to maintain their modern lifestyles, and hydropower was constantly pouring down the Rachel River to the ocean. So the people built flood control systems and a dam to convert hydropower to hydroelectric power. (Funny … the Native Americans didn't have a problem with flood control. When the river rose, they broke camp and moved to higher ground. Hydroelectric power? If you don't build your life around things, you don't need electricity to make them work. With the sun, the moon, and the stars and healthy, vital land at hand, who would want hydroelectric power?)

The salmon still ran.

Building dams and flood control systems takes time, but humans, although impatient, have a way of conquering and using time (and anything else that gets in the way) to accomplish their goals, including construction projects. As the years passed, the construction moved closer to completion, and finally ended. The salmon still ran—but in reduced numbers and size. Soon local inhabitants couldn't catch the quantity and quality of salmon they had in the past. They began to ask, "Where are the salmon?"

But no one seemed to know. Obviously, the time had come to call in the scientists, the experts. The inhabitants' governing officials formed a committee, funded a study, and hired some scientists to tell them what was wrong. "The scientists will know the answer. They'll know what to do," they said, and that was partly true. Notice that they didn't try to ask the Native Americans. They also would have known what to do. The salmon had already told them.

The scientists came and studied the situation, conducted tests, tested their tests, and decided that the salmon population needed to grow. They determined that an increased population could be achieved by building a fish hatchery, which would take the eggs from spawning salmon, raise the eggs to fingerling-sized fish, release them into specially built basins, and later release them to restock the river. A lot of science goes into the operation of a fish hatchery. It can't operate successfully on its own (although Mother Nature never has a serious problem with it when left alone) but must be run by trained scientists and technicians following a proven protocol based on biological studies of salmon life cycles.

When the time was right, the salmon were released into the river—meanwhile, other scientists and engineers realized that some mechanism had to be installed in the dam to allow the salmon to swim downstream to the ocean, and the reverse, as well. In the lives of salmon (anadromous species that spend their adult lives at sea but return to freshwater to spawn), what goes downstream must go upstream. The salmon would eventually need some way of getting back up past the dam and into their home water, their spawning grounds. So, the scientists and engineers devised and installed fish ladders in the dam so the salmon could climb the ladders, scale the dam, and return to their native waters to spawn and die.

After a few years, local Rachel River residents noticed an alarming trend. Studies over a 5-year period showed that no matter how many salmon were released into the river, fewer and fewer returned to spawn each season. So they called in the scientists again. And again they thought, "Don't worry. The scientists will know. They'll tell us what to do." The scientists came in, analyzed the problem, and came up with five conclusions:

1. The Rachel River is extremely polluted from both point and nonpoint sources.
2. The Rachel River Dam had radically reduced the number of returning salmon to the spawning grounds.
3. Foreign fishing fleets off the Pacific Coast were depleting the salmon.
4. Native Americans were removing salmon downstream, before they even got close to the fish ladder at Rachel River Dam.
5. A large percentage of water was being withdrawn each year from rivers for cooling machinery in local factories. Large rivers with rapid flow rates usually can dissipate heat rapidly and suffer little ecological damage unless their flow rates are sharply reduced by seasonal fluctuations. This was not the case, though, with the Rachel River. The large input of heated water from Rachel River area factories back into the slow-moving Rachel River was creating an adverse effect called *thermal pollution*. Thermal pollution and salmon do not mix. First and foremost, increased water temperatures lower the dissolved oxygen (DO) content by decreasing the solubility of oxygen in the river water. Warmer river water also causes aquatic organisms to increase their respiration rates and consume oxygen faster, increasing their susceptibility to disease, parasites, and toxic chemicals. Although salmon can survive in heated water—to a point—many other fish and organisms (the salmon's food supply) cannot. Heated discharge water from the factories also disrupts the spawning process and kills the young fry.

The scientists prepared their written findings and presented them to city officials, who read them and were initially pleased. "Ah!" they said. "Now we know why we have fewer salmon!" But what was the solution? The scientists looked at each other and shrugged. "That's not our job," they said. "Call in the environmental engineers."

The salmon still ran, but not up the Rachel River to its headwaters.

Within days, the city officials hired an environmental engineering firm to study the salmon depletion problem. The environmentalists came up with the same causal conclusions as the scientists, but they also noted the political, economic, and philosophical implications of the situation. The environmentalists explained that most of the pollution constantly pouring into the Rachel River would be eliminated when the city's new wastewater treatment plant came on line and that specific *point-source pollution* would be eliminated. They explained that the state agricultural department and their environmental staff were working with farmers along the lower river course to modify their farming practices and pesticide treatment regimes to help control the most destructive types of *nonpoint-source pollution*. The environmentalists explained that the Rachel River dam's current fish ladder was incorrectly configured but could be modified with minor retrofitting.

The environmentalists went on to explain that the overfishing by foreign fishing fleets off the Pacific Coast was a problem that the federal government was working to resolve with the governments involved. The environmentalists explained that the state of Washington and the federal government were also addressing a problem with the Native Americans fishing the downriver locations, before the salmon ever reached the dam. Both governmental entities were negotiating with the local tribes on this problem. Meanwhile, local tribes had litigation pending against the state and federal government to determine who actually owned fishing rights to the Rachel River and the salmon.

The final problem was thermal pollution from the factories, which was making the Rachel River unfavorable for spawning, decreasing salmon food supply, and killing off the young salmon fry. The environmentalists explained that to correct this problem, the outfalls from the factories would have to be changed and relocated. The environmentalists also recommended construction of a channel basin whereby the ready-to-release salmon fry could be released in a favorable environment, at ambient stream temperatures. This would give them a controlled one-way route to safe downstream locations where they could thrive until it was time to migrate to the sea.

After many debates and newspaper editorials, the city officials put the matter to a vote and voted to fund the projects needed to solve the salmon problem in the Rachel River. Some short-term projects are already showing positive signs of change, long-term projects are underway, and the Rachel River is on its way to recovery. In short, scientists are professionals who study to find *the* answer to a problem through scientific analysis and study. Their interest is in pure science. The environmentalists (also scientists) can arrive at the same causal conclusions as general scientists, but they are also able to factor in socioeconomic, political, and cultural influences, as well.

But, wait! It's not over yet. Concerns over disruption of the wild salmon gene pool by hatchery trout are drawing attention from environmentalists, conservationists, and wildlife biologists. Hatchery- or farm-raised stock of any kind is susceptible to problems caused by, among other things, a lack of free genetic mixing and the spread of disease, infection, and parasites, as well as reinforcement of negative characteristics. When escaped hatchery salmon breed with wild salmon, the genetic strain is changed and diseases can be transmitted. Many problems can arise.

Key Terms

Let's continue now with defining key terms. Many of the following terms can be found in Table 1.1:*

- *Acid rain*—Any form of precipitation made more acidic from falling though air pollutants (primarily sulfur dioxide) and dissolving them.
- *Actinides in the environment*—The sources, environmental behavior, and effects of radioactive actinides in the environment.
- *Air Quality Index*—A standardized indicator of the air quality in a given location.
- *Atmospheric dispersion modeling*—The mathematical simulation of how air pollutants disperse in the ambient atmosphere.
- *Bioremediation*—Any process that uses microorganisms, fungi, green plants, or their enzymes to return the natural environment altered by contaminants to its original condition.
- *Chlorofluorocarbons (CFCs)*—Synthetic chemicals that are odorless, nontoxic, nonflammable, and chemically inert.
- *Electrical resistance heating remediation*—An *in situ* environmental remediation method that uses the flow of alternating current electricity to heat soil and groundwater and evaporate contaminants.
- *Emerging pollutants (contaminants, such as PPCPs)*—Any synthetic or naturally occurring chemical or any microorganism that is not commonly monitored in the environment but has the potential to enter the environment and cause known or suspected adverse ecological and/or human health effects. Pharmaceuticals and personal care products (PPCPs) comprise a very broad, diverse collection of thousands of chemical substances, including prescription and over-the-counter therapeutic drugs, fragrances, cosmetics, sunscreen agents, diagnostic agents, nutrapharmaceuticals, biopharmaceuticals, and many others.
- *Environmental radioactivity*—The study of radioactive material in the human environment.
- *Eutrophication*—A natural process in which lakes receive inputs of plant nutrients as a result of natural erosion and runoff from the surrounding land basin.
- *Fission product*—The atomic fragments left after large nucleus fission.
- *Global dimming*—The gradual reduction in the amount of global direct irradiance at the Earth's surface.
- *Global distillation* (or *grasshopper effect*)—The geochemical process by which certain chemicals, most notably persistent organic pollutants (POPs), are transported from warmer to colder regions of the Earth.

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* Adapted from USEPA, *Pollution Prevention Research Program*, EPA/600/R-92/189, Office of Research and Development, U.S. Environmental Protection Agency, 1992.

- *Global warming*—The long-term increase in the average temperature of the Earth.
- *Herbicide*—Used to kill unwanted plants.
- *Hypoxia*—A phenomenon that occurs in aquatic environments as dissolved oxygen (DO) becomes reduced in concentration to the point where it is detrimental to aquatic orgasms living in the system.
- *Indoor air quality*—A term referring to the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants.
- *Invasive species*—Non-indigenous species (e.g., plants or animals) that adversely affect the habitats they invade economically, environmentally, or ecologically.
- *Life-cycle analysis*—A study of the pollution-generation characteristics and opportunities for pollution prevention associated with the entire life cycle of a product or process. Any change in the product or process has implications for upstream stages (e.g., extraction and processing of raw materials, production and distribution of process inputs) and for downstream stages (e.g., components of a product, its use and ultimate disposal).
- *Light pollution*—Excessive or obtrusive artificial light (photopollution or luminous pollution).
- *Marine debris*—Human-created waste that has deliberately or accidentally become afloat in a waterway, lake, ocean, or sea.
- *Marine pollution*—Harmful, or potentially harmful, effects resulting from the entry into the ocean of chemicals, particles, or industrial, agricultural, and residential waste or from the spread of invasive organisms.
- *Noise pollution*—Unwanted sound that disrupts the activity or balance of human or animal life.
- *Nuclear fallout*—The residual radiation hazard from a nuclear explosion, so named because it "falls out" of the atmosphere into which it is spread during the explosion.
- *Ocean acidification*—The ongoing decrease in the pH of the Earth's oceans, caused by their uptake of anthropogenic carbon dioxide from the atmosphere (Caldeira and Wickett, 2003).
- *Oil spill*—The release of a liquid petroleum hydrocarbon into the environment due to human activity; a form of pollution.
- *Ozone depletion*—Ozone concentrations vary naturally with sunspots, the seasons, and latitude, but these processes are well understood and predictable. Scientists have established records spanning several decades that detail normal ozone levels during these natural cycles. Each natural reduction in ozone levels has been followed by a recovery. Recently, however, convincing scientific evidence has shown that the ozone shield is being depleted well beyond changes due to natural processes (USEPA, 2010).
- *Particulates*—Normally refers to fine dust and fume particles that travel easily through air.
- *Pesticide*—A substance or mixture of substances used to kill pests.
- *Plutonium in the environment*—An article (part) of the actinides series in the environment.
- *Pollution and pollutants*—Terms that refer to all nonproduct output, irrespective of any recycling or treatment that may prevent or mitigate releases to the environment (includes all media).
- *Pollution prevention*—Activities to reduce or eliminate pollution or waste at its source or to reduce its toxicity. It involves the use of processes, practices, or products that reduce or eliminate the generation of pollutants and waste or that protect natural resources through conservation or more efficient utilization. Pollution prevention does not include recycling, energy recovery, treatment, or disposal. Some practices commonly described as in-process recycling may qualify as pollution prevention.
- *Radiation poisoning*—A form of damage to organ tissue due to excessive exposure to ionizing radiation.

- *Radio spectrum pollution*—Straying of waves in the radio and electromagnetic spectrums outside their allocations that can cause problems.
- *Radium* and *radon*—Radium and its decay product, radon gas, are highly radioactive.
- *Resource protection*—In the context of pollution prevention, protecting natural resources by avoiding excessive levels of waste and residues, minimizing the depletion of resources, and ensuring that the environment's capacity to absorb pollutions is not exceeded.
- *Smog*—Term used to describe visible air pollution; a dense, discolored haze containing large quantities of soot, ash, and gaseous pollutants such as sulfur dioxide and carbon dioxide.
- *Soil Guideline Values (SGVs)*—A series of measurements and values used to measure contamination of the soil.
- *Source reduction*—Term defined by the Pollution Prevention Act of 1990 as "any practice which (1) reduces the amount of any hazardous substance, pollutant, or contaminant entering any waste stream or otherwise released into the environment (including fugitive emissions) prior to recycling, treatment, and disposal; and (2) reduces the hazards to public health and the environment associated with the release of such substances, pollutants, or contaminants. The term includes equipment or technology modifications, process or procedure modifications, reformulations or design of products, substitution of raw materials, and improvements in housekeeping, maintenance, training, or inventory control." Source reduction does not entail any form of waste management (e.g., recycling, treatment). The Act excludes from the definition any practice that alters the physical, chemical, or biological characteristics or the volume of a hazardous substance, pollutant, or contaminant through a process or activity which itself is not integral to and necessary for the production of a product or the providing of a service.
- *Surface runoff*—The water flow that occurs when soil is infiltrated to full capacity and excess water from rain, snowmelt, or other sources flows over the land.
- *Thermal pollution*—Increase in water temperature with harmful ecological effects on aquatic ecosystems.
- *Toxic chemical use substitution*—Replacing toxic chemicals with less harmful chemicals even though relative toxicities may not be fully known. Examples include substituting a toxic solvent in an industrial process with a less toxic chemical and reformulating a product to decrease the use of toxic raw materials or the generation of toxic byproducts. The term also refers to efforts to reduce or eliminate the commercial use of chemicals associated with health or environmental risks, including substitution of less hazardous chemicals for comparable uses and the elimination of a particular process or product from the market without direct substitution.
- *Toxics use reduction*—Activities grouped under source reduction where the intent is to reduce, avoid, or eliminate the use of toxics in processes and products so the overall risks to the health of workers, consumers, and the environment are reduced without shifting risks between workers, consumers, or parts of the environment.
- *Uranium*—A naturally occurring element found in low levels within all rock, soil, and water.
- *Visual pollution*—The unattractive or unnatural (human-made) visual elements of a vista, a landscape, or any other thing that a person might not want to look at.
- *Waste*—In theory, applies to nonproduct output of processes and discarded products, irrespective of the environmental medium affected. In practice, since passage of the Resource Conservation and Recovery Act (RCRA), most uses of waste refer exclusively to the hazardous and solid wastes regulated under RCRA and do not include air emissions or water discharges regulated by the Clean Air Act or the Clean Water Act.

- *Waste minimization*—Initially included both treating waste to minimize its volume or toxicity and preventing the generation of waste at the source. The distinction between treatment and prevention became important because some advocates of decreased waste generation believed that an emphasis on waste minimization would deflect resources away from prevention toward treatment. In the current RCRA biennial report, waste minimization refers to source reduction and recycling activities and now excludes treatment and energy recovery.
- *Waste reduction*—Term used by the Congressional Office of Technology Assessment synonymously with source reduction; however, many groups use the term to refer to waste minimization. Therefore, determining the use of waste reduction is important when it is encountered.
- *Wastewater*—The liquid wastestream primarily produced by the five major sources: human and animal waste, household wastes, industrial waste, stormwater runoff, and groundwater infiltration.
- *Water quality*—The physical, chemical, and biological characteristics of water.
- *Water stagnation*—Water at rest, allowing the growth of pathogenic microorganisms to take place.
- *Waterborne diseases*—Caused by pathogenic microorganisms directly transmitted when contaminated drinking water is consumed.

These key terms and definitions, along with Figures 1.1 and 1.2 and Table 1.1, provide some help, but we are still trying to nail down a definitive meaning of pollution. Accordingly, to clear the fog, maybe it will help to look at a few more definitions of the term.

According to Keller (1988, p. 496), pollution is “a substance that is in the wrong place in the environment, in the wrong concentrations, or at the wrong time, such that it is damaging to living organisms or disrupts the normal functioning of the environment.” Again, this definition seems incomplete, although it makes the important point that often pollutants are or were useful—in the right place, in the right concentrations, at the right time. Let’s take a look at some of the other definitions of pollution that have been used over the years:

- Pollution is the impairment of the quality of some portion of the environment by the addition of harmful impurities.
- Pollution is something people produce in large enough quantities that it interferes with our health or wellbeing.
- Pollution is any change in the physical, chemical, or biological characteristics of the air, water, or soil that can affect the health, survival, or activities of human beings or other forms of life in an undesirable way. Pollution does not have to produce physical harm; pollutants such as noise and heat may cause injury but more often cause psychological distress, and aesthetic pollution such as foul odors and unpleasant sights affects the senses.

Pollution that initially affects one medium frequently migrates into the other media; air pollution falls to Earth, contaminating the soil and water; soil pollutants migrate into groundwater; and acid precipitation, carried by air, falls to Earth as rain or snow, altering the delicate ecological balance in surface waters. In our quest for the definitive definition, the source of last resort was consulted: the common dictionary. According to one dictionary, *pollution* is a synonym for *contamination*. A contaminant is a pollutant—a substance present in greater than natural concentrations as a result of human activity and having a net detrimental effect upon its environment or upon something of value in the environment. Every pollutant originates from a source. A receptor is anything that is affected by a pollutant. A sink is a long-time repository of a pollutant. What is actually gained from the dictionary definition is that, because pollution is a synonym for contamination, contaminants are things that contaminate the three environmental mediums (air, water, soil) in some manner. The bottom line is that we have come full circle to the impact and the exactness of what we stated in the beginning of this text: “Pollution is a judgment call.”

Why a judgment call? Because people's opinions differ as to what they consider to be a pollutant based on their assessment of benefits and risks to their health and economic wellbeing. For example, visible and invisible chemicals spewed into the air or water by an industrial facility might be harmful to people and other forms of life living nearby, but if the facility is required to install expensive pollution controls, it might have to shut down or move away. Workers who would lose their jobs and merchants who would lose their livelihoods might feel that the risks from polluted air and water are minor weighed against the benefits of profitable employment. The same level of pollution can also affect two people quite differently. Some forms of air pollution, for example, might cause a slight irritation for a healthy person but cause life-threatening problems for someone with chronic obstructive pulmonary disease, such as emphysema. Differing priorities lead to differing perceptions of pollution (concern about the level of pesticides in foodstuffs that leads to wholesale banning of insecticides is unlikely to help the starving). No one wants to hear that cleaning up the environment is going to have a negative impact on them. Public perception lags behind reality because the reality is sometimes unbearable.

POLLUTION EFFECTS EASY TO SEE, FEEL, TASTE, OR SMELL*

Although pollution is difficult to define, its adverse effects are often relatively easy to see; for example, some rivers are visibly polluted or have an unpleasant odor or apparent biotic population problems (such as fish kill). The infamous Cuyahoga River in Ohio became so polluted it twice caught on fire from oil floating on its surface. Air pollution from automobiles and unregulated industrial facilities is obvious. In industrial cities, soot often drifts onto buildings and clothing and into homes. Air pollution episodes can increase hospital admissions and kill people sensitive to the toxins. Fish and birds are killed by unregulated pesticide use. Trash is discarded in open dumps and burned, releasing impurities into the air. Traffic fumes in city traffic plague commuters daily. Ozone levels irritate the eyes and lungs. Sulfate hazards obscure the view. And it is important to point out that alternative energy sources championed by environmentalists and others, such as wind turbines and solar farms, are also pollutants, contaminants, or environmental hazards (depending on how you define them). How can wind and solar energy cause harm to the environment? Well, if we could ask the bald eagle who makes the mistake of flying into rotating turbine blades or flies too close to solar collectors or reflectors that cook it to a crisp, then the answer would be obvious.

Even if you are not in a position to see pollution, you are still made aware of it through the media. How about the 1984 Bhopal incident, the 1986 Chernobyl nuclear plant disaster, the 1991 pesticide spill into the Sacramento River, the *Exxon Valdez*, or the 1994 oil spill in Russia's Far North? Most of us do remember some of these, even though most of us did not directly witness any of these travesties. Events, whether manmade (e.g., Bhopal) or natural (e.g., Mount St. Helens erupting) disasters, sometimes impact us directly, but if not directly they still get our attention. Worldwide, we see constant reminders of the less dramatic, more insidious, continued, and increasing pollution of our environment. We see or hear reports of dead fish in stream beds, litter in national parks, decaying buildings and bridges, leaking landfills, and dying lakes and forests. On the local scale, air quality alerts may have been issued in your community.

Some people experience pollution more directly, firsthand—what we call "in your face," "in your nose," "in your mouth," "in your skin" type of pollution. Consider the train and truck accidents that release toxic pollutants that force us to evacuate our homes. We become ill after drinking contaminated water or breathing contaminated air or eating contaminated (*Salmonella*-laced) peanut butter products. We can no longer swim at favorite swimming holes because of sewage contamination. We restrict fish, shellfish, and meat consumption because of the presence of harmful chemicals, cancer-causing substances, and hormone residues. We are exposed to nuclear contaminants released to the air and water from uranium-processing plants and other industrial activities.

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* Adapted from Spellman, F.R. and Stoudt, M., *Environmental Science: Principles and Practice*, Government Institutes Press, Lanham, MD, 2013.

UNEXPECTED POLLUTION

On 9/11, if you were not present in New York City or the Pentagon or in that Pennsylvania farm field and not up close and personal with any of these events, then you might not be aware of the catastrophic unleashing of various contaminants into the environment because of the crashes. Or, maybe you did not have access to television coverage clearly showing the massive cloud of dust, smoke, and other ground-level debris engulfing New York City. Maybe you have not had a chance to speak with any of the emergency response personnel who climbed through the contaminated wreckage looking for survivors, These responders were exposed to chemicals and various hazardous materials, many of which we still are not certain of their exact nature. Days later, when rescue turned to recovery, you may not have noticed personnel garbed in moon suits (Level A hazmat response suits) and using instruments to sample and monitor the area for harmful contaminants. If you had not witnessed or known about any of the reactions after the 9/11 event, then it might be reasonable to assume that you might not be aware that these were indeed pollution-emitting events.

In addition to terrorism, vandalism, and other deliberate acts, we pollute our environment with apparent abandon. Many of us who teach various environmental science and health subjects to undergraduate and graduate students often hear students complain that the human race must have a death wish. Students quickly adopt this view based on their research and intern work with various environment-based service entities. During their exposure to all facets of pollution—air, water, and soil contamination—they come to understand that everything we do on Earth contributes pollution of some sort or another to one or all three environmental media.

Science and technology notwithstanding, we damage the environment through use, misuse, and abuse of technology. Frequently, we take advantage of technological advances before we fully understand their long-term effects on the environment. We weigh the advantages that a technological advance can give us against the environment and discount the importance of the environment due to greed, *hubris*, lack of knowledge, or stupidity. We often only examine short-term plans without fully developing how problems may be handled years later. We assume that when the situation becomes critical the technology will be there to fix it. The so-called experts suggest that every problem has a solution and what is needed today is innovation, innovation, and more innovation. No, what is needed first is discovery, then invention, and then finally innovation. When we blindly believe that scientists and engineers will eventually figure out how to prevent or mitigate the pollution of Mother Earth, we ignore the immediate consequences of our technological abuse and the contaminants emanating from such.

Consider this: Although technological advances have provided us with nuclear power, the light bulb and its energy source, plastics, the internal combustion engine, air conditioning, and refrigeration (and scores of other advances that make our modern lives pleasant and comfortable), these advances have affected the Earth's environment in ways we did not expect, in ways we deplore, and in ways we may not be able to live with. In this text, the argument is made that the same science and technology that created or exacerbated pollution events can, in turn, be used to mitigate the misuse of science and technology.

POLLUTION AND ENVIRONMENTAL SCIENCE, HEALTH, AND ENGINEERING

In order to prevent or mitigate pollution events, highly trained interdisciplinary practitioners are needed to monitor air, water, and soil quality. Generally, professionals responsible for environmental pollution monitoring, prevention, or control are thoroughly trained in environmental science or environmental health.

To precisely define *environmental science* as an interdisciplinary study of how the Earth works, to determine how we are affecting the Earth's life-support systems (environment), and to figure out how to deal with the environmental problems we face, we must first break down the term and look at each word separately. The *environment* includes all living and nonliving (such as air, soil, and water) things that influence organisms. *Science* is the observation, identification, description, experimental investigation, and theoretical explanation of natural phenomena. When we combine the two, we are left with a complex interdisciplinary study that must be defined both narrowly and broadly—and then combined—to allow us an accurate definition.

The narrow definition of *environmental science* is the study of the human impact on the physical and biological environment of an organism. In this sense, environmental scientists are interested in determining the effects of pesticides on croplands, learning how acid rain affects vegetation, evaluating the impact of introducing an exotic species of game fish into a pond or lake, and so on.

Beginning in the early 1960s, environmental science evolved out of the studies of natural science, biology, ecology, conservation, and geography. Increasing awareness of the interdependence that exists among all the disparate elements that make up our environment led to the field of study that contains aspects of all of these elements. Although environmental scientists are generalists who may have concentrated their study on a particular specialty, solidly trained environmental scientists have one thing in common: They are well grounded in biological and physical ideas that have been combined with ideas from the social sciences—sociology, economics, and political science—to form the new, interdisciplinary field of environmental science.

Environmental health practitioners, like environmental scientists and environmental engineers, are trained in the major aspects of environmental science; however, they are also concerned with all aspects of the natural and built environment that may affect human health. Unlike the relatively new environmental science and engineering profession, the environmental health profession has its modern-day roots in the sanitary and public health movement of the United Kingdom in the 1880s. Environmental health practitioners address human-health-related aspects of both the natural and the human-made environment. Environmental health concerns are shown in Figure 1.3. Notice that the environmental health concerns shown in Figure 1.3 have much in common with the concerns of environmental scientists and environmental engineers.

In the broadest sense, environmental science, and environmental health, and environmental engineering encompass the social and cultural aspects of the environment. As a mixture of several traditional sciences, political awareness, and societal values, environmental science and environmental health demand examination of more than the concrete physical aspects of the world around us, and many of those political, societal, and cultural aspects are far more slippery (with regard to the so-called "feel good" aspects) than what we can prove as scientific fact. In short, we can accurately say that environmental science and environmental health are pure sciences, because

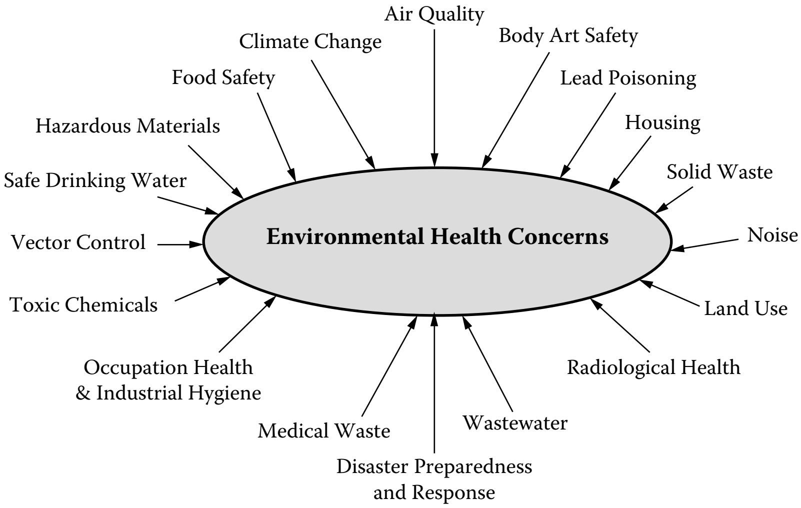

FIGURE 1.3 Environmental health concerns.

they include the study of all of the mechanisms of environmental processes: air, water, and soil. But, they are also an applied science, because they examine problems with the goal of contributing to their solution; they involve the study of the effects of human endeavors and technology thereon. Obviously, to solve environmental problems and understand the issues, environmental scientists and environmental health practitioners need a broad base of information from which to draw. The environment in which we live has been irreversibly affected by advancements in technology—and has been affected for as long as humans have wielded tools to alter their circumstances. As a result of rapid industrialization, overpopulation, and other human activities such as deforestation for agriculture (and the practice of agriculture itself), Earth has become loaded with diverse pollutants that have been released as byproducts. We will continue to alter our environment to suit ourselves as long as we remain a viable species, but to do so wisely we need to closely examine what we do and how we do it.

ENVIRONMENTAL POLLUTION AND TECHNOLOGY: THE CONNECTION

As long as capitalism drives most modern economies, people will desire material things—leading to a high level of consumption. For better or for worse, the human desire to lead the good life (which Americans may interpret as a life enriched by material possessions) is a fact of life. Arguing against someone who wants to purchase a new, modern home with all the amenities or the latest, greatest automobile is difficult. Arguing against people wanting to make a better life for their children by making sure they have all they need and want to succeed in their chosen pursuit is even more difficult. How do you argue against such goals with someone who earns his or her own way and spends his or her hard-earned money at will? Look at the tradeoffs, though, that often affect the environment. That new house purchased with hard-earned money may sit in a field of radon-rich soil or on formerly undeveloped land. That new SUV may get only 8 miles to the gallon. The boat they use on weekends gets even worse mileage and discharges wastes into the local lake, river, or stream. The weekend retreat on the 5 wooded acres is part of the watershed of the local community, and the breeding and migration habitat for several species is disturbed.

The environmental tradeoffs never enter into the average person's mind. Most people don't commonly think about it. In fact, most of us don't think much about the environment until we damage it, until it becomes unsightly, until it is so fouled that it offends us. People can put up with a lot of environmental abuse, especially with our surroundings—until the surroundings no longer please us. We treat our resources the same way. How often do we think about the air we breathe, the water we drink, the soil our agribusiness conglomerates plant our vegetables in? Not often enough.

The typical attitude toward natural resources is often deliberate ignorance. Only when someone must wait in line for hours to fill the car gas tank does gasoline become a concern. Only when he can see—and smell—the air he breathes and coughs when he inhales does air become a visible resource. Water, the universal solvent, causes no concern (and very little thought) until shortages occur, or until it is so foul that nothing can live in it or drink it. Only when we lack water or the quality is poor do we think of water as a resource to worry about. Is soil a resource or is it "dirt?" Unless you farm or plant a garden, soil is only "dirt." Whether you pay any heed to the soil/dirt debate depends on what you use soil for—and on how hungry you are.

Resource utilization and environmental degradation are tied together. While people depend on resources and must use them, this use impacts the environment. A *resource* is usually defined as anything obtained from the physical environment that is of use to humans—the raw materials that support life on Earth. Some resources, such as edible growing plants, water (in many places), and fresh air, are directly available to humans. But, most resources, such as coal, iron, oil, groundwater, game animals, and fish are not. They become resources only when we use science and technology to find them, extract them, process them, and convert them, at a reasonable cost, into usable and acceptable forms. Natural gas, found deep below the Earth's surface, was not a resource until the technology for drilling a well and installing pipes to bring it to the surface

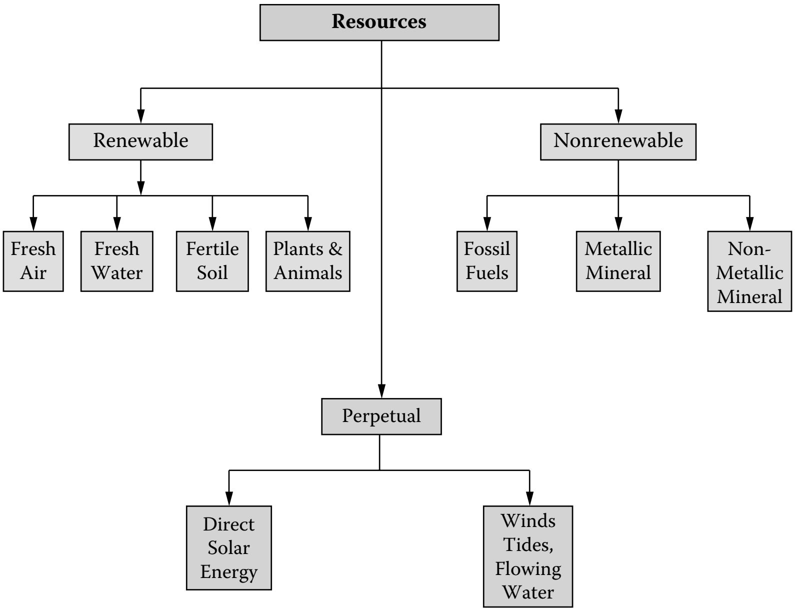

FIGURE 1.4 Major types of resources.

became available. For centuries, humans stumbled across stinky, messy pools of petroleum and had no idea of its potential uses or benefits. When its potential was realized, we exploited petroleum by learning how to extract it and convert (refine) it into heating oil, gasoline, sulfur extract, road tar, and other products.

Earth's natural resources and processes that sustain other species and us are known as *Earth's natural capital*, which includes air, water, soil, forests, grasslands, wildlife, minerals, and natural cycles. Societies are the primary engines of resource use, converting materials and energy into wealth, delivering goods and services, and creating waste or pollution. This provision of necessities and luxuries is often conducted in ways that systematically degrade the Earth's natural capital—the ecosystems that support all life.

Excluding *perpetual resources* (solar energy, tides, wind, and flowing water), two different types of resources are available to us: renewable and nonrenewable (see Figure 1.4). *Renewable resources* (fresh air; fresh water; fertile soil, plants, and animals via genetic diversity) can be depleted in the short run if they are used or contaminated too rapidly but normally will be replaced through natural processes in the long run. Water is a good example. Water is a renewable resource. The amount of water on Earth is constant, although its distribution is not. Water that is not available for safe use (contaminated) is of no value to humankind. Moreover, even though impurities are left behind when water evaporates, the water cycle does not ensure that clean water is always available. Thus, water must be managed; we must sample, monitor, and test it to ensure its safety for consumption.

Because renewable resources are relatively plentiful, we often ignore, overlook, destroy, contaminate, and mismanage them. Mismanage? Yes. Classifying anything as renewable is a double-edged sword. Renewable resources are renewable only to a point. Timber or grass used for grazing must be managed for *maximum sustainable yield* (the highest rate at which a renewable resource can be used without impairing or damaging its ability to be fully renewed). If timber or grass yields exceed this rate, the system gives ever-diminishing returns. Recovery is complicated by the time factor, which is life-cycle dependent. Grass can renew itself in a season or two. Timber takes decades. Any length of time is problematic when people get impatient.

Remember, one of the contributing factors of the plight of the Rachel River salmon was overfishing. When a fishery is pushed past its limit, if the catch is maintained by collecting greater and greater numbers of younger salmon, no increase is possible. If the same practices are used on a wild species, extinction can result. We have no more passenger pigeons, heath hens, Carolina parakeets, dodos, solitaires, or great auks—and many other species are at risk right now, including the Attwater prairie chicken.

Exceeding maximum sustainable yield is only the tip of the iceberg—other environmental, social, and economic problems may develop. Let's look at *overgrazing* (depleting) grass on livestock lands. The initial problem occurs when the grass and other grazing cover are depleted, but secondary problems kick in fast. Without grass, the soil erodes quickly. In very little time, so much soil is gone that the land is no longer capable of growing grass—or anything else. Productive land converted to nonproductive deserts (*desertification*) is a process of *environmental degradation* that impacts social and economic factors. Those who depend on the grasslands must move on, and moving on costs time, energy, and money—and puts more land at risk. Should the same level of poor stewardship of land resources continue on more acreage?

Environmental degradation is not limited to salmon and grass. Let's look at a few other examples. Along with overfishing and overgrazing, land can also be overcultivated. Intense overcultivation reduces soil nutrients and increases erosion to the point where agricultural productivity is reduced, leading to overfertilization, which eventually damages the water supply. If irrigation of agricultural lands proceeds without proper drainage, the excessive accumulation of water or salts in the soil decreases productivity. Environmental degradation takes place when trees are removed from large areas without adequate replanting. The results are destruction of wildlife habitat, increased soil erosion, and flooding. Habitat fragmentation is another problem related to habitat destruction. When habitat is fragmented, species that require distance from human activity are affected.

Take, for example, both greater and lesser prairie chickens in Kansas. Radiotelemetry research demonstrates that prairie chickens are extremely sensitive to human activity. The birds seldom use sand sage within a quarter mile of an inhabited house; a house built on a 1-acre site actually eliminates 160 acres of habitat for the birds. Human habitation isn't the only factor, however. Natural gas compression facilities—and southwest Kansas has a bunch—are noisy, clanging affairs, usually a couple of acres in size. The birds won't use habitat within half a mile of these areas, so that's another 640 acres down the tubes. Lesser chickens seldom venture within a mile of a coal-fired power plant, even though the sand sage habitat surrounding it may be the best on the range. A 30-acre power plant chews up 2500 additional acres of chicken habitat. In addition, lesser chickens rarely nest or raise broods in habitat blocks less than 2000 to 4000 acres in size, nor do the birds frequent habitats along well-traveled roads. Do the math, and pretty soon you see the magnitude of the problem associated with preserving or supplying large, open blocks of the right habitat for chickens (Taylor, 2002).

Land is often environmentally degraded when a metropolitan area expands. In high-growth areas, productive land is covered with concrete, asphalt, buildings, water, or silt to such an extent that agricultural productivity declines and wildlife habitat is lost.

Nonrenewable resources (copper, coal, tin, and oil, among many others) have built up or evolved in a geological time-span. They can't be replaced at will, only over a similar time scale. In this age of advanced technology, we often hear that (for example) when high-grade tin ore runs out (when 80% of its total estimated supply has been removed and used), low-grade tin ore (the other 20%) will become economically workable. This erroneous view neglects energy resource depletion and increasing pollution with lower grade burdens. In short, to find, to extract, and to process the remaining 20% generally costs more than the result is worth. Even with unlimited supplies of energy (impossible according to the *laws of thermodynamics*, discussed later), what if we could extract that last 20%? When it is gone, nothing is going to bring it back except time, measured in centuries and millennia, paired with the elements that produce the resource.

Advances in technology have allowed us to make great strides in creating the "good life." These same technological advances have also amplified environmental degradation. But, not all of the news is bad. Technological advances have also let us (via recycling and reuse) to conserve finite resources—aluminum, copper, iron, plastics, and glass, for example. *Recycling* involves collecting household waste items (e.g., aluminum beverage cans) and reprocessing usable portions. *Reuse* involves using a resource over and over in the same form (e.g., refillable beverage bottles, water).

We discussed the so-called "good life" earlier—modern homes, luxury cars and boats, a second home in the woods. With the continuing depletion of natural resources, prices must be forced upward until attaining the good life, or even gaining a foothold toward it, becomes difficult or impossible—and maintaining it becomes precarious. Ruthless exploitation of natural resources and the environment—overfishing a diminishing species (look at countless marine species populations, for example), intense exploitation of energy and mineral resources, cultivation of marginal land without proper conservation practices, degradation of habitat by unbalanced populations or introduced species, and the problems posed by further technological advances—will result in environmental degradation that will turn the good life into something we don't want to even think about. Our prevailing attitude of fly now and pay later is, along with cowboy science, not pertinent here.

So—what's the answer? Are we looking for the bluebird? What are we to do? What should we do? Can we do anything? Should we even care or think about it? Well, as is pointed out in Example 1.2, to preserve our natural resources and prevent environmental pollution, there are those, such as Garrett Hardin, for example, who would have us privatize the "commons," so to speak.

■ EXAMPLE 1.2. TRAGEDY OF THE COMMONS REVISITED

Garrett Hardin's influential article, "The Tragedy of the Commons," published in *Science* in 1968, describes a dilemma in which multiple individuals acting independently in their own self-interests (sounds so American, does it not?) can ultimately, through overexploitation, destroy a shared limited resource even when it is clear that it is not in anyone's long-term interest for this to happen. With regard to environmental pollution, Hardin points out that the tragedy of the commons, in a reverse way, is not taking something from the commons but of putting something into it (e.g., sewage or chemical, radioactive, and heat wastes in water; noxious and dangerous contaminants into the atmosphere; various forms of visual pollution in line of sight). We can't readily fence the air, water, and soil we depend on; thus, the tragedy of the commons must be prevented by coercive laws or taxing devices that make it cheaper for the polluter to treat his pollutants than discharge them untreated. Hardin considers the pollution problem to be a consequence of population.

CONSEQUENCES OF TECHNOLOGICAL DEVELOPMENT

Properly managed, technological development is a boon to civilization and will continue to be. Technological development isn't the problem—improper use of technology is. Using technology in ways that degrade our environment by introducing undesirable change in our ecosystems is absolutely untenable—we must prevent this from occurring. But, at the same time, we must continue to make advances in technology, we must find further uses for technology, and we must learn to use technology for the benefit of mankind and the environment. Technology and the environment must work hand in hand, not stand opposed. We must also foster respect for, and care for, what we have left.

Just how bad are the problems of technology's influence on environment? Major advances in technology have resulted in enormous transformation and pollution of the environment. While transformation is generally glaringly obvious (e.g., damming a river system), as mentioned, polluting or pollution is not always as clear. Remember that to *pollute* means to impair the purity of some substance or environment. *Air pollution* and *water pollution* refer to alteration of the normal compositions of air and water (their environmental quality) by the addition of foreign matter (e.g., gasoline, sewage).

Technological practices that have contributed to environmental transformation and pollution include the following:

- Extraction, production, and processing of raw natural resources, such as minerals, with accompanying environmental disruption
- Manufacturing enormous quantities of industrial products that consume huge amounts of natural resources and produce large quantities of hazardous waste and water/air pollutants
- Agricultural practices resulting in intensive cultivation of land, irrigation of arid lands, drainage of wetlands, and application of chemicals
- Energy production and use accompanied by disruption and contamination of soil by strip mining, emission of air pollutants, and pollution of water by release of contaminants from petroleum production and the effects of acid rain
- Transportation practices (particularly reliance on the airplane) that cause scarring of land surfaces from airport construction, emission of air pollutants, and greatly increased demands for fuel (energy) resources
- Transportation practices (particularly reliance on automobiles) that cause loss of land by road and storage construction, emission of air pollutants, and increased demand for fuel (energy) resources

Throughout this handbook, we discuss the important aspects of the impact of technology on the environment.

ENVIRONMENTAL ADMINISTRATIVE LAWS AND REGULATIONS

We have spent some time discussing pollution and briefly touched on its ramifications and impacts. So the obvious question becomes how do we protect the environment from pollution and polluters? Actually, there are many ways to prevent or to mitigate pollution. We discuss many of them later in this handbook, but for now it is important to understand that the government is not ignoring pollution. The USEPA works around the clock to either prevent pollution or to mitigate it via the regulatory process. Environmental laws, regulations, standards, and other regulatory tools are used to maintain or clean up our environment. In this section, we summarize the Administrative Procedure Act (APA) and outline in a broad-brush fashion some of the procedures under which laws are developed and applied. This section also discusses the various pollution control laws: Clean Air Act, Clean Water Act, Resource Conservation and Recovery Act, and Toxic Substances Control Act.

ADMINISTRATIVE PROCEDURE ACT (APA)

The Administrative Procedure Act (APA), 5 USC §551 *et seq.* (1946), governs the process by which federal agencies develop and issue regulations; that is, it sets forth various stands for all agency actions. It includes requirements for publishing notices of purposes and final rulemaking in the *Federal Register* and provides opportunities for the public to comment on notices of proposed rulemaking. The APA requires most rules to have a 30-day delayed effective date. In addition to setting forth rulemaking procedures, the APA also addresses other agency actions such as the issuance of policy statements, licenses, and permits. It also provides standards for judicial review if the person has been adversely affected or aggrieved by an agency review.

REGULATORY PROCESS

Earlier we stated that the USEPA works to protect the environment. To accomplish this, the agency uses a variety of tools and approaches, such as partnerships, education programs, and grants. One of the most significant tools is writing regulations. Regulations are mandatory requirements that can apply to individuals, businesses, state or local governments, non-profit organizations, and others.

Although Congress passes the laws that govern the United States, Congress has also authorized the USEPA and other federal agencies to help enforce these laws by creating and enforcing regulations. Below is a brief description of how laws and regulations are developed, what they are, and where to find them, with an emphasis on environmental laws and regulations.

Creating a Law

1. *Congress writes a bill.* A member of Congress proposes a bill, which is a document that, if approved, will become law.
2. *The President approves or vetoes the bill.* If both houses of Congress approve a bill, it goes to the President, who has the option to either approve it to veto it. If approved, the new law is referred to as an act or statute. Some of the better known laws related to the environment are the Clean Air Act, the Clean Water Act, and the Safe Drinking Water Act.
3. *The act is codified in the United States Code.* When an act is passed, the House of Representative standardizes the text of the law and publishes it in the United States Code (USC), which is the codification by subject matter of the general and permanent laws of the United States. Since 1926, the USC has been published every 6 years. In between editions, annual cumulative supplements are published to present the most current information.

Putting the Law to Work

When a law is official, here is how it is put into practice. A law often does not include all the details necessary to explain how an individual, business, or state or local government might follow that law. The United States Code, for example, does not tell you what the speed limit is in front of your house. In order to make the laws work on a day-to-day basis, Congress authorizes certain government agencies, including the USEPA, to create *regulations*, which set specific requirements about what is legal and what isn't. Regulations provide the technical, operational, and legal details necessary to implement laws. For example, a regulation issued by the USEPA to implement the Clean Air Act might explain what levels of a pollutant, such as sulfur dioxide, adequately protect human health and the environment. It would tell industries how much sulfur dioxide they can legally emit into the air and what the penalty would be if they emit too much. When such a regulation has gone into effect, the USEPA then works to help Americans comply with the law and to enforce it.

Creating a Regulation

When developing a regulation, the first thing to do is to ask if such a regulation is needed at all. Every regulation is developed under slightly different circumstances, but this is the general process:

1. *The USEPA proposes a regulation.* The Agency researches the issues and, if necessary, proposes a regulation, also known as a Notice of Proposed Rulemaking (NPRM). The proposal is listed in the *Federal Register* so members of the public can consider it and send their comments to the USEPA. The proposed rule and supporting documents are also filed in the USEPA's official docket at http://www.regulations.gov/#!home.
2. *The USEPA considers any comments and issues a final rule.* Generally, when the USEPA has considered the comments received when the proposed regulation was issued, it revises the regulation accordingly and issues a final rule. This final rule is also published in the *Federal Register* and in the USEPA's official docket at http://www.regulations.gov/#!home.
3. *The regulation is codified in the Code of Federal Regulations*—When a regulation is completed and has been printed in the *Federal Register* as a final rule, it is codified by adding it to the Code of Federal Regulations (CFR). The CFR is the official record of all regulation created by the federal government. It is divided into 50 volumes (titles), each of which focuses on a particular area. Almost all environmental regulations appear in Title 40. The CFR is revised yearly, and one fourth of the volumes are updated every 3 months. Title 40 is revised every July 1.

NATIONAL ENVIRONMENTAL POLICY ACT AND ENVIRONMENTAL IMPACT STATEMENTS

The purpose of the National Environmental Policy Act (NEPA) of 1969 is to encourage harmony between humans and the environment, promote efforts to prevent or eliminate environmental damage, and to enrich humans' understanding of important ecological systems and natural resources. NEPA requires that affected entities consider the potential environmental consequences of its decision before deciding to proceed and provide opportunities for public involvement, which includes participating in scoping, reviewing the draft and final Environmental Impact Statement (EIS), and attending public hearings. An EIS evaluates the environmental actions that an agency plans to undertake with respect to a comprehensive program or set of actions. The purpose of the EIS is to objectively analyze and evaluate the potential significant impacts on environmental resources due to research activities pertinent to whatever action is planned. The EIS will include descriptions of

- Proposed action
- Purpose and need for the proposed action
- Alternatives
- Affected environment
- Environmental consequences of the proposed action and alternatives
- Required mitigations or recommended best management practices (BMPs)

Advantages of the EIS document include the following:

- Full disclosure of the potential effects related to all research that may be authorized
- Incorporation of comprehensive analyses to evaluate cumulative effects effectively
- Formulation of comprehensive mitigation efforts and suggested best management practices (BMPs)
- Reduction of the need to readdress environmental consequences, mitigation measures, and BMPs at the permit-specific level

Environmental factors normally considered during the EIS process (see Figure 1.5) include

- Wildlife
  - Protected species
    - Threatened and endangered species
    - Marine mammals
    - Migratory birds
  - Non-protected species
- Special biological resource areas
    - National marine sanctuaries
    - Essential fish habitat
    - Designated critical habitat
- Coastal zone management
- Water resources
- Human safety
- Socioeconomics
- Noise
- Air quality
- Cultural resources
- Cumulative impacts

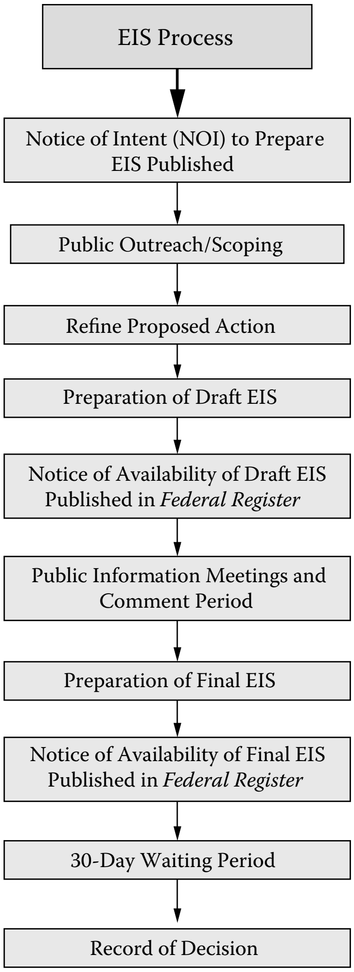

FIGURE 1.5 The EIS process.

BOTTOM LINE

When you throw a stone into a pool of quiet water, the ensuing ripples move out in concentric circles from the point of impact. Eventually, those ripples, much dissipated, reach the edge of the pond, where they break, disturbing the shore environment. When we alter our environment, similar repercussions affect the world around us, and some of these actions will be felt across the world. We use technology to alter our environment to suit our needs, but that same technology can be applied to protect our environment from unrecoverable losses. Environmental engineers must maintain an acute sense of awareness with regard to the global repercussions of problems we create for the environment, problems that extend beyond the boundaries of our own backyard.

Historically, as long as human population numbers remained small, human pollutants could be adequately processed by the environment, but as population numbers increased, human waste began to overwhelm natural systems. As societies become technologically sophisticated, humans begin producing large numbers and volumes of new substances each year. The ability of the environment to absorb and process these substances (to self-purify) has natural limitations. Our environment can only handle so much. Complicating the situation even further, the consumption of resources per person in the developed world increases daily, sometimes dramatically. Consumerism in a throw-away society has led to resource abuse and ever-increasing amounts of pollution being released to the environment. Consequently, pollution has become an increasing source of environmental problems.

Human progress has led inexorably to the soiling of air, water, and soil. Is this trend likely to continue? Maybe, maybe not. We do not know the answer to this vital question but there are some things we do know. We know that total de-industrialization of the developed world is improbable and, barring some major catastrophic event, unlikely and out of the question. A more practical view of pollution is required, one that allows sustainable development of healthy and vigorous industrial activity to provide the goods and services required by modern civilization.

We also know that we must do all this with a sense of balance—that is, the tradeoff we are willing to accept for those things that we do. More specifically, if we want to build a new factory that produces widgets that during the production phase will contribute an unreasonable level of pollutants to our air, water, and soil, we have to ask ourselves a question: Is it worth it? Is the tradeoff between creating jobs and enhancing the material livelihood of several individuals worth the potential damage to the environment? We need to find a middle ground. We must balance our desires against possible or potential results. Thus, what we really have is a balancing act, one we must work hard to maintain.

So what is the bottom line on pollution and its effects on us? That is what this handbook is all about—providing the facts and data to explain and illustrate the bottom line. Throughout we consistently highlight two overriding and connected themes. First, when it comes to pollution and its potential harmful effects on our lives, one thing is certain: We do not know the extent of the problem; in other words, we do not know what we do not know. Second, the politics surrounding the pollution situation can be summed up by the words of philosopher Gerog Hegel, "The nature of tragedy is not the conflict between right and wrong but between right and right."

For now, read this handbook with a mind open to the facts. Further, when you hear someone state that what we need to solve all of Earth's problems is innovation, innovation, and more innovation, you can accept that view or you can refer to what this handbook preaches: Discover, invent, and then innovate to the *n*th degree. Make your own choices, your own decisions, and your own judgments because the real bottom line is that when it comes to defining pollution the reader must make a judgment call.

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2 Units, Standards of Measurement, and Conversions

An engineering handbook that does not include units and conversions is like a book without a table of contents or index. For example, converting units from grams to slugs, centistokes to square feet per second, or pounds per million gallons to milligrams per liter can be accomplished automatically, right away, if you have a mind containing a library of facts and figures and conversions and data and all kinds of that type of stuff. However, if you are normal, there are times when even the most adept, confident, competent, and brilliant engineer or engineer want-to-be must refer to some reference to find some facts. I always hand out a printed copy of units and conversions in my college environmental classes. Most students welcome the handout; however, I have had a few who have shunned it at first, saying that they knew how to convert units and can do it from memory. I like to counter with, "Well, then, that means you know how convert abamperes to statamperes, right?" The look on their faces is always priceless. Students who do not know everything are my kind of students; they are teachable. Because not many of us are human computers with digital memories, this handbook includes a discussion of units, standards of measurement, and conversions. Moreover, because this is the age of energy consumption, renewable energy production, and hydraulic fracturing to capture more energy, energy conversion calculations are also included. By the way, does the reader know the difference, in gallons, between a U.S. fluid barrel and an oil barrel? Don't worry, if you read this chapter you will find out.

UNITS OF MEASUREMENT: THE BASICS

A basic knowledge of units of measurement and how to use them and convert them is essential. Environmental engineers should be familiar with both the U.S. Customary System (USCS), or English system, and the International System of Units (SI). Some of the important units are summarized in Table 2.1, which gives some basic SI and USCS units of measurement that will be encountered. In the study of environmental engineering math operations (and in actual practice), it is quite common to encounter both extremely large quantities and extremely small ones. The concentrations of some toxic substance may be measured in parts per million (ppm) or parts per billion (ppb), for example. To describe quantities that may take on such large or small values, it is useful to have a system of prefixes that accompany the units. Some of the more important prefixes are presented in Table 2.2.

> ***Note:*** For comparative purposes, we like to say that 1 ppm is analogous to a full shotglass of water sitting in the bottom of a full standard-size swimming pool.

CONVERSION FACTORS

Sometimes we have to convert between different units. Suppose that a 60-inch piece of pipe is attached to an existing 6-foot piece of pipe. Joined together, how long are they? Obviously, we cannot find the answer to this question by adding 60 to 6, because the two lengths are given in different units. Before we can add the two lengths, we must convert one of them to the units of the other. Then, when we have two lengths in the same units, we can add them.

TABLE 2.1
Commonly Used Units

Quantity	SI Units	USCS Units
Length	Meter	Foot (ft)
Mass	Kilogram	Pound (lb)
Temperature	Celsius	Fahrenheit (F)
Area	Square meter	Square foot (ft^2)
Volume	Cubic meter	Cubic foot (ft^3)
Energy	Kilojoule	British thermal unit (Btu)
Power	Watt	Btu/hr
Velocity	Meter/second	Mile/hour (mile/hr)

TABLE 2.2
Common Prefixes

Quantity	Prefix	Symbol
10^{-12}	Pico	p
10^{-9}	Nano	n
10^{-6}	Micro	µ
10^{-3}	Milli	m
10^{-2}	Centi	c
10^{-1}	Deci	d
10	Deca	da
10^2	Hecto	h
10^3	Kilo	k
10^6	Mega	M

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

1. 60 in. is really 60 ÷ 12 = 5 ft
2. 5 ft + 6 ft = 11 ft

From the example above, it can be seen that a conversion factor changes known quantities in one unit of measure to an equivalent quantity in another unit of measure. When making the conversion from one unit to another, we must know two things:

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

Confusion over whether to multiply or divide is common; on the other hand, the number that relates the two units is usually known and thus is not a problem. Understanding the proper methodology—the "mechanics"—to use for various operations requires practice and common sense.

Along with using the proper mechanics (and practice and common sense) to make conversions, probably the easiest and fastest method of converting units is to use a conversion table. The simplest conversion requires that the measurement be multiplied or divided by a constant value. For instance, if the depth of wet cement in a form is 0.85 foot, multiplying by 12 inches per foot converts the measured depth to inches (10.2 inches). Likewise, if the depth of the cement in the form is measured as 16 inches, dividing by 12 inches per foot converts the depth measurement to feet (1.33 feet).

Table 2.3 lists many of the conversion factors used in environmental engineering. Note that Table 2.3 is designed with a unit of measure in the left and right columns and a constant (conversion factor) in the center column.

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

Weight, Concentration, and Flow

Using Table 2.3 to convert from one unit expression to another and *vice versa* is good practice; however, when making conversions to solve process computations in water treatment operations, for example, we must be familiar with conversion calculations based on a relationship between weight, flow or volume, and concentration. The basic relationship is

$$\text{Weight} = \text{Concentration} \times (\text{Flow or Volume}) \times \text{Factor} \tag{2.1}$$

Table 2.4 summarizes weight, volume, and concentration calculations. With practice, many of these calculations become second nature to users. The calculations are important relationships and are used often in water/wastewater treatment process control calculations, so on-the-job practice is possible.

These conversion factors are used extensively in water and wastewater operations and are commonly needed to solve problems on licensure examinations; environmental engineers should keep them accessible for all plant operators.

TABLE 2.3
Conversion Table

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

TABLE 2.4
Weight, Volume, and Concentration Calculations

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

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

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

- 1 gallon of water weighs 8.34 pounds; the density is 8.34 lb/gal
- 1 milliliter of water weighs 1 gram; the density is 1 g/mL
- 1 cubic foot of water weighs 62.4 pounds; the density is 62.4 lb/ft^3
- 8.34 lb/gal = milligrams per liter, which is used to convert dosage in mg/L into lb/day/MGD (e.g., 1 mg/L × 10 MGD × 8.34 lb/gal = 83.4 lb/day)
- 1 psi = 2.31 feet of water (head)
- 1 foot head = 0.433 psi
- °F = 9/5(°C + 32)
- °C = 5/9(°F – 32)
- Average water usage, 100 gallons/capita/day (gpcd)
- Persons per single family residence, 3.7

Before working through a few sample conversion problems, it is important to point out that some common units do not necessarily represent the same quantities in all instances. Engineers not totally familiar with SI (or MKS) system of measurement sometimes are confused by the various unit comparisons. To illustrate this point, for example, as shown in Figure 2.1, the pound and slug and the newton and pound do not represent the same quantity of matter and force units, respectively.

CONVERSION EXAMPLES

Use Tables 2.3 and 2.4 to make the conversions that are necessary in the following example problems. Other conversions are presented in appropriate sections of the text.

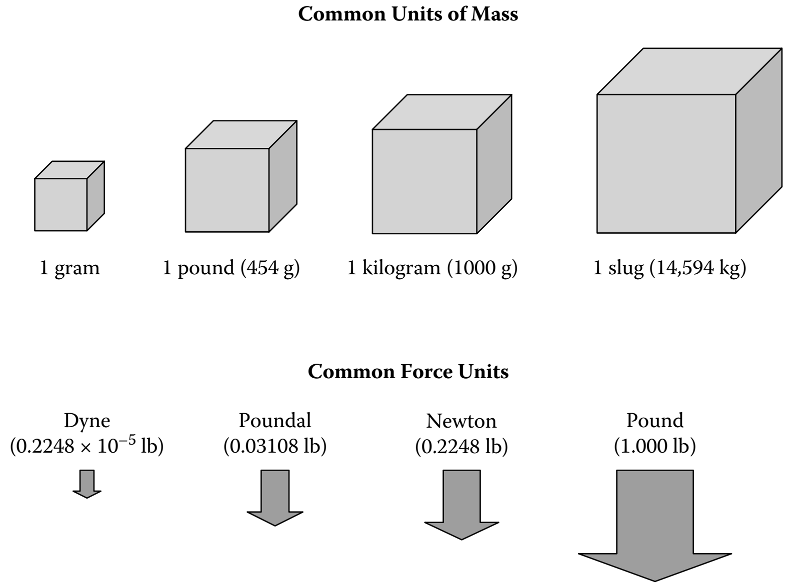

FIGURE 2.1 Common units of mass and force. (Adapted from Lindeburg, M.R., *Environmental Engineering Reference Manual*, 2nd ed., Power to Pass, Belmont CA, 2009.)

■ EXAMPLE 2.1

Convert cubic feet to gallons.

$$\text{Gallons} = \text{Cubic feet (ft}^3\text{)} \times 7.48\ \text{gal/ft}^3$$

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

Solution:

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

■ EXAMPLE 2.2

Convert gallons to cubic feet.

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

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

Solution:

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

■ EXAMPLE 2.3

Convert gallons to pounds.

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

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

Solution:

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

■ EXAMPLE 2.4

Convert pounds to gallons.

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

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

Solution:

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

■ EXAMPLE 2.5

Convert milligrams per liter to pounds.

> ***Note:*** Concentrations in milligrams per liter or parts per million determined by laboratory testing must be converted to quantities of pounds, kilograms, pounds per day, or kilograms per day.

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

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

Solution:

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

■ EXAMPLE 2.6

Convert milligrams per liter to pounds per day.

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

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

Solution:

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

■ EXAMPLE 2.7

Convert milligrams per liter to kilograms per day.

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

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

Solution:

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

■ EXAMPLE 2.8

Convert pounds to milligrams per liter.

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

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

Solution:

$$\begin{aligned}\text{Concentration} &= \frac{\text{Quantity (lb)}}{\text{Volume (MG)} \times 8.34\ \text{lb/MG/mg/L}}\\ &= \frac{89{,}990\ \text{lb}}{4.45\ \text{MG} \times 8.34\ \text{lb/MG/mg/L}} = 2425\ \text{mg/L}\end{aligned}$$

■ EXAMPLE 2.9

Convert pounds per day to milligrams per liter.

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

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

Solution:

$$\begin{aligned}\text{Concentration} &= \frac{\text{Quantity (lb/day)}}{\text{Volume (MGD)} \times 8.34\ \text{lb/MG/mg/L}}\\ &= \frac{4820\ \text{lb/day}}{25.2\ \text{MGD} \times 8.34\ \text{lb/MG/mg/L}} = 22.9\ \text{mg/L}\end{aligned}$$

■ EXAMPLE 2.10

Convert pounds to flow in million gallons per day.

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

Problem: If 9640 lb of solids must be removed per day from an activated biosolids process, and the waste activated biosolids concentration is 7699 mg/L, how many million gallons per day of waste activated biosolids must be removed?

Solution:

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

■ EXAMPLE 2.11

Convert million gallons per day to gallons per minute.

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

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

Solution:

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

■ EXAMPLE 2.12

Convert million gallons per day to gallons per day.

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

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

Solution:

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

■ EXAMPLE 2.13

Convert million gallons per day to cubic feet per second (cfs).

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

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

Solution:

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

■ EXAMPLE 2.14

Convert gallons per minute to million gallons per day.

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

Problem: The flow meter indicates that the current flow rate is 1469 gpm. What is the flow rate in million gallons per day?

Solution:

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

■ EXAMPLE 2.15

Convert gallons per day to million gallons per day.

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

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

Solution:

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

■ EXAMPLE 2.16

Convert flow in cubic feet per second to million gallons per day.

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

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

Solution:

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

■ EXAMPLE 2.17

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

Solution: Water weighs 8.34 lb/gal; therefore,

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

■ EXAMPLE 2.18

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

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

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

$$\text{Volume of piling} = 0.785 \times (1.33\ \text{ft})^2 \times 16\ \text{ft} = 22.22\ \text{ft}^3$$

$$12.4\ \text{lb/ft}^3 \times 22.22\ \text{ft}^3 = 275.5\ \text{lb}$$

■ EXAMPLE 2.19

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

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

$$8.34\ \text{lb/gal} \times 1.22 = 10.2\ \text{lb/gal}$$

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

$$408\ \text{lb/min} \times 1440\ \text{min/day} = 587{,}520\ \text{lb/day}$$

■ EXAMPLE 2.20

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

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

$$\frac{30\ \text{lb water displaced}}{62.4\ \text{lb/ft}^3} = 0.48\ \text{ft}^3$$

The cinder block volume is 0.48 ft^3, which weighs 70 lb; thus,

$$70\ \text{lb} \div 0.48\ \text{ft}^3 = 145.8\ \text{lb/ft}^3\ \text{density of cinder block}$$

$$\text{Specific gravity} = \frac{\text{Density of cinder block}}{\text{Density of water}} = \frac{145.8\ \text{lb/ft}^3}{62.4\ \text{lb/ft}^3} = 2.34$$

TEMPERATURE CONVERSIONS

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

- $°\text{C} = 5/9(°\text{F} - 32)$
- $°\text{F} = 9/5(°\text{C}) + 32$

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

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

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

> ***Note:*** At the same temperature, higher numbers are associated with the Fahrenheit scale and lower numbers with the Celsius scale. This important relationship helps you decide whether to multiply by 5/9 or 9/5.

■ EXAMPLE 2.21

Problem: Suppose that we wish to convert 240°F to Celsius.

Solution: Using the three-step process, we proceed as follows:

1. Add 40°

$$240° + 40° = 280°$$

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

$$(5/9) \times 280° = 156°\text{C}$$

3. Now subtract 40°.

$$156°\text{C} - 40°\text{C} = 116°\text{C}$$

Therefore, 240°F = 116°C.

■ EXAMPLE 2.22

Problem: Convert 22°C to Fahrenheit.

Solution:

1. Add 40°:

$$22° + 40° = 62°$$

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

$$(9/5) \times 62° = 112°$$

3. Subtract 40:

$$112° - 40° = 72°$$

Thus, 22°C = 72°F.

Obviously, knowing how to make these temperature conversion calculations is useful, but it is generally more practical to use a temperature conversion table.

TABLE 2.5
SI Base Units

Quantity	Name	Symbol
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Electric current	Ampere	A
Temperature	Kelvin	K
Amount of substance	Mole	mol
Luminous intensity	Candela	cd

MKS SYSTEM (SI UNITS)

The MKS system (so named because it uses the meter, kilogram, and second as base units) is comprised of SI units. All other units are derived from the base units, which are listed in Table 2.5. This is a fully consistent system; there is only one recognized unit for each variable (physical quantity).

DID YOU KNOW?

An abampere, in electricity, is a centimeter-gram-second unit of electromagnetic current, equivalent to 10 amperes. A statampere is the electric unit of current equal to the current produced by an electromotive force of 1 statvolt acting through a resistance of 1 statohm. An abampere is multiplied by 2.99793×10^{10} to obtain a statampere.

DID YOU KNOW?

Environmental engineers find that identifying certain quantities used in the United States can be confusing. For example, at the beginning of this chapter, readers were asked if they know how many gallons are contained in a barrel of U.S. liquid as compared to a barrel of petroleum. Refer to the list below:

Atmosphere	Standard atmosphere
Barrel (oil)	42 gallons
Barrel (U.S. fluid)	31.5 gallons
Btu	Tradition (thermochemical) value
Calories	Thermochemical
Gallons	U.S., liquid
Horsepower	U.S. or mechanical
Ounces	Avoirdupois
Pints	U.S. liquid
Pounds	Avoirdupois
Quarts	U.S. liquid
Tons	Short tons (2000 pounds)

INTRODUCTION TO ENERGY

> Eventually, growth in the globe's population and material economy will confront humanity. When this occurs (and it will), we will either adjust and survive or we will simply join the ranks of the dinosaurs, dodo birds, passenger pigeons, golden toads, and other species currently experiencing the Sixth Extinction.

During a recent Rabbit and Grasshopper conversation, Grasshopper told his friend, Rabbit: "To fix their energy, population, unemployment, and other economic problems, what humans need right now, my friend, is innovation, innovation, and more innovation." After deliberate and well-practiced thumping of his foot, Rabbit replied, "No, my long-legged friend, to fix all of humankind's economic problems what they need first is discovery, discovery, discovery and then invention, invention, invention, finally followed by innovation, innovation, innovation. Oh, and some human leadership, brain power, common sense, and accountability would also help." Grasshopper thought a moment and then observed, "Well, they aren't too smart, them humans. All they need to do is ask us. We know how to economize and how to do all the rest." Rabbit replied: "Right on, Grasshopper!"

ENVIRONMENTAL ENGINEERING PERSPECTIVE ON ENERGY*

The motive force, the capacity to do the work behind the operation of just about anything and everything, is energy. Energy is essential for most activities of modern society. Whether we use energy in the form of wood, fossil fuels, or electricity, the goal is to make life comfortable and convenient—that is, to maintain the so-called "good life." We use electricity for our lights and fans, air conditioners, water heaters, room heaters, ovens, microwaves, washing machines, dryers, cell phones, computers, and toasters. We use fossil fuels to run our buses, trucks, trains, airplanes, and ships; thus, transportation accounts for a large percentage of all the energy used.

Most people understand the importance of energy in their lives, but few understand the interface between energy and its usage and its mining, or its discovery, invention, or innovative uses, and the role of the environmental engineer in all of this. Water use and the safety and health of energy workers are the primary concerns of environmental engineers. The water requirements of energy production, especially as used in hydraulic fracking operations, are currently a major concern. Specifically, environmental engineers are concerned with the fate of the water that has been used to frack for gas and oil. What is to be done with the fracked, contaminated wastewater? Environmental engineers tasked with addressing this problem must consider the water use of all of our energy options using life-cycle analysis; they must then come up with new ways to recycle water quickly and reduce the overall water requirements through new technologies. Because environmental engineers must know something about energy and energy production, the following section is provided.

DEFINING ENERGY†

Defining energy can be accomplished by providing a technical definition or a characterization in layman terms. Because the purpose of this book is to reach technical readers as well as a wide range of general readers, definitions provided within it are best described as being both technical and nontechnical based. Consider the definition of energy, for example; it can be defined in a number of ways. In the broad sense, energy means the capacity of something—a person, an animal, or a physical system (machine)—to do work and produce change. In layman terms, energy is the amount of force or power that, when applied, can move an object from one position to another. It can also be used to describe someone doing energetic things, such as running, talking, and acting in a lively and vigorous way. It is used in science to describe how much potential a physical system has to change.

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[*] Adapted from Spellman, F.R., *Economics for the Environmental Professional*, CRC Press, Boca Raton, FL, 2015.

[†] Adapted from Spellman, F.R., *The Environmental Impacts of Renewable Energy*, CRC Press, Boca Raton, FL, 2014.

It also is used in economics to describe the part of the market where energy itself is harnessed and sold to consumers. For our purposes in this text, energy can be defined as simply something that can do work or the capacity of a system to do work.

There are two basic forms of energy: *kinetic energy* and *potential energy*. Kinetic energy is energy at work or in motion—that is, moving energy; for example, a car in motion or a rotating shaft has kinetic energy. In billiards, a player gives the cue ball kinetic energy when she strikes the ball with the cue. As the ball rolls, it exerts kinetic energy. When the ball comes into contact with another ball, it transmits its kinetic energy, allowing the next ball to be accelerated. Potential energy is stored energy, such as the energy stored in a coiled or stretched spring or an object stationed above a table. A roller coaster has the greatest potential energy when it is stopped at the top of a long drop. Another example of potential energy is when a can of carbonated soda remains unopened. The can is pressurized with gas that is not in motion but that has potential energy. When the can is opened, the gas is released and the potential energy is converted to kinetic energy.

According to the law of conservation of energy, energy cannot be made or destroyed but can be made to change forms. Moreover, when energy changes from one form to another, the amount of energy stays the same. Let's consider an example of the law of conservation of energy: The initial energy of something is measured. The energy then changes from potential (stored) energy to kinetic (moving) and back again. After that, the energy is measured again. The energy measured at the start is the same as that measured at the end; it will always be the same. One caveat to this explanation is that we now know that matter can be made into energy through processes such as nuclear fission and nuclear fusion. The law of conservation of energy has therefore been modified or amplified to become the law of conservation of matter and energy.

TYPES OF ENERGY

The many types of energy include the following:

- Kinetic (motion) energy
- Water energy
- Potential (at rest) energy
- Elastic energy
- Nuclear energy
- Chemical energy
- Sound energy
- Internal energy
- Heat/thermal energy
- Light (radiant) energy
- Electric energy

Energy sources can also be categorized as renewable or nonrenewable. When we use electricity in our home, the electrical power was probably generated by burning coal, by a nuclear reaction, or by a hydroelectric plant at a dam (EIA, 2009); therefore, coal, nuclear, and hydropower are called *energy sources*. When we fill up a gas tank, the source might be petroleum or ethanol made by growing and processing corn. Energy sources are divided into two groups—*renewable* (an energy source that can be easily replenished) and *nonrenewable* (an energy source that we are using up and cannot recreate; petroleum, for example, was formed millions of years ago from the remains of ancient sea plants and animals). In the United States, most of our energy comes from nonrenewable energy sources. Coal, petroleum, natural gas, propane, and uranium are nonrenewable energy sources. They are used to make electricity, to heat our homes, to move our cars, and to manufacture all kinds of products. Renewable and nonrenewable energy sources can be used to produce secondary energy sources, including electricity and hydrogen. Renewable energy sources include the following:

- Solar
- Hydro
- Wind
- Geothermal
- Ocean thermal energy conversion
- Tidal energy
- Hydrogen burning
- Biomass burning

Renewable energy (energy sources that can be easily replenished) is the focus of this text. Unfortunately (depending on your point of view), nonrenewable energy sources on Earth are available in limited quantities and may vanish within the next 100 years. Moreover, keep in mind that nonrenewable sources are *not* environmental friendly and can have serious effects on our health. Notwithstanding the environmental and health impacts of using nonrenewable energy sources, it is important to point out both sides of the argument—that is, the benefits derived and non-benefits obtained by using these sources.

Nonrenewable Energy

Benefits

- Nonrenewable sources are easy to use.
- A small amount of nuclear energy will produce a large amount of power.
- Nonrenewable energy sources have little competition.
- Nonrenewable energy sources are relatively inexpensive when converting from one type of energy to another.

Non-Benefits

- Nonrenewable sources will expire some day.
- The speed at which such resources are being used can bring about serious environmental changes.
- Nonrenewable sources release toxic gases in the air when burned and can further exacerbate ongoing, cyclical climate change.
- Because nonrenewable sources are becoming scarcer, prices of these sources will begin to soar.

Renewable Energy

Benefits

- Wind, sun, ocean, and geothermal energy are available in abundant quantities and are free to use.
- Renewable sources have low carbon emissions; therefore, they are considered to be environmentally friendly.
- Renewable energy helps stimulate the economy and create job opportunities.
- Renewable energy sources enable the country to become energy independent, not having to rely on foreign (often hostile) sources.

Non-Benefits

- Initial set-up costs of renewable energy sources are quite high.
- Solar energy is limited to daytime availability and cannot be obtained during the night or a rainy season.
- Geothermal energy can bring toxic chemicals from beneath the surface of the earth up to the top and can cause environmental damage.

- Hydroelectric dams are expensive to build and can affect natural flow and wildlife.
- Wind energy production requires high winds and must be sited properly to be effective. Also, wind turbines are tall structures that can affect bird populations.

ENERGY USE IN THE UNITED STATES

Use of energy in the United States is shared by four major sectors of the economy. Each end-use sector consumes electricity produced by the electric power sector (EIA, 2013a):

- *Commercial*—18% (buildings such as offices, malls, stores, schools, hospitals, hotels, warehouses, restaurants, places of worship, and more)
- *Industrial*—32% (facilities and equipment used for manufacturing, agriculture, mining, and construction)
- *Residential*—21% (homes and apartments)
- *Transportation*—28% (vehicles that transport people or goods, such as cars, trucks, buses, motorcycles, trains, subways, aircraft, boats, barges, and even hot-air balloons)

Primary energy consumption in the United States was almost three times greater in 2012 than in 1949. In all but 18 of the years between 1949 and 2012, primary energy consumption increased over the previous year.

The year 2009 provided a sharp contrast to the historical trend, in part due to the economic recession. Real gross domestic product (GDP) fell 2% compared to 2008, and energy consumption declined by nearly 5%, the largest single year decline since 1949. Decreases occurred in all four of the major end-use sectors: commercial (3%), industrial (9%), residential (3%), and transportation (3%) (EIA, 2013a).

MEASURING ENERGY

Energy can be measured. That is, the amount of energy a thing has can be given a number. As in other kinds of measurements, there are measurement units. The units of measurement for measuring energy are used to make the numbers understandable and meaningful. The SI unit for both energy and work is the joule (J). It is named after James Joule, who discovered that heat is a type of energy. In terms of SI units, 1 joule = 1 newton-meter, and 1 joule = 1 $kg{\cdot}m^2{\cdot}s^{-2}$. The energy unit of measurement for electricity is the kilowatt-hour (kWh); 1 kWh is equivalent to 3,600,000 J (3600 kJ or 3.6 MJ). A common way to express energy is in the British thermal unit (Btu) (see Table 2.6). A Btu is the amount of heat energy it takes to raise the temperature of 1 pound of water by 1°F at sea level. MBtu stands for 1 million Btu, which can also be expressed as 1 decatherm (10 therms). The MBtu is occasionally used as a standard unit of measurement for natural gas and provides a

TABLE 2.6
Btu Conversion Factors

Energy Source	Physical Units and Btu (Weighted Averages)
Electricity	1 kilowatt-hour = 3412 Btu
Natural gas	1 cubic foot = 1028 Btu = 0.01 therms
Motor gasoline	1 gallon = 124,000 Btu
Diesel fuel	1 gallon = 139,000 Btu
Heating oil	1 gallon = 139,000 Btu
Propane	1 gallon = 91,333 Btu
Wood	1 cord = 20,000,000 Btu

convenient basis for comparing the energy content of various grades of natural gas and other fuels. One cubic foot of natural gas produces approximately 1000 Btu, so 1000 ft^3 of gas is comparable to 1 MBtu. MBtu is occasionally expressed as MMBtu, which is intended to represent a thousand thousand Btu.

- 1000 joules = 1 Btu
- 1000 joules = 1 kilojoule = 1 Btu
- 1 therm = 100,000 Btu

CLEAN ENERGY PARAMETERS AND CALCULATIONS

Energy is an input fundamental to economic systems (Harris, 2006). Our current economic practice depends overwhelmingly on nonrenewable fossil fuels (90% of our energy supply), including oil, coal, and natural gas. As environmental professionals we are concerned not only with the cost of energy but also with the cost to the environment resulting from the use of nonrenewable energy supplies. Calculations related to the conversion of greenhouse gas emission numbers into different types of equivalent units and other pertinent calculations and conversions are discussed below.

> **Note:** With regard to global warming potentials (GWPs), some of the equivalencies in the calculator are reported as CO_2 equivalents (CO_2e). These are calculated using GWPs from the Intergovernmental Panel on Climate Change's Fourth Assessment report.

ELECTRICITY REDUCTION (KILOWATT-HOURS)

The U.S. Environmental Protection Agency's Greenhouse Gas Equivalencies Calculator uses the Emissions & Generation Resource Integrated Database (eGRID) of U.S. annual non-baseload CO_2 output emission rates to convert reductions of kilowatt-hours into avoided units of carbon dioxide emissions. Most users of the Equivalencies Calculator who seek equivalencies for electricity-related emissions want to know equivalencies for emissions reductions due to energy efficiency or renewable energy programs. These programs are not generally assumed to affect baseload emissions (the emissions from power plants that run all the time), but rather non-baseload generation (power plants that are brought online as necessary to meet demand). For that reason, the Equivalencies Calculator uses a non-baseload emissions rate (USEPA, 2014).

EMISSION FACTOR

$$6.89551 \times 10^{-4} \text{ metric tons } CO_2/\text{kWh}$$

> ***Note:*** This calculation does not include any greenhouse gases other than CO_2, and it does not include line losses. Individual subregion non-baseload emissions rates are also available on the eGRID website. To estimate indirect greenhouse gas emissions from electricity use, use Power Profiler or eGRID subregion annual output emission rates as the default emission factor.

GALLONS OF GASOLINE CONSUMED

To obtain the number of grams of carbon dioxide emitted per gallon of gasoline combusted, the heat content of the fuel per gallon is multiplied by the kg CO_2 per heat content of the fuel. In the preamble to the joint USEPA, Department of Transportation, and National Highway Traffic Safety Administration rulemaking on May 7, 2010, that established the initial National Program fuel economy standards for model years 2012 to 2016, the agencies stated that they had agreed to use a common conversion factor of 8887 grams of CO_2 emissions per gallon of gasoline consumed (OFR, 2010). This value assumes that all the carbon in the gasoline is concerted to CO_2 (IPCC, 2006).

Calculation

8887 grams of CO_2 per gallon of gasoline = 8.887×10^{-3} metric tons CO_2 per gallon of gasoline.

PASSENGER VEHICLES PER YEAR

Passenger vehicles are defined as two-axle, four-tire vehicles, including passenger cars, vans, pickup trucks, and sport/utility vehicles. In 2011, the weighted average combined fuel economy of cars and light trucks was 21.4 miles per gallon (MPG) (FHWA, 2013). The average number of vehicle miles traveled in 2011 was 11,318 miles per year. In 2011, the ratio of carbon dioxide emissions to total greenhouse gas emissions (including carbon dioxide, methane, and nitrous oxide, all expressed as carbon dioxide equivalents) for passenger vehicles was 0.988 (USEPA, 2013a,b). The amount of carbon dioxide emitted per gallon of motor gasoline burned was 8.89×10^{-3} metric tons, as calculated above.

To determine annual greenhouse gas emissions per passenger vehicle, the following methodology was used: The amount of vehicle miles traveled (VMT) was divided by average gas mileage to determine gallons of gasoline consumed per vehicle per year. The number of gallons of gasoline consumed was multiplied by carbon dioxide per gallon of gasoline to determine carbon dioxide emitted per vehicle per year. Carbon dioxide emissions were then divided by the ratio of carbon dioxide emissions to total vehicle greenhouse gas emissions to account for vehicle methane and nitrous oxide emissions.

Calculation

(8.89×10^{-3} metric tons CO_2 per gallon of gasoline) × (11,318 $VMT_{\text{car/truck average}}$) × (1/21.4 $MPG_{\text{car/truck average}}$) × [(1 CO_2, CH_4, and N_2O)/0.988 CO_2] = 4.75 metric tons CO_2e per vehicle per year.

MILES DRIVEN BY THE AVERAGE PASSENGER VEHICLE

Passenger vehicles are defined as two-axle, four-tire vehicles, including passenger cars, vans, pickup trucks, and sport/utility vehicles. In 2011, the weighted average combined fuel economy of cars and light trucks combined was 21.4 miles per gallon (FHWA, 2013). In 2011, the ratio of carbon dioxide emissions to total greenhouse gas emissions (including carbon dioxide, methane, and nitrous oxide, all expressed as carbon dioxide equivalents) for passenger vehicles was 0.988 (USEPA, 2013a,b). The amount of carbon dioxide emitted per gallon of motor gasoline burned is 8.89×10^{-3} metric tons, as calculated earlier. To determine annual greenhouse gas emission per mile, the following methodology was used: Carbon dioxide emissions per gallon of gasoline were divided by the average fuel economy of vehicles to determine carbon dioxide emitted per mile traveled by a typical passenger vehicle per year. Carbon dioxide emissions were then divided by the ratio of carbon dioxide emissions to total vehicle greenhouse gas emissions to account for vehicle methane and nitrous oxide emissions.

Calculation

(8.89×10^{-3} metric tons CO_2 per gallon of gasoline) × 1/21.4 $MPG_{\text{car/truck average}}$ × [(1 CO_2, CH_4, and N_2O)/0.988 CO_2] = 4.20×10^{-4} metric tons CO_2e per mile.

THERMS OF NATURAL GAS

Carbon dioxide emissions per therm are determined by multiplying the heat content times the carbon coefficient times the fraction oxidized times the ratio of the molecular weight of carbon dioxide to that of carbon (C) (44/12). The average heat content of natural gas is 0.1 mmBtu per therm, and the average carbon coefficient of natural gas is 14.47 kg carbon per mmBtu (USEPA, 2013c). The fraction oxidized to CO_2 is 100% (IPCC, 2006).

Note: When using this equivalency, please keep in mind that it represents the CO_2 equivalency for natural gas burned as a fuel, not natural gas released to the atmosphere. Direct methane emissions released to the atmosphere (without burning) are about 21 times more powerful than CO_2 in terms of their warming effect on the atmosphere.

Calculation

(0.1 mmBtu/1 therm) × (14.46 kg C per mmBtu) × (44 g CO_2 per 12 g C) × (1 metric ton/1000 kg) = 0.005302 metric tons CO_2 per therm.

BARRELS OF OIL CONSUMED

Carbon dioxide emissions per barrel of crude oil are determined by multiplying the heat content times the carbon coefficient times the fraction oxidized times the ratio of the molecular weight of carbon dioxide to that of carbon (44/12). The average heat content of crude oil is 5.80 mmBtu per barrel, and the average carbon coefficient of crude oil is 20.31 kg carbon per mmBtu (USEPA, 2013c). The fraction oxidized to CO_2 is 100% (IPCC, 2006).

Calculation

(5.80 mmBtu/barrel) × (20.31 kg C per mmBtu) × (44 g CO_2 per 12 g C) × (1 metric ton/1000 kg) = 0.43 metric tons CO_2 per barrel.

TANKER TRUCKS FILLED WITH GASOLINE

The amount of carbon dioxide emitted per gallon of motor gasoline burned is 8.89×10^{-3} metric tons, as calculated earlier. A barrel equals 42 gallons, and a typical gasoline tanker truck contains 8500 gallons (IPCC, 2006; OFR, 2010).

Calculation

(8.89×10^{-3} metric tons CO_2 per gallon) × (8500 gal per tanker truck) = 75.54 metric tons CO_2 per tanker truck.

NUMBER OF INCANDESCENT BULBS SWITCHED TO COMPACT FLUORESCENT BULBS

A 13-watt compact fluorescent light (CFL) bulb produces the same light output as a 60-watt incandescent light bulb. Annual energy consumed by a light bulb is calculated by multiplying the power (60 watts) by the average daily use (3 hours/day) by the number of days per year (365). Assuming an average daily use of 3 hours per day, an incandescent bulb consumes 65.7 kWh per year, and a compact fluorescent light bulb consumes 14.2 kWh per year (USEPA, 2013d). Annual energy savings from replacing an incandescent light bulb with an equivalent compact fluorescent bulb are calculated by subtracting the annual energy consumption of the compact fluorescent light bulb (14.2 kWh) from the annual energy consumption of the incandescent bulb (65.7 kWh).

Carbon dioxide emissions reduced per light bulb switched from an incandescent bulb to a compact fluorescent bulb are calculated by multiplying the annual energy savings by the national average non-baseload carbon dioxide output rate for delivered electricity. The national average non-baseload carbon dioxide output rate for generated electricity in 2010 was 1519.6 lb CO_2 per megawatt-hour (USEPA, 2014), which translates to about 1637.5 lb CO_2 per megawatt-hour for delivered electricity (assuming transmission and distribution losses at 7.2%) (EIA, 2013b; USEPA, 2014).

Calculation

47 watts × 3 hr/day × 365 days/year × 1 kWh/1000 Wh = 51.5 kWh/year/bulb replaced.
51.5 kWh/bulb/year × 1637.5 lb CO_2 per MWh delivered electricity × 1 MWh/1000 kWh × 1 metric ton/2204.6 lb = 3.82×10^{-2} metric tons CO_2 per bulb replaced.

Fluorescent Lamps and Ballasts*

The Energy Policy Act of 1992, Executive Order 13123, and the Federal Acquisition Regulation, Part 23, Section 704 (48 CFR 23.704), instituted guidelines for federal agencies to purchase energy-efficient products. Lighting accounts for 20 to 25% of the United States' electricity consumption. Retrofitting with automatic controls and energy-efficient fluorescent lamps and ballasts yields paybacks within 2 to 5 years; however, the best reason for retrofitting an old lighting system—increasing the productivity of workers—is often overlooked.

Fluorescent Lighting Nomenclature

The pattern for interpreting fluorescent lamp names is FWWCCT-DD where

F = Fluorescent lamp
WW = Nominal power in watts (4, 5, 8, 12, 15, 20, 33, …)
CC = Color (W, white; CW, cool white; WW, warm white; …)
T = Tubular bulb.
DD = Diameter of the tube in eighths of an inch (T8 bulb has a diameter of 1 inch, T12 bulb has a diameter of 1.5 inches, …)

Thus, an F40CWT-12 lamp, for example, is a 40-watt cool white fluorescent lamp with a 1.5-inch tubular bulb.

Background on Costs

With electricity costing 8 cents per kilowatt hour, a typical 40-watt T12 fluorescent lamp will use $64 worth of electricity over its lifetime. The purchase price of the bulb ($2) accounts for just 3% of the life-cycle costs of owning and operating a lighting system, and energy accounts for 86% of the cost. Thus, the operating cost breakdown for F40T12 fluorescent lamps is energy at 86%, maintenance at 11%, and the lamp itself at 3%. These calculations readily justify the cost of more expensive lamps that produce better quality light, save energy, and increase productivity. The effect of lighting on human performance and productivity is complex. Direct effects of poor lighting include the inability to resolve detail, fatigue, and headaches. Lighting may indirectly affect someone's mood or hormonal balance.

> ***Note:*** The Hawthorne effect is a phenomenon whereby workers improve or modify an aspect of their behavior in response to a change in their lighting environment.

A small change in human performance dwarfs all costs associated with lighting. The typical annual costs of 1 square foot of office space are as follows:

Heating and cooling	$2
Lighting	$0.50
Floor space	$100
Employee salary and benefits	$400

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[*] Adapted from USDA, *Fluorescent Lamp Retrofits: Savings or Fantasy?*, U.S. Department of Agriculture, Washington, DC, 2001 (http://www.fs.fed.us/t-d/pubs/htmlpubs/htm01712310/).

Cutting lighting consumption in half saves about 25¢ per square foot each year. A 1% increase in human productivity would save $4 per square foot each year. Costs will vary from facility to facility, but the relative magnitudes of these costs are not likely to change. The focus needs to be on providing quality lighting to meet occupants' needs; however, it is possible to improve lighting quality while reducing energy costs thanks to improvements in lighting technology.

Best Types of Fluorescent Lamps and Ballasts

The "warmness" of a light is determined by its color temperature, expressed in degrees kelvin (K); the word kelvin is not capitalized. The kelvin scale is an absolute, thermodynamic temperature scale using as its null point absolute zero, the temperature at which all normal thermal motion ceases in the classical description of thermodynamics. The kelvin is defined as the fraction of 1/273.16 of the thermodynamic temperature of the triple point of water (exactly 0.01°C or 32.0018°F). In other words, it is defined such that the triple point of water is exactly 273.16 K.

The higher the correlated color temperature, the cooler the light. Offices should use intermediate or neutral light. This light creates a friendly, yet businesslike environment. Neutral light sources have a correlated color temperature of 3500 K. The color rendition index measures the quality of light. The higher the color rendition index, the better people see for a given amount of light. Currently available 4-foot fluorescent lamps have indexes of 70 to 98. Lamps with different correlated color temperatures and color rendition indexes should not be used in the same space. The correlated color temperature and color rendition index should be specified when ordering lamps.

The best lighting system for each operating dollar is realized with T8 fluorescent lamps that have a color rendition index of 80 or higher. Compared to standard T12 fluorescent lamps, T8 lamps have better balance between the surface area containing the phosphors that fluoresce and the arc stream that excites them. This means that T8 lamps produce more light for a given amount of energy. In Europe, T5 lamps are popular. They are more efficient than T8 lamps but cost more than twice as much. The availability of T5 lamps and fixtures is limited in the United States. T8 lamps are currently preferred.

A quick comparison of light output shows how important it is to specify ballast factor and whether the ballast is electronic or magnetic. Electronic ballasts last twice as long as magnetic ballasts, use less energy, have a lower life-cycle cost, and operate the lamp at much higher frequencies. Operating fluorescent lamps at higher frequencies improves their efficiency and eliminates the characteristic 60-cycle buzz and strobe-lighting effect associated with fluorescent lights. The 60-cycle strobe-lighting effect may case eye fatigue and headaches. Electronic ballasts are especially desirable in shops with rotating equipment. The 60-cycle strobe-lighting effect produced by magnetic ballasts can cause rotating equipment to appear stationary. All new buildings and retrofits should use electronic ballasts.

Fluorescent Lamps and Ballast Life

Most fluorescent lamps have a rated life of 12,000 to 20,000 hours. The rated life is the time it takes for half of the bulbs to fail when they are cycled on for 3 hours and off for 20 minutes. Cycling fluorescent lamps off and on will reduce lamp life. On the other hand, turning a lamp off when it is not needed will reduce its operating hours and increase its useful life. Electricity—not lamps—accounts for the largest percentage of the operating cost of a lighting system. It is economical to turn off fluorescent lights if they are not being used. According to the Certified Ballast Manufacturers Association, the average magnetic ballast lasts about 75,000 hours, or 12 to 15 years, with normal use. The optimum economic life of a fluorescent lighting system with magnetic ballasts is usually about 15 years. At this point, dirt on reflectors and lenses has significantly reduced light output. Other factors may make it desirable to retrofit a lighting system before the end of the 12- to 15-year life cycle. Those factors include increased productivity, utility rebates, and high energy costs.

Economic Analysis

When considering the benefits of retrofitting, more lamps per existing fixture yield more energy savings per fixture and a better payback. Higher than average energy or demand of the initial installation costs or a utility rebate will also produce a faster payback. Ballast factor can be used to adjust light levels. A high ballast factor increases lumens (a measure of light output), allowing fewer lamps to provide the same amount of light. For example, when electronic ballasts with a high ballast factor are used, two-lamp fixtures will produce as much light as three-lamp fixtures. This reduces the cost of the fixtures and improves the payback. An economic analysis of retrofitting three-lamp fixtures and magnetic ballasts with two-lamp fixtures with a high-ballast-factor electronic ballast yields a payback of slightly more than 2 years. With regard to fluorescent lamp retrofit payback, a simple payback (SPB) is the time, in years, it will take for the savings (in present value) to equal the cost of the initial installation (in present value). The following calculations do not account for interest rates.

■ EXAMPLE 2.24

Problem: Compute the SPB using the following formula:

$$\text{SPB} = (\text{Cost of installed equipment} - \text{Deferred maintenance} - \text{Rebates}) \div (\text{Total energy dollar savings per year})$$

The costs to replace a T12 lamp magnetic ballast system with a T8 lamp electronic ballast system are as follows:

- New fixtures (including fixture, two T8 lamps, and electronic ballast) cost \$30 per fixture.
- Installation cost is \$10 per fixture.
- Deferred cost of cleaning existing fixtures is \$5 per fixture.
- The power company offers a one-time \$8 per fixture rebate for replacing magnetic-ballasted T12 lamps with electronic-ballasted T8 lamps.

Solution:

- Total project cost for 100 fixtures = (\$30 + \$10 – \$5 – \$8) × (100 fixtures) = \$2700.
- Total energy dollar savings per year = Lighting energy savings + Cooling savings – Heating costs = \$1459 + \$120 – \$262 = \$1,317 per year.
- SPB = \$2700/(\$1317 per year) = 2.05 years.

It is obvious that retrofitting an existing lighting system that uses F40T12 lamps and magnetic ballasts with F32T8 lamps and electronic ballasts can provide a very attractive payback.

HOME ENERGY USE

In 2012, there were 113.93 million homes in the United States. On average, each home consumed 12,069 kWh of delivered electricity. Nationwide household consumption of natural gas, liquefied petroleum gas, and fuel oil totaled 4.26, 0.51, and 0.51 quadrillion Btu, respectively, in 2012 (EIA, 2013c). Averaged across households in the United States, this amounts to 52,372 cubic feet of natural gas, 70 barrels of liquefied petroleum gas, and 47 barrels of fuel oil per home. The national average carbon dioxide output rate for generated electricity in 2010 was 1232 lb CO_2 per megawatt-hour (USEPA, 2014), which translates to about 1328.0 lb CO_2 per megawatt-hour for delivered electricity (assuming transmission and distribution losses at 7.2%) (EIA, 2013c; USEPA, 2014). The average carbon dioxide coefficient of natural gas is 0.0544 kg CO_2 per cubic foot. The fraction oxidized to CO_2 is 100% (IPCC, 2006). The average carbon dioxide coefficient of distillate fuel oil is 429.61 kg CO_2 per 42-gallon barrel (USEPA, 2013c). The fraction oxidized to CO_2 is 100% (IPCC, 2006).

The average carbon dioxide coefficient of liquefied petroleum gases is 219.3 kg CO_2 per 42-gallon barrel (USEPA, 2011). The fraction oxidized to CO_2 is 100% (IPCC, 2006). Total single-family home electricity, natural gas, distillate fuel oil, and liquefied petroleum gas consumption figures were converted from their various units to metric tons of CO_2 and added together to obtain total CO_2 emissions per home.

Calculation

1. *Electricity*—12,069 kWh per home × (1232.4 lb CO_2 per MWh generated) × 1/(1-0.072) MWh delivered/MWh generated × 1 MWh/1000 kWh × 1 metric ton/2204.6 lb = 7.270 metric tons CO_2 per home.
2. *Natural gas*—52,372 cubic feet per home × 0.0544 kg CO_2 per cubic foot × 1/1000 kg/metric ton = 2.85 metric tons CO_2 per home.
3. *Liquid petroleum gas*—70.4 gallons per home × 1/42 barrels/gallon × 219.3 kg CO_2 per barrel × 1/1000 kg/metric ton = 0.37 metric tons CO_2 per home.
4. *Fuel oil*—47 gallons per home × 1/42 barrels/gallon × 429.61 kg CO_2 per barrel × 1/1000 kg/metric ton = 0.48 metric tons CO_2 per home.

Total CO_2 emissions for energy use per home is equal to 7.270 metric tons CO_2 for electricity + 2.85 metric tons CO_2 for natural gas + 0.37 metric tons CO_2 for liquid petroleum gas + 0.48 metric tons CO_2 for fuel oil = 10.97 metric tons CO_2 per home per year.

NUMBER OF TREE SEEDLINGS GROWN FOR 10 YEARS

A medium-growth coniferous tree, planted in an urban setting and allowed to grow for 10 years, sequesters 23.2 lb of carbon. This estimate is based on the following assumptions:

- Medium-growth coniferous trees are raised in a nursery for 1 year until they become 1 inch in diameter at 4.5 feet above the ground (the size of tree purchased in a 15-gallon container).
- The nursery-grown trees are then planted in a suburban/urban setting; the trees are not densely planted.
- The calculation takes into account "survival factors" developed by the U.S. Department of Energy (USDOE, 1998). For example, after 5 years (1 year in the nursery and 4 in the urban setting), the probability of survival is 68%; after 10 years, the probability declines to 59%. For each year, the sequestration rate (in pounds per tree) is multiplied by the survival factor to yield a probability-weighted sequestration rate. These values are summed over the 10-year period, beginning from the time of planting, to derive the estimate of 23.2 lb of carbon per tree.

Please note the following caveats to these assumptions:

- Although most trees take 1 year in a nursery to reach the seedling stage, trees grown under different conditions and trees of certain species may take longer—up to 6 years.
- Average survival rates in urban areas are based on broad assumptions, and the rates will vary significantly depending on site conditions.
- Carbon sequestration depends on growth rate, which varies by location and other conditions.
- This method estimates only direct sequestration of carbon and does not include the energy savings that result from buildings being shaded by urban tree cover.

To convert to units of metric tons CO_2 per tree, multiply by the ratio of the molecular weight of carbon dioxide to that of carbon (44/12) and the ratio of metric tons per pound (1/2204.6).

Calculation

(23.2 lb C per tree) × (44 units CO_2 ÷ 12 units C) × (1 metric ton ÷ 2204.6 lb) = 0.039 metric ton CO_2 per urban tree planted.

ACRES OF U.S. FORESTS STORING CARBON FOR ONE YEAR

Growing forests accumulate and store carbon. Through the process of photosynthesis, trees remove CO_2 from the atmosphere and store it as cellulose, lignin, and other compounds. The rate of accumulation is equal to growth minus removals (i.e., harvest for the production of paper and wood) minus decomposition. In most U.S. forests, growth exceeds removals and decomposition, so the amount of carbon stored nationally is increasing overall.

Data for U.S. Forests

The *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2010* (USEPA, 2012) provides data on the net greenhouse gas flux resulting from the use and changes in forest land areas. Note that the term *flux* is used here to encompass both emission of greenhouse gases to the atmosphere and removal of carbon from the atmosphere. Removal of carbon from the atmosphere is also referred to as *carbon sequestration*. Forest land in the United States includes land that is at least 10% stocked with trees of any size, or, in the case of stands dominated by certain western woodland species for which stocking parameters are not available, at least 5% crown cover by trees of any size. Timberland is defined as unreserved productive forest land producing or capable of producing crops of industrial wood. Productivity is at a minimum rate of 20 ft^3 of industrial wood per acre per year. The remaining portion of forest land is classified as "reserved forest land," which is forest withdrawn from timber use by statute or regulation, or "other forest land," which includes forests on which timber is growing at a rate less than 20 ft^3 per acre per year (Smith et al., 2010).

Calculation

Annual net change in carbon stocks per year in year n = (Carbon $\text{stocks}_{(t+1)}$ – Carbon stocks_t) ÷ Area of land remaining in the same land-use category.

1. Determine the carbon stock change between years by subtracting carbon stocks in year t from carbon stocks in year (t + 1). (This includes carbon stocks in the above-ground biomass, below-ground biomass, dead wood, litter, and soil organic carbon pools.)
2. Determine the annual net change in carbon stocks (i.e., sequestration) per area by dividing the carbon stock change in U.S. forests from step 1 by the total area of U.S. forests remaining in forests in year (n + 1) (i.e., the area of land that did not change land-use categories between the time periods).

Applying these calculations to data developed by the USDA Forest Service for the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* yields a result of 150 metric tons of carbon per hectare (or 61 metric tons of carbon per acre) for the carbon stock density of U.S forests in 2010, with an annual net change in carbon stock per area in 2010 of 0.82 metric tons of carbon sequestered per hectare per year (or 0.33 metric tons of carbon sequestered per acre per year). These values include carbon in the five forest pools of above-ground biomass, below-ground biomass, deadwood, litter, and soil organic carbon, and they are based on state-level Forest Inventory and Analysis (FIA) data. Forest carbon stocks and carbon stock change are based on the stock difference methodology and algorithms described by Smith et al. (2010).

CONVERSION FACTOR FOR CARBON SEQUESTERED ANNUALLY BY ONE ACRE OF AVERAGE U.S. FOREST

The following calculation is an estimate for "average" U.S. forests in 2010 (i.e., for U.S. forests as a whole in 2010). Significant geographical variations underlie the national estimates, and the values calculated here might not be representative of individual regions of states. To estimate carbon sequestered for additional acres in one year, simply multiply the number of acres by 1.22 metric tons CO_2 per acre per year. From 2000 to 2010, the average annual sequestration per area was 0.73 metric tons carbon per hectare per year (or 0.30 metric tons carbon per acre per year) in the United States, with a minimum value of 0.36 metric tons carbon per hectare per year (or 0.15 metric tons carbon per acre per year) in 2000, and a maximum value of 0.83 metric tons carbon per hectare per year (or 0.34 metric tons carbon per acre per year) in 2006.

Calculation

(–0.33 metric ton C per acre per year) × (44 units CO_2 ÷ 12 units C) = –1.22 metric tons CO_2 sequestered annually by one acre of average U.S. forest.

ACRES OF U.S. FOREST PRESERVED FROM CONVERSION TO CROPLANDS

The carbon stock density of U.S. forests in 2010 was 150 metric tons of carbon per hectare (or 61 metric tons of carbon per acre) (USEPA, 2012). This estimate is composed of the five carbon pools of above-ground biomass (52 metric tons carbon per hectare), below-ground biomass (10 metric tons carbon per hectare), dead wood (9 metric tons carbon per hectare), litter (17 metric tons carbon per hectare), and soil organic carbons (62 metric tons carbon per hectare).

The *Inventory of U.S. Greenhouse Gas Emissions and Sinks* estimates soil carbon stock changes using U.S.-specific equations and data from the USDA Natural Resource Inventory and the CENTURY biogeochemical model (USEPA, 2012). When calculating carbon stock changes in biomass due to conversion from forestland to cropland, the IPCC (2006) guidelines indicate that the average carbon stock change is equal to the carbon stock change due to removal of biomass from the outgoing land use (i.e., forestland) plus the carbon stocks from one year of growth in the incoming land use (i.e., cropland), or the carbon in biomass immediately after the conversion minus the carbon in biomass prior to the conversion plus the carbon stocks from one year of growth in the incoming land use (i.e., cropland). The carbon stock in annual cropland biomass after 1 year is 5 metric tons carbon per hectare, and the carbon content of dry above-ground biomass is 45% (IPCC, 2006). Therefore, the carbon stock in cropland after 1 year of growth is estimated to be 2.25 metric tons carbon per hectare (or 0.91 metric tons carbon per acre).

The averaged reference soil carbon stock (for high-activity clay, low-activity clay, and sandy soils for all climate regions in the United States) is 40.83 metric tons carbon per hectare (USEPA, 2012). Carbon stock change in soils is time dependent, with a default time period for transition between equilibrium soil organ carbon values of 20 years for mineral soils in cropland systems (IPCC, 2006). Consequently, it is assumed that the change in equilibrium mineral soil organic carbon will be annualized over 20 years to represent the annual flux. The IPCC (2006) guidelines indicate that there are insufficient data to provide a default approach or parameters to estimate carbon stock change from dead organic matter pools or below-ground carbon stocks in perennial cropland.

Calculation

- *Annual change in biomass carbon stocks on land converted to other land-use category:*

$$\Delta C_B = \Delta C_G + C_{Conversion} - \Delta C_L$$

where

ΔC_B = Annual change in carbon stocks in biomass due to growth on land converted to another land-use category.

ΔC_G = Annual increase in carbon stocks in biomass due to growth on land converted to another land-use category (i.e., 2.25 metric tons C per hectare).

$C_{Conversion}$ = Initial change in carbon stocks in biomass on land converted to another land-use category; the sum of the carbon stocks in above-ground, below-ground, deadwood, and litter biomass (–88.47 metric tons C per hectare). Immediately after conversion from forestland to cropland, biomass is assumed to be zero, as the land is cleared of all vegetation before planting crops.

ΔC_L = Annual decrease in biomass stocks due to losses from harvesting, fuel wood gathering, and disturbances on land converted to other land-use category (assumed to be zero).

Thus, $\Delta C_B = \Delta C_G + C_{Conversion} - \Delta C_L = -86.22$ metric tons carbon per hectare per year of biomass carbon stocks are lost when forestland is converted to cropland.

- *Annual change in organic carbon stocks in mineral soils:*

$$\Delta C_{Mineral} = (SOC_O - SOC_{(O-T)}) \div D$$

where

$\Delta C_{Mineral}$ = Annual change in carbon stocks in mineral soils.

SOC_O = Soil organic carbon stock in last year of inventory time period (i.e., 40.83 mt C per hectare).

$SOC_{(O-T)}$ = Solid organic carbon stock at beginning of inventory time period (i.e., 62 mt carbon per hectare).

D = Time dependence of stock change factors which is the default time period for transition between equilibrium SOC values (i.e., 20 years for cropland systems).

Therefore, $\Delta C_{Mineral} (SOC_O - SOC_{(O-T)}) \div D = (40.83 - 62) \div 20 = -1.06$ metric tons carbon per hectare per year of soil organic carbon are lost.

Consequently, the change in carbon density from converting forestland to cropland would be –86.22 metric tons of carbon per hectare per year of biomass plus –1.06 metric tons carbon per hectare per year of soil organic carbon, or a total loss of 87.28 metric tons carbon per hectare per year (or –35.32 metric tons carbon per acre per year).

To convert to carbon dioxide, multiply by the ratio of the molecular weight of carbon dioxide to that of carbon (44/12), to yield a value of –320.01 metric tons CO_2 per hectare per year (or –129.51 metric tons CO_2 per acre per year).

$$(-35.32 \text{ metric tons C per acre per year}) \times (44 \text{ units } CO_2 \div 12 \text{ units C})$$
$$= -129.51 \text{ metric tons } CO_2 \text{ per acre per year}$$

To estimate the amount of carbon dioxide not emitted when an acre of forest is preserved from conversion to cropland, simply multiply the number of acres of forest not converted by –129.51 mt CO_2e per acre per year. Note that this calculation method assumes that all of the forest biomass is oxidized during clearing; that is, none of the burned biomass remains as charcoal or ash. Also note that this estimate only includes mineral soil carbon stocks, as most forests in the contiguous United States are growing on mineral soils. In the case of mineral soil forests, soil carbon stocks could be replenished or even increased, depending on the starting stocks, how the agricultural lands are managed, and the time frame over which the lands are managed.

PROPANE CYLINDERS USED FOR HOME BARBECUES

Propane is 81.7% carbon, and the fraction oxidized is 100% (IPCC, 2006; USEPA, 2013c). Carbon dioxide emissions per pound of propane were determined by multiplying the weight of propane in a cylinder times the carbon content percentage times the fraction oxidized times the ratio of the molecular weight of carbon dioxide to that of carbon (44/12). Propane cylinders vary with respect to size; for the purpose of this equivalency calculation, a typical cylinder for home use was assumed to contain 18 pounds of propane.

Calculation

(18 lb propane per cylinder) × (0.817 lb C per lb propane) × (0.4536 kg/lb) × (44 kg CO_2 per 12 kg C) × (1 metric ton/1000 kg) = 0.024 metric tons CO_2 per cylinder.

RAILCARS OF COAL BURNED

The average heat content of coal consumed in the United States in 2013 was 21.48 mmBtu per metric ton (EIA, 2014). The average carbon coefficient of coal combusted for electricity generation in 2012 was 26.05 kg carbon per mmBtu (USEPA, 2013c). The fraction oxidized is 100% (IPCC, 2006). Carbon dioxide emissions per ton of coal were determined by multiplying the heat content times the carbon coefficient times the fraction oxidized times the ratio of the molecular weight of carbon dioxide to that of carbon (44/12). The amount of coal in an average railcar was assumed to be 100.19 short tons, or 90.89 metric tons (Hancock and Sreekanth, 2001).

Calculation

(21.48 mmBtu/metric ton coal) × (26.05 kg C per mmBtu) × (44 g CO_2 per 12 g C) × (90.89 metric tons coal per railcar) × (1 metric ton/1000 kg) = 186.50 metric tons CO_2 per railcar.

POUNDS OF COAL BURNED

The average heat content of coal consumed in the United States in 2013 was 21.48 mmBtu per metric ton (EIA, 2014). The average carbon coefficient of coal combusted for electricity generation in 2012 was 26.05 kg carbon per mmBtu (USEPA, 2013c). The fraction oxidized is 100% (IPCC, 2006). Carbon dioxide emissions per pound of coal were determined by multiplying the heat content times the carbon coefficient times that fraction oxidized times the ratio of the molecular weight of carbon dioxide to that of carbon (44/12).

Calculations

(21.48 mmBtu/metric ton coal) × (26.05 kg C per mmBtu) × (44 g CO_2 per 12g C) × (1 metric ton coal per 2204.6 lb coal) × (1 metric ton/1000 kg) = 9.31×10^{-4} metric tons CO_2 per pound of coal.

TONS OF WASTE RECYCLED INSTEAD OF LANDFILLED

To develop the conversion factor for recycling rather than landfilling waste, emission factors from the USEPA's Waste Reduction Model (WARM) were used (USEPA, 2013e). These emission factors were developed following a life-cycle assessment methodology using estimation techniques developed for national inventories of greenhouse gas emissions. According to WARM, the net emission reduction from recycling mixed recyclables (e.g., paper, metals, plastics), compared with a baseline in which the materials are landfilled, is 0.73 metric tons of carbon equivalent per short ton. This factor was then converted to metric tons of carbon dioxide equivalent by multiplying by 44/12, the molecular weight ratio of carbon dioxide to carbon.

Calculation

(0.76 metric tons of carbon equivalent per ton) × (44 g CO_2 per 12 g C) = 2.79 metric tons CO_2 equivalent per ton of waste recycled instead of landfilled.

Garbage Trucks of Waste Recycled Instead of Landfilled

The carbon dioxide equivalent emissions avoided from recycling instead of landfilling 1 ton of waste are 2.67 metric tons CO_2e per ton, as calculated in the previous section. Carbon dioxide emissions reduced per garbage truck full of waste were determined by multiplying emissions avoided from recycling instead of landfilling 1 ton of waste by the amount of waste in an average garbage truck. The amount of waste in an average garbage truck was assumed to be 7 tons (USEPA, 2002, 2013).

Calculation

(2.79 metric tons CO_2e/ton of waste recycled instead of landfilled) × (7 tons/garbage truck) = 19.51 metric tons CO_2e per garbage truck of waste recycled instead of landfilled.

Coal-Fired Power Plant Emissions for One Year

In 2010, a total of 454 power plants used coal to generate at least 95% of their electricity (USEPA, 2014). These plants emitted 1,729,127,770.8 metric tons of CO_2 in 2010. Carbon dioxide emissions per power plant were calculated by dividing the total emissions from power plants whose primary source of fuel was coal by the number of power plants.

Calculation

(1,729,127,770.8 metric tons of CO_2) × (1/454 power plants) = 3,808,651 metric tons CO_2 per coal-fired power plant.

Wind Turbines Installed

In 2012, the average nameplate capacity of wind turbines installed in the United States was 1.94 MW, and the average wind capacity factor in the United States was 31% (USDOE, 2013). Electricity generation from an average wind turbine can be determined by multiplying the average nameplate capacity of a wind turbine in the United States (1.94 MW) by the average U.S. wind capacity factor (0.31) and by the number of hours per year. It is assumed that the electricity generated from an installed wind turbine would replace marginal sources of grid electricity. The U.S. annual non-baseload CO_2 output emission rate to convert reductions of kilowatt-hours into avoided units of carbon dioxide emissions is 6.89551×10^{-4}. Carbon dioxide emissions avoided per wind turbine installed are determined by multiplying the average electricity generated per wind turbine in a year by the national average non-baseload grid electricity CO_2 output rate (USEPA, 2012).

Calculations

(1.94 MW average capacity) × (0.31) × (8760 hours/year) × (1000 kWh/MWh) × (6.89551×10^{-4} metric tons CO_2 per kWh reduced) = 3633 metric tons CO_2 per wind turbine installed.

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3 Math Operations Review

> Note everything that counts can be counted, and not everything that can be counted counts.
>
> **—Albert Einstein**

INTRODUCTION

Most calculations required by environmental engineers require a knowledge of the basics, such as addition, subtraction, multiplication, division, and sequence of operations, among others. Although many of these operations are fundamental tools within each environmental practitioner's toolbox, these tools must be used on a consistent basis to remain sharp. Environmental practitioners should master basic math definitions and the formation of problems, as daily operations require calculation of percentages, averages, simple ratios, geometric dimensions, threshold odor numbers, and force, pressure, and head, as well as the use of dimensional analysis and advanced math operations. With regard to advanced math operations, an in-depth knowledge of algebra, linear algebra, vectors, trigonometry, analytic geometry, differential calculus, integral calculus, and differential equations is required in certain environmental engineering design and analysis operations; however, we leave discussion of these higher operations to the math textbooks.

BASIC MATH TERMINOLOGY AND DEFINITIONS

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

- An *integer*, or an *integral number*, is a whole number; thus, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12 are the first 12 positive integers.
- A *factor*, or *divisor*, of a whole number is any other whole number that exactly divides it; thus, 2 and 5 are factors of 10.
- A *prime number* in math is a number that has no factors except itself and 1; examples of prime numbers are 1, 3, 5, 7, and 11.
- A *composite number* is a number that has factors other than itself and 1. Examples of composite numbers are 4, 6, 8, 9, and 12.
- A *common factor*, or *common divisor*, of two or more numbers is a factor that will exactly divide each of them. If this factor is the largest factor possible, it is called the *greatest common divisor*. Thus, 3 is a common divisor of 9 and 27, but 9 is the greatest common divisor of 9 and 27.
- A *multiple* of a given number is a number that is exactly divisible by the given number. If a number is exactly divisible by two or more other numbers, it is a common multiple of them. The least (smallest) such number is called the *lowest common multiple*. Thus, 36 and 72 are common multiples of 12, 9, and 4; however, 36 is the lowest common multiple.
- An *even number* is a number exactly divisible by 2; thus, 2, 4, 6, 8, 10, and 12 are even integers.
- An *odd number* is an integer that is not exactly divisible by 2; thus, 1,3, 5, 7, 9, and 11 are odd integers.
- A *product* is the result of multiplying two or more numbers together; thus, 25 is the product of 5 × 5. Also, 4 and 5 are factors of 20.

- A *quotient* is the result of dividing one number by another; for example, 5 is the quotient of 20 ÷ 4.
- A *dividend* is a number to be divided; a *divisor* is a number that divides; for example, in 100 ÷ 20 = 5, 100 is the dividend, 20 is the divisor, and 5 is the quotient.
- *Area* is the area of an object, measured in square units.
- *Base* is a term used to identify the bottom leg of a triangle, measured in linear units.
- *Circumference* is the distance around an object, measured in linear units. When determined for other than circles, it may be called the *perimeter* of the figure, object, or landscape.
- *Cubic units* are measurements used to express volume (cubic feet, cubic meters, etc.).
- *Depth* is the vertical distance from the bottom of the tank to the top. This is normally measured in terms of liquid depth and given in terms of sidewall depth (SWD), measured in linear units.
- *Diameter* is the distance from one edge of a circle to the opposite edge passing through the center, measured in linear units.
- *Height* is the vertical distance from the base or bottom of a unit to the top or surface.
- *Linear units* are measurements used to express distances: feet, inches, meters, yards, etc.
- *Pi* (π) is a number in calculations involving circles, spheres, or cones ($\pi = 3.14$).
- *Radius* is the distance from the center of a circle to the edge, measured in linear units.
- *Sphere* is a container shaped like a ball.
- *Square units* are measurements used to express area, square feet, square meters, acres, etc.
- *Volume* is the capacity of the unit (how much it will hold), measured in cubic units (cubic feet, cubic meters) or in liquid volume units (gallons, liters, million gallons).
- *Width* is the distance from one side of the tank to the other, measured in linear units.

KEY WORDS

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

SEQUENCE OF OPERATIONS

Mathematical operations such as addition, subtraction, multiplication, and division are usually performed in a certain order or sequence. Typically, multiplication and division operations are done prior to addition and subtraction operations. In addition, mathematical operations are also generally performed from left to right using this hierarchy. The use of parentheses is also common to set apart operations that should be performed in a particular sequence. Consider the expression $2 + 3 \times 4$. You might say the solution is 20 but if you know the rules then you would answer (correctly) 24. The preceding expression may be rendered $2 + (3 \times 4)$, but the brackets are unnecessary if you know the rules, as multiplication has precedence even without the parentheses.

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

SEQUENCE OF OPERATIONS RULES

Rule 1

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

Rule 2

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

Rule 3

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

Rule 4

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

Rule 5

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

Rule 6

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

SEQUENCE OF OPERATIONS EXAMPLES

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

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

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

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

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

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

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

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

or by steps:

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

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

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

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

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

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

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

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

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

Consider the following classic example of sequence of operations (Stapel, 2012):

Problem: Simplify $4 - 3[4 - 2(6 - 3)] \div 2$.

Solution:

$$4 - 3\,[4 - 2(6 - 3)] \div 2$$

$$4 - 3[4 - 2(3)] \div 2$$

$$4 - 3[4 - 6] \div 2$$

$$4 - 3[-2] \div 2$$

$$4 + 6 \div 2$$

$$4 + 3 = 7$$

PERCENT

The word "percent" means "by the hundred." Percentage is usually designated by the symbol %; thus, 15% means 15 percent or 15/100 or 0.15. These equivalents may be written in the reverse order: 0.15 = 15/100 = 15%. In wastewater treatment, percent is frequently used to express plant performance and for control of biosolids treatment processes. When working with percent, the following key points are important:

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

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

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

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

- When using percentages in calculations (such as when calculating hypochlorite dosages and when the percent available chlorine must be considered), the percentage must be converted to an equivalent decimal number; this is accomplished by dividing the percentage by 100. For example, calcium hypochlorite (HTH) contains 65% available chlorine. What is the decimal equivalent of 65%? Because 65% means 65 per hundred, divide 65 by 100: 65/100, which is 0.65.

- Decimals and fractions can be converted to percentages. The fraction is first converted to a decimal, then the decimal is multiplied by 100 to get the percentage. For example, if a 50-foot-high water tank has 26 feet of water in it, how full is the tank in terms of the percentage of its capacity?

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

$$0.52 \times 100 = 52$$

Thus, the tank is 52% full.

■ EXAMPLE 3.1

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

Solution:

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

■ EXAMPLE 3.2

Problem: Convert 48% to decimal percent.

Solution:

$$\text{Decimal percent} = \frac{\text{Percent}}{100} = \frac{48}{100} = 0.48$$

■ EXAMPLE 3.3

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

Solution:

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

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

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

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

■ EXAMPLE 3.4

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

Solution:

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

■ EXAMPLE 3.5

Problem: Convert 0.55 to percent.

Solution:

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

(To convert 0.55 to 55%, we multiply by 100, or simply move the decimal point two places to the right.)

■ EXAMPLE 3.6

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

Solution:

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

■ EXAMPLE 3.7

Problem: What is the percentage of 3 ppm?

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

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

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

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

■ EXAMPLE 3.8

Problem: How many mg/L is a 1.4% solution?

Solution:

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

■ EXAMPLE 3.9

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

Solution: Because 1 gal of water = 8.34 lb,

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

■ EXAMPLE 3.10

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

Solution: Let x be the weight of AC; thus,

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

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

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

■ EXAMPLE 3.11

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

Solution:

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

■ EXAMPLE 3.12

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

Solution:

$$\text{Efficiency} = \frac{\text{hp output}}{\text{hp input}} \times 100\% = \frac{26.5 \text{ hp}}{40 \text{ hp}} \times 100\% = 66\%$$

SIGNIFICANT DIGITS

When rounding numbers, the following key points are important:

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

■ EXAMPLE 3.13

Problem: Round off the following numbers to one decimal.

Solution:

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

RULE

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

■ EXAMPLE 3.14

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

Solution:

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

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

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

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

■ EXAMPLE 3.15

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

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

■ EXAMPLE 3.16

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

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

■ EXAMPLE 3.17

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

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

■ EXAMPLE 3.18

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

Solution: There are six significant figures: 2, 7, 0, 0, 0, 0. In this case, the .0 in 27,000.0 means that the measurement is precise to 1/10 unit. The zeros indicate measured values and are not used solely to place the decimal point.

POWERS AND EXPONENTS

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

- *Powers* are used to identify *area*, as in square feet, and *volume*, as in cubic feet.
- Powers can also be used to indicate that a number should be squared, cubed, etc. This later designation is the number of times a number must be multiplied times itself.

- If all of the factors are alike, such as $4 \times 4 \times 4 \times 4 = 256$, the product is called a *power.* Thus, 256 is a power of 4, and 4 is the *base* of the power. A power is a *product* obtained by using a base a certain number of times as a factor.
- Instead of writing $4 \times 4 \times 4 \times 4$, it is more convenient to use an *exponent* to indicate that the factor 4 is used as a factor four times. This exponent, a small number placed above and to the right of the base number, indicates how many times the base is to be used as a factor. Using this system of notation, the multiplication $4 \times 4 \times 4 \times 4$ is written as 4^4. The ^{4} is the exponent, showing that 4 is to be used as a factor 4 times.
- These same consideration apply to letters (*a*, *b*, *x*, *y*, etc.) as well; for example:

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

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

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

■ EXAMPLE 3.19

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

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

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

■ EXAMPLE 3.20

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

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

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

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

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

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

Another example is

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

POWERS OF 1	POWERS OF 10
$1^0 = 1$	$10^0 = 1$
$1^1 = 1$	$10^1 = 10$
$1^2 = 1$	$10^2 = 100$
$1^3 = 1$	$10^3 = 1000$
$1^4 = 1$	$10^4 = 10,000$

■ EXAMPLE 3.21

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

Solution:

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

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

AVERAGES (ARITHMETIC MEAN)

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

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

■ EXAMPLE 3.22

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

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

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

$$7.8 \div 7 = 1.11$$

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

DEFINITION

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

■ EXAMPLE 3.23

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

Solution:

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

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

■ EXAMPLE 3.24

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

Solution: The mean capacity of the storage tanks is

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

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

Notice that no tank in Example 2.24 has a capacity anywhere close to the mean.

■ EXAMPLE 3.25

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

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

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

Solution:

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

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

■ EXAMPLE 3.26

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

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

What is the average SS?

Solution:

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

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

RATIO

A ratio is the established relationship between two numbers; it is simply one number divided by another number. For example, if someone says, "I'll give you four to one the Redskins over the Cowboys in the Super Bowl," what does that person mean? Four to one, or 4:1, is a ratio. If someone gives you four to one, it's his or her $4 to your $1. As another more pertinent example, if an average of 3 cubic feet (ft^3) of screenings are removed from each million gallons (MG) of wastewater treated, the ratio of screenings removed to treated wastewater is 3:1. Ratios are normally written using a colon (such as 2:1) or as a fraction (such as 2/1). When working with ratios, the following key points are important to remember.

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

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

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

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

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

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

Cross-multiplying,

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

Transposing,

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

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

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

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

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

■ EXAMPLE 3.27

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

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

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

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

■ EXAMPLE 3.28

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

Solution:

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

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

■ EXAMPLE 3.29

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

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

Solution:

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

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

■ EXAMPLE 3.30

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

Solution:

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

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

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

■ EXAMPLE 3.31

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

Solution:

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

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

■ EXAMPLE 3.32

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

Solution:

$$\frac{F}{M} = \frac{\text{Amount of BOD}}{\text{Amount of VSS}} = \frac{250\text{ mg/L} \times 7.2\text{ L}}{1900\text{ mg/L} \times 1.6\text{ L}} = \frac{0.59}{1} = 0.59$$

DIMENSIONAL ANALYSIS

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

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

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

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

BASIC OPERATION: DIVISION OF UNITS

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

Horizontal to vertical

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

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

The same procedures are applied in the following examples.

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

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

BASIC OPERATION: DIVIDE BY A FRACTION

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

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

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

Another example is

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

BASIC OPERATION: CANCEL OR DIVIDE NUMERATORS AND DENOMINATORS

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

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

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

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

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

Question: How do we calculate units that include exponents?

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

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

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

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

Multiply the numerator and denominator to obtain

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

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

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

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

Multiply the numerator and denominator to obtain

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

and cancel common terms to obtain

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

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

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

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

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

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

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

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

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

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

Let's try division of the two dimensions instead:

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

Invert the denominator and multiply to get

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

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

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

■ EXAMPLE 3.33

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

Solution:

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

Multiply the numerators and denominator of the fraction:

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

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

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

■ EXAMPLE 3.34

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

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

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

Dimensional analysis can be used to check the math setup:

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

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

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

■ EXAMPLE 3.35

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

Solution:

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

■ EXAMPLE 3.36

Problem: One million gallons per day equals how many cubic feet per second (cfs)?

Solution:

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

■ EXAMPLE 3.37

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

Solution:

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

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

■ EXAMPLE 3.38

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

Solution:

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

THRESHOLD ODOR NUMBER

The environmental practitioner responsible for water supplies soon discovers that taste and odor are the most common customer complaints. Odor is typically measured and expressed in terms of a *threshold odor number* (TON), the ratio by which the sample has to be diluted with odor-free water for the odor to become virtually unnoticeable. In 1989, the USEPA issued a Secondary Maximum Contaminant Level (SMCL) of 3 TON for odor.

Note: Secondary Maximum Contaminant Levels are parameters not related to health.

When a dilution is used, a number can be devised in clarifying odor.

$$\text{TON (threshold odor number)} = \frac{V_T + V_P}{V_T} \tag{3.3}$$

where

V_T = Volume tested

V_P = Volume of dilution with odor-free distilled water

For $V_P = 0$, TON = 1 (lowest value possible)

For $V_P = V_T$, TON = 2

For $V_P = 2V_T$, TON = 3

$\vdots$

■ EXAMPLE 3.39

Problem: The first detectable odor is observed when a 50-mL sample is diluted to 200 mL with odor-free water. What is the TON of the water sample?

Solution:

$$\text{TON} = \frac{200}{V_T} = \frac{200 \text{ mL}}{50 \text{ mL}} = 4$$

GEOMETRICAL MEASUREMENTS

Environmental engineers involved in fisheries, water/wastewater treatment plants, and other operations dealing with tanks, basins, and ponds operations must know the area and volume of all tanks, basins, and ponds they deal with. For example, in water and wastewater treatment plant operations, the plant configuration usually consists of a series of tanks and channels. Proper design and operational control requires engineers and operators to perform several process control calculations. Many of these calculations include parameters such as the circumference or perimeter, area, or volume of the tank or channel as part of the information necessary to determine the result. Many process calculations require computation of surface areas. Moreover, in fisheries operations, exact measurements of area and volume are essential to calculate stocking rates and chemical applications. Stocking fish in a pond of uncertain area can result in poor production, disease, and possibly death. Chemical treatments can be ineffective if the volume or area is underestimated and can be potentially lethal if they are overestimated (Masser and Jensen, 1991). To aid in performing these calculations, the following definitions and relevant equations used to calculate areas and volumes for several geometric shapes are provided.

DEFINITIONS

Area—The area of an object, measured in square units.
Base—The term used to identity the bottom leg of a triangle, measured in linear units.
Circumference—The distance around an object, measured in linear units. When determined for other than circles, it may be called the *perimeter* of the figure, object, or landscape.
Cubic units—Measurements used to express volume (cubic feet, cubic meters, etc.).
Depth—The vertical distance from the bottom the tank to the top. It is normally measured in terms of liquid depth and given in terms of *sidewall depth* (SWD), measured in linear units.
Diameter—The distance, measured in linear units, from one edge of a circle to the opposite edge passing through the center.
Height—The vertical distance, measured in linear units, from one end of an object to the other.
Length—The distance, measured in linear units, from one end of an object to the other.
Linear units—Measurements used to express distance (e.g., feet, inches, meters, yards).
Pi (π)—A number in the calculations involving circles, spheres, or cones ($\pi = 3.14$).
Radius—The distance, measured in linear units, from the center of a circle to the edge.
Sphere—A container shaped like a ball.
Square units—Measurements used to express area (e.g., square feet, square meters, acres).
Volume—The capacity of a unit (how much it will hold), measured in cubic units (e.g., cubic feet, cubic meters) or in liquid volume units (e.g., gallons, liters, million gallons).
Width—The distance from one side of the tank to the other, measured in linear units.

RELEVANT GEOMETRIC EQUATIONS

Circumference C of a circle: $C = \pi d = 2\pi r$
Perimeter P of a square with side a: $P = 4a$
Perimeter P of a rectangle with sides a and b: $P = 2a + 2b$
Perimeter P of a triangle with sides a, b, and c: $P = a + b + c$
Area A of a circle with radius r ($d = 2r$): $A = \pi d^2/4 = \pi r^2$
Area A of duct in square feet when d is in inches: $A = 0.005454d^2$
Area A of a triangle with base b and height h: $A = 0.5bh$
Area A of a square with sides a: $A = a^2$
Area A of a rectangle with sides a and b: $A = ab$
Area A of an ellipse with major axis a and minor axis b: $A = \pi ab$
Area A of a trapezoid with parallel sides a and b and height h: $A = 0.5(a + b)h$
Area A of a duct in square feet when d is in inches: $A = \pi d^2/576 = 0.005454d^2$
Volume V of a sphere with a radius r ($d = 2r$): $V = 1.33\pi r^3 = 0.1667\pi d^3$
Volume V of a cube with sides a: $V = a^3$

Volume V of a rectangular solid (sides a and b and height c):	$V = abc$
Volume V of a cylinder with a radius r and height H:	$V = \pi r^2 h = \pi d^2 h/4$
Volume V of a pyramid:	$V = 0.33$

GEOMETRICAL CALCULATIONS

Perimeter and Circumference

On occasion, it may be necessary to determine the distance around grounds or landscapes. To measure the distance around property, buildings, and basin-like structures, either the perimeter or circumference must be determined. The *perimeter* is the distance around an object; a border or outer boundary. *Circumference* is the distance around a circle or circular object, such as a clarifier. Distance is a linear measurement that defines the distance (or length) along a line. Standard units of measurement such as inches, feet, yards, and miles and metric units such as centimeters, meters, and kilometers are used.

The perimeter (P) of a rectangle (a four-sided figure with four right angles) is obtained by adding the lengths (L_i) of the four sides (see Figure 3.1):

$$\text{Perimeter} = L_1 + L_2 + L_3 + L_4 \tag{3.4}$$

■ EXAMPLE 3.40

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

Solution:

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

■ EXAMPLE 3.41

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

Solution:

$$P = (2 \times \text{length}) + (2 \times \text{width}) = (2 \times 100\text{ ft}) + (2 \times 50\text{ ft}) = 200\text{ ft} + 100\text{ ft} = 300\text{ ft}$$

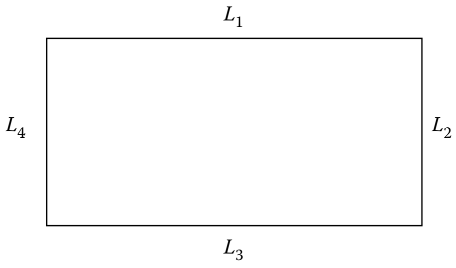

FIGURE 3.1 Perimeter.

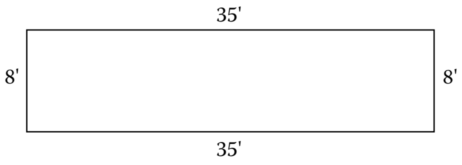

FIGURE 3.2 Perimeter of a rectangle for Example 3.40.

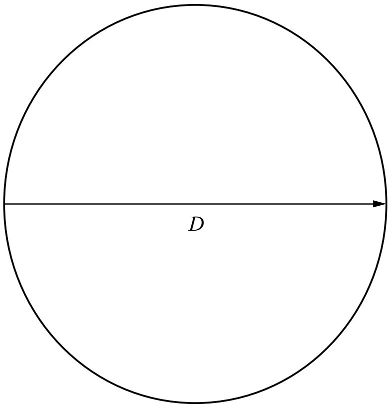

FIGURE 3.3 Diameter of circle.

■ EXAMPLE 3.42

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

Solution:

$$P = (2 \times \text{length}) + (2 \times \text{width})$$

$$= (2 \times 8\text{ in.}) + (2 \times 8\text{ in.}) = 16\text{ in.} + 16\text{ in.} = 32\text{ in.}$$

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

$$C = \pi \times D \tag{3.5}$$

where
C = Circumference.
π = pi = 3.1416.
D = Diameter.

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

■ EXAMPLE 3.43

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

Solution:

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

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

■ EXAMPLE 3.44

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

Solution:

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

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

■ EXAMPLE 3.45

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

Solution:

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

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

Area

For area measurements in water/wastewater operations, three basic shapes are particularly important—namely, circles, rectangles, and triangles. Area is the amount of surface an object contains or the amount of material it takes to cover the surface. The area on top of a chemical tank is called the *surface area*. The area of the end of a ventilation duct is called the *cross-sectional area* (the area at right angles to the length of ducting). Area is usually expressed in square units, such as square inches (in.^2) or square feet (ft^2). Land may also be expressed in terms of square miles (sections) or acres (43,560 ft^2) or in the metric system as hectares. In fisheries operations, pond stocking rates, limiting rates, and other important management decisions are based on surface area (Masser and Jensen, 1991).

If contractor's measurements or country field offices of the U.S Department of Agricultural Soil Conservation Service do not have records on basin, lake, or pond measurements, then surveying basins, tanks, lagoons, and ponds using a transit is the most accurate way to determine area. Less accurate but acceptable methods of measuring basin or pond area are chaining and pacing. Inaccuracies in these methods come from mismeasurements and measurement over uneven or sloping terrain. Measurements made on flat or level areas are the most accurate.

Chaining uses a surveyor's chain or tape of known length. Stakes are placed at each end of the tape. The stakes are used to set or locate the starting point for each progressive measurement and to maintain an exact count of the number of times the tape was moved. Sight down the stakes to keep the measurement in a straight line. The number of times the tape is moved multiplied by the length of the tape equals the total distance.

Pacing uses the average distance of a person's pace or stride. To determine your pace length, measure a 100-foot distance and pace it, counting the number of strides. Pace in a comfortable and natural manner. Repeat the procedure several times and get an average distance for your stride. It is good practice to always pace a distance more than once and average the number of paces (Masser and Jennings, 1991). The formula for calculating distances from pacing is

$$\text{Distance (ft)} = \text{Total number of paces} \times \text{Length of average pace}$$

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

$$\text{Area} = L \times W \tag{3.6}$$

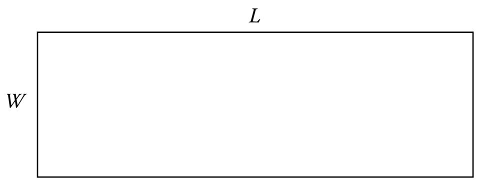

FIGURE 3.4 Rectangle.

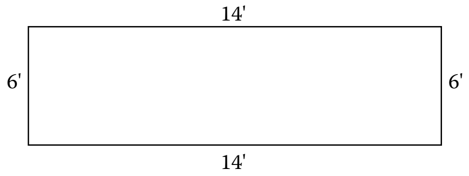

FIGURE 3.5 Area of a rectangle for Example 3.46.

EXAMPLE 3.46

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

Solution:

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

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

$$A = \pi \times r^2 \tag{3.7}$$

where

A = Area.

π = pi = 3.14.

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

EXAMPLE 3.47

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

Solution:

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

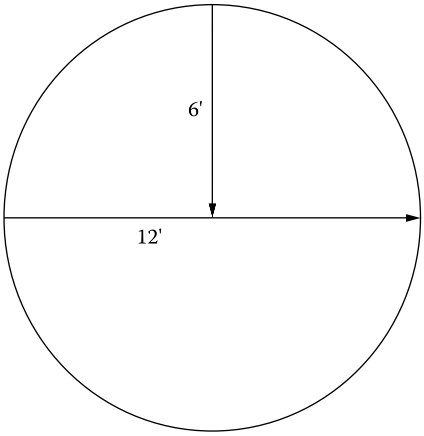

FIGURE 3.6 Area of a circle for Example 3.47.

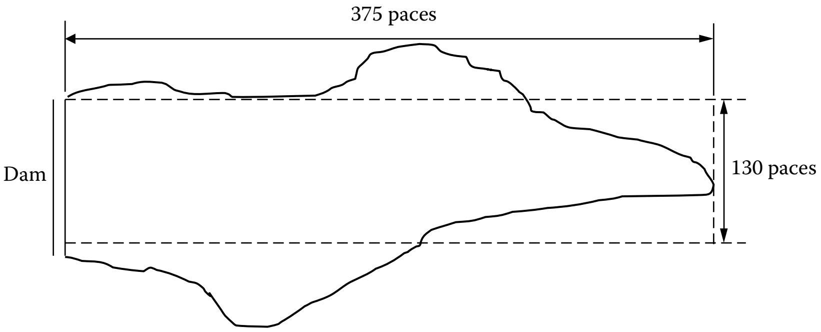

FIGURE 3.7 Pond area calculation.

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

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

$$A = \pi \times D \times H \tag{3.8}$$

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

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

Many ponds are watershed ponds that have been built by damming valleys. These ponds are irregular in shape. If no good records exist on the pond, then a reasonable estimate can be made by chaining or pacing off the pond margins and using the following procedures to calculate area:

1. Draw the general shape of the pond on graph paper.
2. Draw a rectangle over the pond shape that would approximate the area of the pond if some water was eliminated and placed onto an equal amount of land. This will give you a rectangle on which to base the calculation of area (see Figure 3.7).
3. Mark the corners of the rectangle (from the drawing) on the ground around the pond and chain or pace its length and width. For example, a length of 375 paces and a width of 130 paces and a pace length of 2.68 (for example) would be equal to 1005 ft (375 paces × 2.68 ft/pace) by 348.4 ft.
4. Multiply the length times width to get the approximate pond area. For example, 1005 ft × 348.4 ft = 350,142 ft^2 or 8.04 acres (350,142 ÷ 43,500).

Volume

Volume is the amount of space occupied by or contained in an object (see Figure 3.8). It is expressed in cubic units, such as cubic inches (in.^3), cubic feet (ft^3), or acre-feet (1 acre-foot = 43,560 ft^3). The volume (V) of a rectangular object is obtained by multiplying the length times the width times the depth or height:

$$V = L \times W \times H \tag{3.9}$$

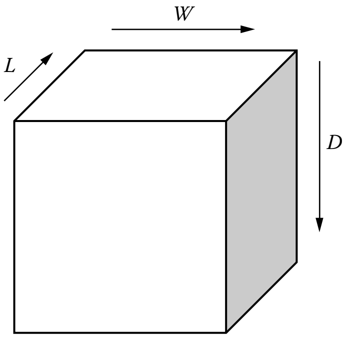

FIGURE 3.8 Volume.

where

V = Volume.
L = Length.
W = Width.
H (or D) = Height (or depth).

■ EXAMPLE 3.48

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

Solution:

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

For environmental practitioners involved with fisheries and water/wastewater operators, representative surface areas are most often rectangles, triangles, circles, or a combination of these. Practical volume formulas used in fisheries and water/wastewater calculations are given in Table 3.2.

When determining the volume of round pipe and round surface areas, the following examples are helpful.

■ EXAMPLE 3.49

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

Solution:

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

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

TABLE 3.2
Volume Formulas

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

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

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

3. Find the volume (V):

$$V = L \times \pi \times r^2$$

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

■ EXAMPLE 3.50

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

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

$$V = H \times \pi \times r^2$$

$$V = 96 \text{ in.} \times \pi \times (12 \text{ in.})^2$$

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

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

Volume of Cone

$$\text{Volume of cone} = \frac{\pi}{12} \times \text{Diameter} \times \text{Diameter} \times \text{Height} \tag{3.10}$$

Note that

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

Note: The diameter used in the formula is the diameter of the base of the cone.

■ EXAMPLE 3.51

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

Solution:

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

Volume of Sphere

$$\text{Volume of sphere} = \frac{\pi}{6} \times \text{Diameter} \times \text{Diameter} \times \text{Diameter} \tag{3.11}$$

Note that

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

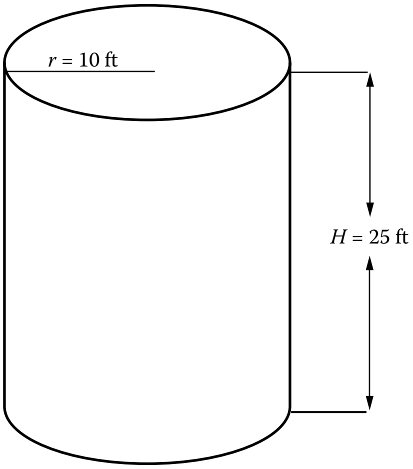

FIGURE 3.9 Circular or cylindrical water tank.

■ EXAMPLE 3.52

Problem: What is the volume (ft^3) of a spherical gas storage container with a diameter of 60 ft?

Solution:

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

Circular process and various water and chemical storage tanks are commonly found in water/wastewater treatment. A circular tank consists of a circular floor surface with a cylinder rising above it (see Figure 3.9). The volume of a circular tank is calculated by multiplying the surface area times the height of the tank walls.

■ EXAMPLE 3.53

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

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

Solution:

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

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

$$V = A \times H = 314\text{ ft}^2 \times 25\text{ ft} = 7850\text{ ft}^3 \times 7.48\text{ gal/ft}^3 = 58{,}718\text{ gal}$$

FORCE, PRESSURE, AND HEAD CALCULATIONS

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

- *Force*—The push exerted by water on any confined surface. Force can be expressed in pounds, tons, grams, or kilograms.
- *Pressure*—The force per unit area. The most common way of expressing pressure is in pounds per square inch (psi).
- *Head*—The vertical distance or height of water above a reference point. Head is usually expressed in feet. In the case of water, head and pressure are related.

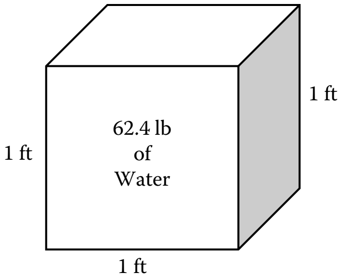

FIGURE 3.10 One cubic foot of water weighs 62.4 lb.

FORCE AND PRESSURE

Figure 3.10 helps to illustrate these terms. A cubical container measuring 1 foot on each side can hold 1 cubic foot of water. A basic fact of science states that 1 cubic foot of water weighs 62.4 lb and contains 7.48 gal. The force acting on the bottom of the container is 62.4 lb/ft^2. The area of the bottom in square inches is

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

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

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

If we use the bottom of the container as our reference point, the head would be 1 foot. From this, we can see that 1 foot of head is equal to 0.433 psi—an important parameter to remember. Figure 3.11 illustrates some other important relationships between pressure and head.

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

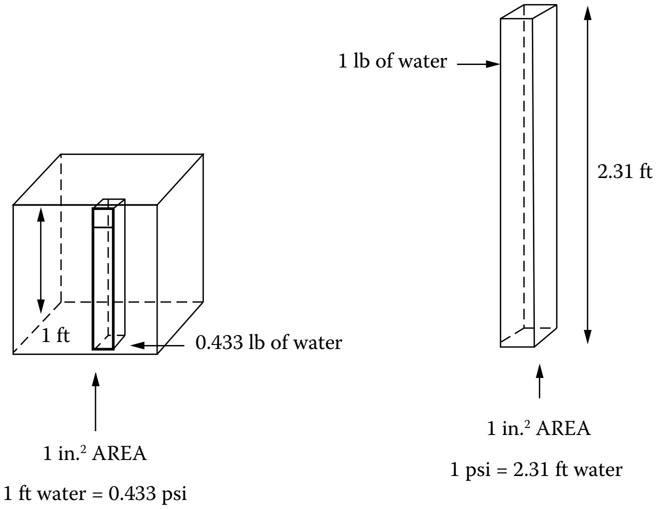

FIGURE 3.11 Relationship between pressure and head.

Using the preceding information, we can develop Equations 3.12 and 3.13 for calculating pressure and head:

$$\text{Pressure (psi)} = 0.433 \times \text{Head (ft)} \tag{3.12}$$

$$\text{Head (ft)} = 2.31 \times \text{Pressure (psi)} \tag{3.13}$$

HEAD

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

$$\text{Total head} = \text{Static head} + \text{Friction head} + \text{Velocity head} \tag{3.14}$$

Static Head

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

$$\text{Static head} = \text{Discharge elevation} - \text{Supply elevation} \tag{3.15}$$

■ EXAMPLE 3.54

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

Solution:

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

Friction Head

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

$$\text{Friction head (ft)} = \text{Energy losses due to friction} \tag{3.16}$$

Velocity Head

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

$$\text{Velocity head (ft)} = \text{Energy losses to maintain velocity} \tag{3.17}$$

Total Dynamic Head (Total System Head)

$$\text{Total head} = \text{Static head} + \text{Friction head} + \text{Velocity head} \tag{3.18}$$

Pressure and Head

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

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

■ EXAMPLE 3.55

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

Solution:

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

Head and Pressure

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

$$\text{Pressure (psi)} = \frac{\text{Head (ft)}}{2.31 \text{ ft/psi}} \tag{3.20}$$

■ EXAMPLE 3.56

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

Solution:

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

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

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

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

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

Note: 1 foot of head = 0.433 psi.

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

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

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

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

■ EXAMPLE 3.57

Problem: Convert 40 psi to feet head.

Solution:

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

■ EXAMPLE 3.58

Problem: Convert 40 ft to psi.

Solution:

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

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

■ EXAMPLE 3.59

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

Solution:

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

■ EXAMPLE 3.60

Problem: Convert 15 psi to feet.

Solution:

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

■ EXAMPLE 3.61

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

Solution:

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

■ EXAMPLE 3.62

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

Solution:

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

■ EXAMPLE 3.63

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

Solution:

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

■ EXAMPLE 3.64

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

Solution: Change miles to feet, then to psi:

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

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

■ EXAMPLE 3.65

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

Solution:

1. Change MG to cubic feet:

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

2. Using volume, solve for depth:

$$\text{Volume} = 0.785 \times D^2 \times \text{Depth}$$

$$267{,}380\text{ ft}^3 = 0.785 \times (150)^2 \times \text{Depth}$$

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

■ EXAMPLE 3.66

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

Solution:

1. Convert pressure to feet of water:

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

2. Convert psi to psf:

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

■ EXAMPLE 3.67

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

Solution:

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

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

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

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

REVIEW OF ADVANCED ALGEBRA KEY TERMS AND CONCEPTS

Advanced algebraic operations (linear, linear differential, and ordinary differential equations) have in recent years become an essential part of the mathematical background required by environmental engineers, among others. It is not the intent here to provide complete coverage of the topics (environmental practitioners are normally well grounded in these critical foundational areas), but it is important to review the key terms and relevant concepts. Key definitions include the following:

Algebraic multiplicity of an eigenvalue—The algebraic multiplicity of eigenvalue c of matrix A is the number of times the factor $(t - c)$ occurs in the characteristic polynomial of A.

Basis for a subspace—A basis for subspace W is a set of vectors $\{\mathbf{v}_1, \ldots, \mathbf{v}_k\}$ in W such that

1. $\{\mathbf{v}_1, \ldots, \mathbf{v}_k\}$ is linearly independent, and
2. $\{\mathbf{v}_1, \ldots, \mathbf{v}_k\}$ spans W.

Characteristic polynomial of a matrix—The characteristic polynomial of $n \times n$ matrix A is the polynomial in t given by the formula $\det(A - tI)$.

Column space of a matrix—The subspace spanned by the columns of the matrix considered as a set of vectors (also see row space).

Consistent linear system—A system of linear equations is consistent if it has at least one solution.

Defective matrix—Matrix A is defective if A has an eigenvalue whose geometric multiplicity is less than its algebraic multiplicity.

Diagonalizable matrix—A matrix is diagonalizable if it is similar to a diagonal matrix.

Dimension of a subspace—The dimension of subspace W is the number of vectors in any basis of W. (If W is the subspace $\{\mathbf{0}\}$, then we say that its dimension is 0.)

Echelon form of a matrix—A matrix is in row echelon form if

1. All rows that consist entirely of zeros are grouped together at the bottom of the matrix, and
2. The first (counting left to right) nonzero entry in each nonzero row appears in a column to the right of the first nonzero entry in the preceding row (if there is a preceding row).

Eigenspace of a matrix—The eigenspace associated with the eigenvalue c of matrix A is the null space of $A - cl$.

Eigenvalue of a matrix—An eigenvalue of matrix A is scalar c such that $A\mathbf{x} = c\mathbf{x}$ holds for some nonzero vector $\mathbf{x}$.

Eigenvector of a matrix—An eigenvector of square matrix A is a nonzero vector $\mathbf{x}$ such that $A\mathbf{x} = c\mathbf{x}$ holds for some scalar c.

Elementary matrix—A matrix that is obtained by performing an elementary row operation on an identity matrix.

Equivalent linear systems—Two systems of linear equations in n unknowns are equivalent if they have the same set of solutions.

Geometric multiplicity of an eigenvalue—The geometric multiplicity of eigenvalue c of matrix A is the dimension of the eigenspace of c.

Homogeneous linear system—A system of linear equations $A\mathbf{x} = \mathbf{b}$ is homogeneous if $\mathbf{b} = 0$.

Inconsistent linear system—A system of linear equations is inconsistent if it has no solutions.

Inverse of a matrix—Matrix B is an inverse for matrix A if $AB = BA = I$.

Invertible matrix—A matrix is invertible if it has no inverse.

Least-squares solution of a linear system—A least-squares solution to a system of linear equations $A\mathbf{x} = \mathbf{b}$ is a vector $\mathbf{x}$ that minimizes the length of the vector $A\mathbf{x} - \mathbf{b}$.

Linear combination of vectors—Vector $\mathbf{v}$ is a linear combination of the vectors $\mathbf{v}_1, \ldots, \mathbf{v}_k$ if there exist scalars $a_1, \ldots, a_k$ such that $\mathbf{v} = a_1\mathbf{v}_1 + \ldots + a_k\mathbf{v}_k$.

Linear dependence relation for a set of vectors—A linear dependence relation for the set of vectors $\{\mathbf{v}_1, \ldots, \mathbf{v}_k\}$ is an equation of the form $a_1\mathbf{v}_1 + \ldots + a_k\mathbf{v}_k = 0$, where the scalars $a_1, \ldots, a_k$ are zero.

Linearly dependent set of vectors—The set of vectors $\{\mathbf{v}_1, \ldots, \mathbf{v}_k\}$ is linearly dependent if the equation $a_1\mathbf{v1} + \ldots + a_k\mathbf{v}_k = 0$ has a solution where not all the scalars $a_1, \ldots, a_k$ are zero (i.e., if $\{\mathbf{v}_1, \ldots, \mathbf{v}_k\}$ satisfies a linear dependence relation).

Linearly independent set of vectors—The set of vectors $\{\mathbf{v}_1, \ldots, \mathbf{v}_k\}$ is linearly independent if the only solution to the equation $a_1\mathbf{v}_1 + \ldots + a_k\mathbf{v}_k = 0$ is the solution where all the scalars $a_1, \ldots, a_k$ are zero (i.e., if $\{\mathbf{v}_1, \ldots, \mathbf{v}_k\}$ does not satisfy any linear dependence relation).

Linear transformation—A linear transformation from V to W is a function T from V to W such that

1. $T(\mathbf{u} + \mathbf{v}) = T(\mathbf{u}) + T(\mathbf{v})$ for all vectors $\mathbf{u}$ and $\mathbf{v}$ in V.
2. $T(a\mathbf{v}) = aT(\mathbf{v})$ for all vectors $\mathbf{v}$ in V and all scalars a.

Nonsingular matrix—Square matrix A is nonsingular if the only solution to the equation $A\mathbf{x} = 0$ is $\mathbf{x} = 0$.

Null space of a linear transformation—The null space of linear transformation T is the set of vectors $\mathbf{v}$ in its domain such that $T(\mathbf{v}) = 0$.

Null space of a matrix—The null space of $m \times n$ matrix A is the set of all vectors $\mathbf{x}$ in R^n such that $A\mathbf{x} = 0$.

Nullity of a linear transformation—The nullity of linear transformation T is the dimension of its null space.

Nullity of a matrix—The dimension of its null space.

Orthogonal complement of a subspace—The orthogonal complement of subspace S of R^n is the set of all vectors $\mathbf{v}$ in R^n such that $\mathbf{v}$ is orthogonal to every vector in S.

Orthogonal set of vectors—A set of vectors in R^n is orthogonal if the dot product of any two of them is 0.

Orthogonal linear transformation—Linear transformation T from V to W is orthogonal if $T(\mathbf{v})$ has the same length as $\mathbf{v}$ for all vectors $\mathbf{v}$ in V.

Orthogonal matrix—Matrix A is orthogonal if A is invertible and its inverse equals its transpose; that is, $A^{-1} = A^T$.

Orthonormal set of vectors—A set of vectors in R^n is orthonormal if it is an orthogonal set and each vector has length 1.

Range of a linear transformation—The range of linear transformation T is the set of all vectors $T(\mathbf{v})$, where $\mathbf{v}$ is any vector in its domain.

Rank of a linear transformation—The rank of a linear transformation (and hence of any matrix regarded as a linear transformation) is the dimension of its range. Note that a theorem tells us that the two definitions of rank of a matrix are equivalent.

Rank of a matrix—The rank of matrix A is the number of nonzero rows in the reduced row echelon form of A; that is, the dimension of the row space of A.

Reduced row echelon form of a matrix—A matrix is in reduced row echelon form if

1. The matrix is in row echelon form.
2. The first nonzero entry in each nonzero row is the number 1.
3. The first nonzero entry in each nonzero row is the only nonzero entry in its column.

Row equivalent matrices—Two matrices are row equivalent if one can be obtained from the other by a sequence of elementary row operations.

Row operations—The elementary row operations performed on a matrix are

1. Interchange two rows.
2. Multiply a row by a nonzero scalar.
3. Add a constant multiple of one row to another.

Row space of a matrix—The subspace spanned by the rows of the matrix considered as a set of vectors.

Similar matrices—Matrices A and B are similar if there is a square invertible matrix S such that $S^{-1}AS = B$.

Singular matrix—Square matrix A is singular if the equation $A\mathbf{x} = 0$ has a nonzero solution for $\mathbf{x}$.

Span of a set of vectors—The span of the set of vectors $\{\mathbf{v}_1, \ldots, \mathbf{v}_k\}$ is the subspace V consisting of all linear combinations of $\mathbf{v}_1, \ldots, \mathbf{v}_k$. One also says that the subspace V is spanned by the set of vectors $\{\mathbf{v}_1, \ldots, \mathbf{v}_k\}$ and that this set of vectors spans V.

Subspace—A subset W of R^n is a subspace of R^n if

1. The zero vector is in W.
2. $\mathbf{x} + \mathbf{y}$ is in W whenever $\mathbf{x}$ and $\mathbf{y}$ are in W.
3. $a\mathbf{x}$ is in W whenever $\mathbf{x}$ is in W and a is any scalar.

Symmetric matrix—Matrix A is symmetric if it equals its transpose; that is, $A = A^T$.

QUADRATIC EQUATIONS

$$ax^2 + bx + c = 0$$

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

When studying a discipline that does not include mathematics, one thing is certain: The discipline under study has little or nothing to do with environmental practice.

QUADRATIC EQUATIONS AND ENVIRONMENTAL PRACTICE

A logical question at this point might be why is the quadratic equation important in environmental practice? The logical answer is that the quadratic equation is used in environmental practice to find solutions to problems primarily dealing with length and time determinations. Stated differently: The quadratic equation is a tool, an important tool that belongs in every environmental practitioner's toolbox.

To the student of mathematics, this explanation might seem somewhat strange. Math students know, for example, that there will be two solutions to a quadratic equation. In environmental disciplines such as environmental engineering, many times only one solution is meaningful. For example, if we are dealing with a length, a negative solution to the equation may be mathematically possible but is not the solution we would use. Negative time, obviously, would also pose the same problem.

So what is the point? The point is that we often need to find a solution to certain mathematical problems. In environmental problems involving the determination of length and time using quadratic equations, we will end up with two answers. In some instances, a positive answer and a negative answer may result. One of these answers is usable; thus, we would use it. Real engineering is about modeling situations that occur naturally and using the model to understand what is happening or maybe to predict what will happen in future. The quadratic equation is often used in modeling because it is a beautifully simple curve (Bourne, 2013).

KEY TERMS

- a is the coefficient of x^2.
- b is the coefficient of x.
- c is a number in the quadratic equation (not a coefficient of any x term).
- Simple equations are equations in which the unknown appears only in the first degree.
- Pure quadratic equations are equations in which the unknown appears only in the second degree.
- Affected quadratic equations are equations containing the first and second degree of an unknown.

QUADRATIC EQUATIONS: THEORY AND APPLICATION

The equation $6x = 12$ is a form of equation familiar to most of us. In this equation the unknown appears only in the first degree, so it is a simple equation or linear equation. Those experienced in mathematics know that not all equations reduce to this form. For instance, when an equation has been reduced, the result may be an equation in which the square of the unknown equals some number, as in $x^2 = 5$. In this equation, the unknown appears only in the second degree, so it is a pure quadratic equation. In some cases, when an equation is simplified and reduced, the resulting equation contains the square and first power of the unknown, which equal some number, such as $x^2 - 5x = 24$. An equation containing the first and second degree of an unknown is an affected quadratic equation.

Quadratic equations, and certain other forms, can be solved with the aid of factoring. The procedure for solving a quadratic equation by factoring is as follows:

1. Collect all terms on the left and simplify to the form $ax^2 + bx + c = 0$.
2. Factor the quadratic expression.
3. Set each factor equal to zero.
4. Solve the resulting linear equations.
5. Check the solution in the original equation.

■ EXAMPLE 3.68

Problem: Solve $x^2 - x - 12 = 0$.

Solution:

1. Factor the quadratic expression.

$$(x - 4)(x + 3) = 0$$

2. Set each factor equal to zero.

$$x - 4 = 0 \qquad x + 3 = 0$$

3. Solve the resulting linear equations.

$$x = 4 \qquad x = -3$$

Thus, the roots are $x = 4$ and $x = -3$.

4. Check the solution in the original equation.

$$(4)^2 - 4 - 12 = 0 \qquad (-3)^2 - (-3) - 12 = 0$$

$$0 = 0 \qquad\qquad 0 = 0$$

Many times factoring is either too time consuming or not possible. The formula shown below is called the quadratic formula. It expresses the quadratic equation in terms of its coefficients. The quadratic formula allows us to quickly solve for x with no factoring.

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{3.21}$$

To use the quadratic equation, just substitute the appropriate coefficients into the equation and solve.

DERIVATION OF THE QUADRATIC EQUATION FORMULA

The equation $ax^2 + bx + c = 0$, where a, b, and c are any numbers, positive or negative, represents any quadratic equation with one unknown. When this general equation is solved, the solution can be used to determine the unknown value in any quadratic equation. The solution follows.

■ EXAMPLE 3.69

Problem: Solve $ax^2 + bx + c = 0$ for x.

Solution:

1. Subtract c from both members:

$$ax^2 + bx = -c$$

2. Divide both members by a:

$$x^2 + \frac{b}{a}(x) = -\frac{c}{a}$$

3. Add $(b/2a)^2$ to both sides:

$$x^2 + \left(\frac{b}{a}\right)(x) + \left(\frac{b}{2a}\right)^2 = -\frac{c}{a} + \left(\frac{b}{2a}\right)^2$$

4. Complete the square:

$$\left(x + \frac{b}{2a}\right)^2 = -\frac{c}{a} + \left(\frac{b}{2a}\right)^2$$

5. Take the square root of both members:

$$x + \frac{b}{2a} = \pm\sqrt{-\frac{c}{a} + \left(\frac{b}{2a}\right)^2}$$

6. Subtract $b/2a$ from both members:

$$x = -\frac{b}{2a} \pm \sqrt{-\frac{c}{a} + \left(\frac{b}{2a}\right)^2}$$

Thus, the following quadratic formula is obtained:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Using the Quadratic Equation

■ EXAMPLE 3.70

Problem: After conducting a study and deriving an equation representing time, we arrive at the following equation:

$$x^2 = 5x + 6 = 0$$

Solution: All like terms have been combined and the equation is set to equal zero. Use the quadratic formula to solve the problem:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

From our equation, $a = 1$ (the coefficient of x^2), $b = –5$ (the coefficient of x), and $c = 6$ (the constant or third term). Substituting these coefficients in the quadratic formula:

$$x = \frac{-(-5) \pm \sqrt{(-5)^2 - 4(1)(6)}}{2(1)}$$

$$x = \frac{5 \pm \sqrt{25 - 4}}{2}$$

$$x = \frac{5 \pm 1}{2}$$

$$x = 3, 2$$

Note: The roots may not always be rational (integers), but the procedure is the same.

TRIGONOMETRIC RATIOS

$$\sin A = a/c \quad \cos A = b/c \quad \tan A = a/b$$

> We owe a lot to the Indians, who taught us how to count, without which no worthwhile scientific discovery could have been made.
>
> **—Albert Einstein**

> Trigonometry is the branch of mathematics that is used to compute unknown angles and sides of triangles. The word *trigonometry* is derived from the Greek words for triangle and measurement. Trigonometry is based on the principles of geometry. Many problems require the use of geometry and trigonometry.
>
> **Smith and Peterson (2007)**

TABLE 3.4
Definition of Trigonometric Ratios

Sine of angle *A*	$\dfrac{\text{Measure of leg opposite angle } A}{\text{Measure of hypotenuse}}$	$\sin A = a/c$
Cosine of angle *A*	$\dfrac{\text{Measure of leg adjacent to angle } A}{\text{Measure of hypotenuse}}$	$\cos A = b/c$
Tangent of angle *A*	$\dfrac{\text{Measure of leg opposite angle } A}{\text{Measure of leg adjacent to angle } A}$	$\tan A = a/b$

TRIGONOMETRIC FUNCTIONS AND THE ENVIRONMENTAL PRACTITIONER

Typically, environmental practitioners are called upon to make calculations involving the use of various trigonometric functions. Consider slings, for example; they are commonly used with cranes, derricks, and hoists to lift a load and move it to the desired location. For the environmental professional responsible for safety and health, knowledge of the properties and limitations of the sling, the type and condition of material being lifted, the weight and shape of the object being lifted, the angle of the sling to the load being lifted, and the environment in which the lift is to be made are all important considerations to be evaluated before the safe transfer of material can take place. Later, we put many of the following principles to work in determining sling load and working load on a ramp (inclined plane)—that is, to solve force-type problems. For now, we discuss the basic trigonometric functions used to make such calculations.

TRIGONOMETRIC RATIOS OR FUNCTIONS

In trigonometry, all computations are based on certain ratios (i.e., trigonometric functions). The trigonometric ratios or functions are sine, cosine, tangent, cotangent, secant, and cosecant. It is important to understand the definition of the ratios given in Table 3.4 and defined in terms of the lines shown in Figure 3.12.

> ***Note:*** In a right triangle, the side opposite the right angle is the longest side. This side is called the *hypotenuse*. The other two sides are the *legs*.

■ EXAMPLE 3.71

Problem: Find the sine, cosine, and tangent of angle *Y* in Figure 3.13.

Solution:

$$\sin Y = \frac{\text{Opposite leg}}{\text{Hypotenuse}} = \frac{9}{15} = 0.60$$

$$\cos Y = \frac{\text{Adjacent leg}}{\text{Hypotenuse}} = \frac{12}{15} = 0.80$$

$$\tan Y = \frac{\text{Opposite leg}}{\text{Adjacent leg}} = \frac{9}{12} = 0.75$$

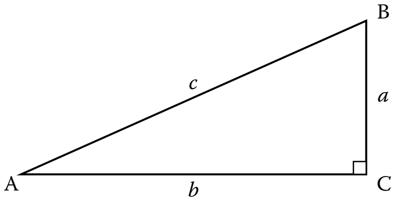

FIGURE 3.12 Right triangle.

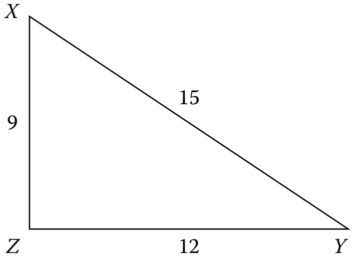

FIGURE 13.13 Illustration for Examples 3.71 and 3.72.

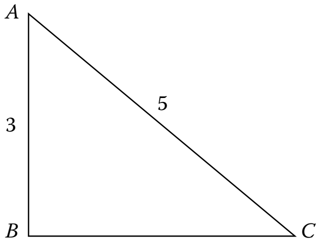

FIGURE 3.14 Illustration for Example 3.73.

■ EXAMPLE 3.72

Problem: Using Figure 3.13, find the measure of angle x to the nearest degree.

Solution:

$$\sin x = \frac{\text{Opposite leg}}{\text{Hypotenuse}} = \frac{12}{15} = 0.8$$

Use a scientific calculator to find the angle measure with a sine of 0.8.

Enter: 0.8 [2nd] or [INV]
Result: 53.13010235

So, the measure of angle $x = 53°$.

■ EXAMPLE 3.73

Problem: For the triangle shown in Figure 3.14, find sin C, cos C, and tan C.

Solution:

$$\sin C = 2/5;\ \cos C = 4/5;\ \tan C = 3/4$$

REFERENCES AND RECOMMENDED READING

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4 Environmental Modeling and Algorithms

> Who has measured the waters in the hollow of the hand, or with the breadth of his hand marked off the heavens? Who has held the dust of the earth in a basket, or weighed the mountains on the scales and the hills in a balance?
>
> **—Isaiah 40:12**

> *Algorithm*—The word comes from the Persian author Abu Ja'far Mohammed ibn Musa al-Khomwarizmi, who wrote a book with arithmetic rules dating from about 825 AD.

INTRODUCTION

There is a growing interest in the field of environmental monitoring and quantitative assessment of environmental problems. For some years now, the results of environmental models and assessment analyses have been influencing environmental regulation and policies. These results are widely cited by politicians in forecasting consequences of such greenhouse gas emissions as carbon dioxide (CO_2) and in advocating dramatic reductions of energy consumption at local, national, and international levels. For this reason, and because environmental modeling is often based on extreme conceptual and numerical intricacy and uncertain validity, environmental modeling has become one of the most controversial topics of applied mathematics.

Having said this, environmental modeling continues to be widely used in environmental practice, with its growth limited only by the imagination of the modelers. Environmental problem-solving techniques incorporating the use of modeling are widely used in watershed management, surface water monitoring, flood hazard mapping, climate modeling, and groundwater modeling, among others. It is important to keep in mind, however, that modelers often provide models for product developers who use the results to describe what their products are based on and why.

This chapter does not provide a complete treatment of environmental modeling. For the reader who desires such a treatment, we highly recommend Nirmalakhandan (2002) and NIST (2012). Much of the work presented in this chapter is modeled after these works. Here, we present an overview of quantitative operations implicit to environmental modeling processes.

Environmental modeling has become an important tool in the environmental engineer's well-equipped toolbox. Using an analogy, we can say that if a typical skilled handyperson's toolbox contains a socket set ratchet and several different sized wrench attachments, then the well-equipped environmental practitioner's toolbox includes a number of environmental models (socket set ratchets) with a varying set of algorithms (socket wrench attachments). Although a complete treatment or discussion of algorithms is beyond the scope of this book, we do provide basic underlying explanations of what algorithms are and examples of their applications in cyberspace. For those interested in a more complete discussion of algorithms, there are many excellent texts on the general topic. We list several of these resources in the recommended reading section at the end of the chapter.

BASIC STEPS FOR DEVELOPING AN EFFECTIVE MODEL

The basic steps used for model building are the same across all modeling methods. The details vary somewhat from method to method, but an understanding of the common steps, combined with the typical underlying assumptions needed for the analysis, provides a framework in which the results from almost any method can be interpreted and understood. The basic steps of the model-building process are

1. Model selection
2. Model fitting
3. Model validation

These three basic steps are used iteratively until an appropriate model for the data has been developed. In the model selection step, plots of the data, process knowledge, and assumptions about the process are used to determine the form of the model to be fit to the data. Then, using the selected model and possibly information about the data, an appropriate model-fitting method is used to estimate the unknown parameters in the model. When the parameter estimates have been made, the model is then carefully assessed to see if the underlying assumptions of the analysis appear plausible. If the assumptions seem valid, the model can be used to answer the scientific or engineering questions that prompted the modeling effort. If the model validation identifies problems with the current model, however, then the modeling process is repeated using information from the model validation step to select or fit an improved model.

The three basic steps of process modeling described in the paragraph above assume that the data have already been collected and that the same dataset can be used to fit all of the candidate models. Although this is often the case in mode-building situations, one variation on the basic model-building sequence comes up when additional data are needed to fit a newly hypothesized model based on a model fit to the initial data. In this case, two additional steps, experimental design and data collection, can be added to the basic sequence between model selection and mode-fitting.

WHAT ARE MODELS USED FOR?

Models are used for four main purposes:

1. Estimation
2. Prediction
3. Calibration
4. Optimization

A brief explanation of the different uses of models is provided below (NIST, 2012):

- *Estimation*—The goal of estimation is to determine the value of the regression function (i.e., the average value of the response variable) for a particular combination of the values of the predictor variables. Regression function values can be estimated for any combination of predictor variable values, including values for which no data have been measured or observed. Function values estimated for points within the observed space of predictor variable values are sometimes called *interpolations*. Estimation of regression function values for points outside the observed space of predictor variable values, called *extrapolations*, are sometimes necessary but require caution.

- *Prediction*—The goal of prediction is to determine either
  1. The value of a new observation of the response variable, or
  2. The values of a specified proportion of all future observations of the response variable for a particular combination of the values of the predictor variables. Predictions can be made for any combination of predictor variable values, including values for which no data have been measured or observed. As in the case of estimation, predictions made outside the observed space of predictor variable values are sometimes necessary but require caution.
- *Calibration*—The goal of calibration is to quantitatively relate measurements made using one measurement system to those of another measurement system. This is done so that measurements can be compared in common units or to tie results from a relative measurement method to absolute units.
- *Optimization*—Optimization is performed to determine the values of process inputs that should be used to obtain the desired process output. Typical optimization goals might be to maximize the yield of a process, to minimize the processing time required to fabricate a product, or to hit a target product specification with minimum variation in order to maintain specified tolerances.

MEDIA MATERIAL CONTENT

Media material content is a measure of the material contained in a bulk medium, quantified by the ratio of the amount of material present to the amount of the medium. The terms *mass*, *moles*, or *volume* can be used to quantify the amounts. Thus, the ratio can be expressed in several forms such as mass or moles of material per volume of medium, resulting in mass or molar concentration; moles of material per mole of medium, resulting in mole fraction; and volume of material per volume of medium, resulting in volume fraction.

When dealing with mixtures of materials and media, the use of different forms of measures in the ratio to quantify material content may become confusing. With regard to mixtures, the ratio can be expressed in concentration units. The *concentration* of a chemical (liquid, gaseous, or solid) substance expresses the amount of substance present in a mixture. There are many different ways to express concentration. Chemists use the term *solute* to describe the substance of interest and the term *solvent* to describe the material in which the solute is dissolved. For example, in a can of soft drink (a solution of sugar in carbonated water), there are approximately 12 tablespoons of sugar (the solute) dissolved in the carbonated water (the solvent). In general, the component that is present in the greatest amount is the solvent. Some of the more common concentration units are

1. *Mass per unit volume.* Some concentrations are expressed in milligrams per milliliter (mg/mL) or milligrams per cubic centimeter (mg/cm^3). Note that 1 mL = 1 cm^3 and that a cubic centimeter is sometimes denoted as a "cc." Mass per unit volume is handy when discussing how soluble a material is in water or a particular solvent—for example, "the solubility of substance x is 4 grams per liter."
2. *Percent by mass.* Also called weight percent or percent by weight, this is simply the mass of the solute divided by the total mass of the solution and multiplied by 100%:

$$\text{Percent by mass} = \frac{\text{Mass of component}}{\text{Mass of solution}} = 100\% \tag{4.1}$$

The mass of the solution is equal to the mass of the solute plus the mass of the solvent. For example, a solution consisting of 30 g of sodium chloride and 70 g of water would be 30% sodium chloride by mass: [(30 g NaCl)/(30 g NaCl + 70 g water)] × 100% = 30%. To avoid confusion as to whether a solution is percent by weight or percent by volume, "w/w" (for weight to weight) is often added after the concentration—for example, "10% potassium iodide solution in water (w/w)."

3. *Percent by volume*. Also called volume percent or volume/volume percent, this is typically only used for mixtures of liquids. Percent by volume is simply the volume of the solute divided by the sum of the volumes of the other components multiplied by 100%. If we mix 30 mL of ethanol and 70 mL of water, the percent ethanol by volume will be 30%, but the total volume of the solution will *not* be 100 mL (although it will be close), because ethanol and water molecules interact differently with each other than they do with themselves. To avoid confusion as to whether we have a percent by weight or percent by volume solution, we can label this mixture as "30% ethanol in water (v/v)," where v/v stands for "volume to volume."
4. *Molarity*. Molarity is the number of moles of solute dissolved in 1 liter of solution. For example, a quantity of 90 g of glucose (molar mass = 180 g/mol) is equal to (90 g)/(180 g/mol) = 0.50 moles of glucose. If we place this glucose in a flask and add water until the total volume is 1 liter, we would have a 0.5 molar solution. Molarity is usually denoted with *M* (e.g., a 0.50-*M* solution). Recognize that molarity is moles of solute per liter of solution, not per liter of solvent. Also recognize that molarity changes slightly with temperature because the volume of a solution changes with temperature.
5. *Molality*. Molality is used for calculations of colligative properties; it is the number of moles of solute dissolved in 1 kilogram of solvent. Notice the two key differences between molarity and molality. Molality uses mass rather than volume and uses solvent instead of solution:

$$\text{Molality} = \frac{\text{Moles of solute}}{\text{Kilograms of solution}} \tag{4.2}$$

   Unlike molarity, molality is independent of temperature because mass does not change with temperature. If we were to place 90 g of glucose (0.50 mol) in a flask and then add 1 kg of water we would have a 0.50-molal solution. Molality is usually denoted with a small *m* (e.g., a 0.50-*m* solution).
6. *Parts per million*. Parts per million (ppm) works like percent by mass but is more convenient when there is only a small amount of solute present. Parts per million is defined as the mass of the component in solution divided by the total mass of the solution multiplied by 10^6 (one million):

$$\text{Parts per million} = \frac{\text{Mass of component}}{\text{Mass of solution}} \times 1,000,000 \tag{4.3}$$

   A solution with a concentration of 1 ppm has 1 gram of substance for every million grams of solution. Because the density of water is 1 g/mL and we are adding such a tiny amount of solute, the density of a solution at such a low concentration is approximately 1 g/mL. Therefore, in general, 1 ppm implies 1 mg of solute per liter of solution. Finally, recognize that 1% = 10,000 ppm. Therefore, something that has a concentration of 300 ppm could also be said to have a concentration of (300 ppm)/(10,000 ppm/percent) = 0.03% percent by mass.
7. *Parts per billion*. Parts per billion (ppb) works like above, but we multiply by 1 billion (10^9) (be aware that the word "billion" has different meanings in different countries). A solution with 1 ppb of solute has 1 µg (10^{-6}) of material per liter.
8. *Parts per trillion*. Parts per trillion (ppt) works like parts per million and parts per billion except that we multiply by 1 trillion (10^{12}). There are few, if any, solutes that are harmful at concentrations as low as 1 ppt.

MATERIAL CONTENT: LIQUID PHASES*

Mass concentration, molar concentration, or mole fraction can be used to quantify material content in liquid phases:

$$\text{Mass concentration of component } i \text{ in water} = p_{i,w} = \frac{\text{Mass of material } i}{\text{Volume of water}} \tag{4.4}$$

$$\text{Molar concentration of component } i \text{ in water} = C_{i,w} = \frac{\text{Moles of material } i}{\text{Volume of water}} \tag{4.5}$$

Because moles of material = mass/molecular weight (MW), mass concentrations ($p_{i,w}$) are related by the following:

$$C_{i,w} = \frac{p_{i,w}}{\text{MW}_i} \tag{4.6}$$

For molarity M, $[X]$ is the molar concentration of X.

The mole fraction (X) of a single chemical in water can be expressed as follows:

$$\text{Mole fraction } X = \frac{\text{Moles of component/chemical}}{\text{Total moles of solution (moles of chemical + moles of water)}} \tag{4.7}$$

For dilute solutions, the moles of chemical in the denominator of the above equation can be ignored in comparison to the moles of water (n_w) and can be approximated by

$$X = \frac{\text{Moles of chemical}}{\text{Moles of water}} \tag{4.8}$$

If X is less than 0.02, an aqueous solution can be considered dilute. On a mass basis, similar expressions can be formulated to yield mass fractions. Mass fractions can also be expressed as a percentage or as other ratios such as parts per million (ppm) or parts per billion (ppb).

The mole fraction of a component in a solution is simply the number of moles of that component divided by the total moles of all of the components. We use the mole fraction because the sum of the individual fractions should equal 1. This constraint can reduce the number of variables when modeling mixtures of chemicals. Mole fractions are strictly additive. The sum of the mole fractions of all components is equal to 1. Mole fraction X_i of component i in an n-component mixture is defined as follows:

$$X_i = \frac{\text{Moles of } i}{\left(\sum_{1}^{n} n_i\right) + n_w} \tag{4.9}$$

$$\text{The sum of all mole fractions} = \left(\sum_{1}^{n} x_w\right) = 1 \tag{4.10}$$

---

[*] Subscripts for components are $i = 1, 2, 3, \ldots, n$, and subscripts for phases are g = gas, a = air, l = liquid, w = water, s = solids and soil.

For dilute solutions of multiple chemicals (as in the case of single-chemical systems), mole fraction X_i of component *i* in an *n*-component mixture can be approximated by the following:

$$X = \frac{\text{Moles of } i}{n_w} \tag{4.11}$$

Note that the preceding ratio is known as an *intensive property* because it is independent of the system and the mass of the sample. An intensive property is any property that can exist at a point in space. Temperature, pressure, and density are good examples. On the other hand, an *extensive property* is any property that depends on the size (or extent) of the system under consideration. Volume is an example. If we double the length of all edges of a solid cube, the volume increases by a factor of eight. Mass is another. The same cube will undergo an eightfold increase mass when the length of the edges is doubled.

> ***Note:*** The material content in solid and gas phases is different from those in liquid phases. For example, the material content in solid phases is often quantified by a ratio of masses and is expressed as ppm or ppb. The material content in gas phases is often quantified by a ratio of moles or volumes and is expressed as ppm or ppb. It is preferable to report gas-phase concentrations at standard temperature and pressure (STP; 0°C and 769 mmHg or 273 K and 1 atm).

■ EXAMPLE 4.1

Problem: A certain chemical has a molecular weight of 80. Derive the conversion factors to quantify the following:

1. 1 ppm (volume/volume) of the chemical in air in molar and mass concentration form.
2. 1 ppm (mass ratio) of the chemical in water in mass and molar concentration form.
3. 1 ppm (mass ratio) of the chemical in soil in mass ratio form.

Solution:

1. *Gas phase*—The volume ratio of 1 ppm can be converted to the mole or mass concentration form using the assumption of ideal gas, with a molar volume of 22.4 L/g mol at STP conditions (273 K and 1.0 atm.).

$$1 \text{ ppm} = \frac{1 \text{ m}^3 \text{ chemical}}{1{,}000{,}000 \text{ m}^3 \text{ of air}}\left(\frac{\text{mol}}{22.4 \text{ L}}\right)\left(\frac{1000 \text{ L}}{\text{m}^3}\right) = 4.46 \times 10^{-5} \text{ mol/m}^3$$

$$= 4.46 \times 10^{-5} \text{ mol/m}^3\left(\frac{80 \text{ g}}{\text{gmol}}\right) = 0.0035 \text{ g/m}^3 = 3.5 \text{ mg/m}^3 = 3.5\ \mu\text{g/L}$$

The general relationship is 1 ppm = (MW/22.4) mg/m^3.

2. *Water phase*—The mass ratio of 1 ppm can be converted to mole or mass concentration form using the density of water, which is 1 g/cm^3 at 4°C and 1 atm:

$$1 \text{ ppm} = \frac{1 \text{ g chemical}}{1{,}000{,}000 \text{ g of water}}\left(1 \text{ g/cm}^3\right)\left(1{,}000{,}000 \text{ cm}^3/\text{m}^3\right) = 1 \text{ g/m}^3 = 1 \text{ mg/L}$$

$$= 1 \text{ g/m}^3\left(\frac{\text{mol}}{80 \text{ g}}\right) = 0.0125 \text{ mol/m}^3$$

3. *Soil phase*—The conversion is direct:

$$1 \text{ ppm} = \frac{1 \text{ g chemical}}{1{,}000{,}000 \text{ g of soil}}\left(\frac{1000 \text{ g}}{\text{kg}}\right)\left(\frac{1000 \text{ mg}}{\text{g}}\right) = 1 \text{ mg/kg}$$

■ EXAMPLE 4.2

Problem: Analysis of a water sample from a pond gave the following results: volume of sample = 2 L, concentration of suspended solids in the sample = 15 mg/L, concentration of dissolved chemical = 0.01 mol/L, and concentration of the chemical adsorbed onto the suspended solids = 400 µg/g solids. If the molecular weight of the chemical is 125, determine the total mass of the chemical in the sample.

Solution:

Dissolved concentration = Molar concentration × MW:

$$0.001 \text{ mol/L} \times 125 \text{ g/mol} = 0.125 \text{ g/L}$$

Dissolved mass in sample = Dissolved concentration × Volume:

$$(125 \text{ g/L}) \times (2 \text{ L}) = 0.25 \text{ g}$$

Mass of solids in sample = Concentration of solids × Volume:

$$(25 \text{ mg/L} \times (2 \text{ L}) = 50 \text{ mg} = 0.05 \text{ g}$$

Adsorbed mass in sample = Adsorbed concentration × Mass of solids:

$$(400 \text{ µg/g}) \times (0.05 \text{ g}) \times \left(\frac{1 \text{ g}}{10^6 \text{ µg}}\right) = 0.00020 \text{ g}$$

Thus, the total mass of chemical in the sample = 0.25 g + 0.00020 g = 0.25020 g.

PHASE EQUILIBRIUM AND STEADY STATE

The concept of phase equilibrium (balance of forces) is an important one in environmental modeling. In the case of mechanical equilibrium, consider the following example. A cup sitting on a table top remains at rest because the downward force exerted by the Earth's gravity action on the cup's mass (this is what is meant by the "weight" of the cup) is exactly balanced by the repulsive force between atoms that prevents two objects from simultaneously occupying the same space, acting in this case between the table surface and the cup. If you pick up the cup and raise it above the tabletop, the additional upward force exerted by your arm destroys the state of equilibrium as the cup moves upward. If one wishes to hold the cup at rest above the table, it is necessary to adjust the upward force to exactly balance the weight of the cup, thus restoring equilibrium.

For more pertinent examples (chemical equilibrium, for example) consider the following. Chemical equilibrium is a dynamic system in which chemical changes are taking place in such a way that there is no overall change in the composition of the system. In addition to partial ionization, equilibrium situations include simple reactions such as when the air in contact with a liquid is saturated with the liquid's vapor, meaning that the rate of evaporation is equal to the rate of condensation. When a solution is saturated with a solute, this means that the rate of dissolving is just equal to the rate of precipitation from solution. In each of these cases, both processes continue. The equality of rate creates the illusion of static conditions. The point is that no reaction actually goes to completion.

Equilibrium is best described by the principle of Le Chatelier, which sums up the effects of changes in any of the factors influencing the position of equilibrium. It states that a system in equilibrium, when subjected to a stress resulting from a change in temperature, pressure, or concentration and causing the equilibrium to be upset, will adjust its position of equilibrium to relieve the stress and reestablish equilibrium.

What is the difference between steady state and equilibrium? Steady state implies no changes with passage of time. Likewise, equilibrium can also imply no change of state with passage of time. In many situations, this is the case—the system is not only at steady state but also at equilibrium. However, this is not always the case. In some cases, where the flow rates are steady but the phase contents, for example, are not being maintained at the equilibrium values, the system is at steady state but not at equilibrium.

MATH OPERATIONS AND LAWS OF EQUILIBRIUM

Earlier we observed that no chemical reaction goes to completion. There are qualitative consequences of this insight that go beyond the purpose of this text, but in this text we are interested in the basic quantitative aspects of equilibria. The chemist usually starts with the chemistry of the reaction and fully utilizes chemical intuition before resorting to mathematical techniques. That is, science should always precede mathematics in the study of physical phenomena. Note, however, that most chemical problems do not require exact, closed-form solutions, and the direct application of mathematics to a problem can lead to an impasse. Several basic math operations and fundamental laws from physical chemistry and thermodynamics serve as the tools, blueprints, and foundational structures of mathematical models. They can be used and applied to environmental systems under certain conditions to solve a variety of problems. Many laws serve as important links between the state of a system, its chemical properties, and its behavior. As such, some of the basic math operations used to solve basic equilibrium problems and laws essential for modeling the fate and transport of chemicals in natural and engineered environmental systems are reviewed in the following sections.

SOLVING EQUILIBRIUM PROBLEMS

In the following math operations, we provide examples of the various forms of combustion of hydrogen to yield water to demonstrate the solution of equilibrium problems. Let's first consider the reaction at 1000.0 K where all constituents are in the gas phase and the equilibrium constant is 1.15×10^{10} atm^{-1}. This reaction is represented by the following equation and equilibrium constant expression (Equation 4.12):

$$2H_2\ (g) + O_2\ (g) = 2H_2O\ (g)$$

$$K = [H_2O]^2/[H_2]^2[O_2] \tag{4.12}$$

where concentrations are given as partial pressures in atm. Observe that K is very large; consequently, the concentration of water is large and/or the concentration of at least one of the reactants is very small.

■ EXAMPLE 4.3

Problem: Consider a system at 1000.0 K in which 4.00 atm of oxygen is mixed with 0.500 atm of hydrogen and no water is initially present. Note that oxygen is in excess and hydrogen is the limiting reagent. Because the equilibrium constant is very large, virtually all of the hydrogen is converted to water, yielding $[H_2O] = 0.500$ atm and $[O_2] = 4.000 - 0.5(0.500) = 3.750$ atm. The final concentration of hydrogen, a small number, is an unknown, the only unknown.

Solution: Using the equilibrium constant expression, we obtain

$$1.15 \times 10^{10} = (0.500)^2/[H_2]^2(3.750)$$

from which we determine that $[H_2] = 2.41 \times 10^{-6}$ atm. Because this is a small number, our initial approximation is satisfactory.

■ EXAMPLE 4.4

Problem: Again, consider a system at 1000.0 K, where 0.250 atm of oxygen is mixed with 0.500 atm of hydrogen and 2000 atm of water.

Solution: Again, the equilibrium constant is very large and the concentration of least reactants must be reduced to a very small value.

$$[H_2O] = 2.000 + 0.500 = 2.500 \text{ atm}$$

In this case, oxygen and hydrogen are present in a 1:2 ratio, the same ratio given by the stoichiometric coefficients. Neither reactant is in excess, and the equilibrium concentrations of both will be very small values. We have two unknowns but they are related by stoichiometry. Because neither product is in excess and one molecule of oxygen is consumed for two of hydrogen, the ratio $[H_2]/[O_2] = 2/1$ is preserved during the entire reaction and $[H_2] = 2[O_2]$:

$$1.15 \times 10^{10} = 2.500^2/(2[O_2])^2[O_2]$$

$$[O_2] = 5.14 \times 10^{-4} \text{ atm and } [H_2] = 2[O_2] = 1.03 \times 10^{-3} \text{ atm}$$

LAWS OF EQUILIBRIUM

Some of the laws essential for modeling the fate and transport of chemicals in natural and engineered environmental system include the following:

- Ideal gas law
- Dalton's law
- Raoult's law
- Henry's law

Ideal Gas Law

An ideal gas is defined as one in which all collisions between atoms or molecules are perfectly elastic and in which there are no intermolecular attractive forces. One can visualize it as collections of perfectly hard spheres that collide but otherwise do not interact with each other. In such a gas, all the internal energy is in the form of kinetic energy and any change in the internal energy is accompanied by a change in temperature. An ideal gas can be characterized by three state variables:

absolute pressure (P), volume (V), and absolute temperature (T). The relationship between them may be deduced from kinetic theory and is called the *ideal gas law*:

$$P \times V = n \times R \times T = N \times k \times T \tag{4.13}$$

where

P = Absolute pressure.
V = Volume.
n = Number of moles.
R = Universal gas constant = 8.3145 J/mol·K or 0.821 L·atm/mol·K.
T = Absolute temperature.
N = Number of molecules.
k = Boltzmann constant = 1.38066×10^{-23} J/K = R/N_A, where N_A is Avogadro's number (6.0221×10^{23}).

> ***Note:*** At standard temperature and pressure (STP), the volume of 1 mol of ideal gas is 22.4 L, a volume called the *molar volume of a gas*.

■ EXAMPLE 4.5

Problem: Calculate the volume of 0.333 mol of gas at 300 K under a pressure of 0.950 atm.

Solution:

$$V = \frac{n \times R \times T}{P} = \frac{0.333\text{ mol} \times 0.0821\text{ L} \cdot \text{atm/mol} \cdot \text{K} \times 300\text{ K}}{0.959\text{ atm}} = 8.63\text{ L}$$

Most gases in environmental systems can be assumed to obey this law. The ideal gas law can be viewed as arising from the kinetic pressure of gas molecules colliding with the walls of a container in accordance with Newton's laws, but there is also a statistical element in the determination of the average kinetic energy of those molecules. The temperature is taken to be proportional to this average kinetic energy; this invokes the idea of kinetic temperature.

Dalton's Law

Dalton's law states that the pressure of a mixture of gases is equal to the sum of the pressures of all of the constituent gases alone. Mathematically, this can be represented as

$$P_{Total} = P_1 + P_2 + \ldots + P_n \tag{4.14}$$

where

P_{Total} = Total pressure.
$P_1, \ldots$ = Partial pressure.

and

$$\text{Partial } P = \frac{n_j \times R \times T}{V} \tag{4.15}$$

where n_j is the number of moles of component j in the mixture.

> ***Note:*** Although Dalton's law explains that the total pressure is equal to the sum of all of the pressures of the parts, this is only absolutely true for ideal gases, but the error is small for real gases.

■ EXAMPLE 4.6

Problem: The atmospheric pressure in a lab is 102.4 kPa. The temperature of a water sample is 25°C at a pressure of 23.76 torr. If we use a 250-mL beaker to collect hydrogen from the water sample, what are the pressure of the hydrogen and the moles of hydrogen using the ideal gas law?

Solution:

1. Make the following conversions—A torr is 1 mm of mercury at standard temperature. In kilopascals, that would be 3.17 (1 mmHg = 7.5 kPa). Convert 250 mL to 0.250 L and 25°C to 298 K.
2. Use Dalton's law to find the hydrogen pressure:

$$P_{Total} = P_{Water} + P_{Hydrogen}$$

$$102.4 \text{ kPa} = 3.17 \text{ kPa} + P_{Hydrogen}$$

$$P_{Hydrogen} = 99.23 \text{ kPa}$$

3. Recall that the ideal gas law is

$$P \times V = n \times R \times T$$

where P is pressure, V is volume, n is the number of moles, R is the ideal gas constant (8.31 L·kPa/mol·K or 0.821 L·atm/mol·K), and T is temperature. Therefore,

$$99.2 \text{ kPa} \times 0.250 \text{ L} = n \times 8.31 \text{ L·kPa/mol·K} \times 298 \text{ K}$$

Rearranged:

$$n = 99.2 \text{ kPa} \times 0.250 \text{ L}/8.31 \text{ L·kPa/mol·K}/298 \text{ K}$$

$$n = 0.0100 \text{ mol or } 1.00 \times 10^{-2} \text{ mol hydrogen}$$

Raoult's Law

Raoult's law states that the vapor pressure of mixed liquids is dependent on the vapor pressures of the individual liquids and the molar fraction of each present. Accordingly, for concentrated solutions where the components do not interact, the resulting vapor pressure (P) of component a in equilibrium with other solutions can be expressed as

$$P = x_a \times P_a \tag{4.16}$$

where

P = Resulting vapor pressure.
x_a = Mole fraction of component a in solution.
P_a = Vapor pressure of pure a at the same temperature and pressure as the solution.

Henry's Law

Henry's law states that the mass of a gas that dissolves in a definite volume of liquid is directly proportional to the pressure of the gas, provided the gas does not react with the solvent. A formula for Henry's law is

$$P = H \times x \tag{4.17}$$

where P is the partial pressure of a gas above the solution, H is Henry's constant, and x is the solubility of a gas in the solution phase.

TABLE 4.1
Henry's Law Constants (*H*)

	Henry's Law Constant	
Chemical	**(atm × m^3/mol)**	**(dimensionless)**
Aroclor 1254	2.7×10^{-3}	1.2×10^{-1}
Aroclor 1260	7.1×10^{-3}	3.0×10^{-1}
Atrazine	3×10^{-9}	1×10^{-7}
Benzene	5.5×10^{-3}	2.4×10^{-1}
Benz[*a*]anthracene	5.75×10^{-6}	2.4×10^{-4}
Carbon tetrachloride	2.3×10^{-2}	9.7×10^{-1}
Chlorobenzene	3.7×10^{-3}	1.65×10^{-1}
Chloroform	4.8×10^{-3}	2.0×10^{-1}
Cyclohexane	0.18	7.3
1,1-Dichloroethane	6×10^{-3}	2.4×10^{-1}
1,2-Dichloroethane	10^{-3}	4.1×10^{-2}
cis-1,2-Dichloroethene	3.4×10^{-3}	0.25
trans-1,2-Dichlorethene	6.7×10^{-3}	0.23
Ethane	4.9×10^{-1}	20
Ethanol	6.3×10^{-6}	—
Ethylbenzene	8.7×10^{-3}	3.7×10^{-1}
Lindane	4.8×10^{-7}	2.2×10^{-5}
Methane	0.66	27
Methylene chloride	3×10^{-3}	1.3×10^{-1}
n-Octane	2.95	121
Pentachlorophenol	3.4×10^{-6}	1.5×10^{-4}
n-Pentane	1.23	50.3
Perchloroethane	8.3×10^{-3}	3.4×10^{-1}
Phenanthrene	3.5×10^{-5}	1.5×10^{-3}
Toluene	6.6×10^{-3}	2.8×10^{-1}
1,1,1-Trichloroethane (TCA)	1.8×10^{-2}	7.7×10^{-1}
Trichloroethene (TCE)	1×10^{-2}	4.2×10^{-1}
o-Xylene	5.1×10^{-3}	2.2×10^{-1}
Vinyl chloride	2.4	99

Source: Adapted from Lyman, W.J. et al., *Handbook of Chemical Property Estimation Methods*, American Chemical Society, Washington, DC, 1990.

Henry's law constant (*H*) is a partition coefficient usually defined as the ratio of the concentration of a chemical in air to its concentration in water at equilibrium. Henry's law constants generally increase with increased temperature, primarily due to the significant temperature dependency of chemical vapor pressures. Solubility is much less affected by the changes in temperature that are normally found in the environment (Hemond and Fechner-Levy, 2000). *H* can be expressed either in a dimensionless form or with units. Table 4.1 lists the Henry's law constants for some common environmental chemicals.

CHEMICAL TRANSPORT SYSTEMS

In environmental modeling, environmental practitioners have a fundamental understanding of the phenomena involved with the transport of certain chemicals through the various components of the environment. The primary transport mechanism at the microscopic level is molecular *diffusion* driven by concentration gradients; whereas, mixing and bulk movement of the medium are the primary transport mechanisms at the macroscopic level. Transport by molecular diffusion and mixing is referred to as *dispersive transport*; transport by bulk movement of the medium is referred to as *advective transport.* Advective and dispersive transports are fluid-element driven. Advection, for example, is the movement of dissolved solute with flowing groundwater. The amount of contaminant being transported is a function of its concentration in the groundwater and the quantity of groundwater flowing, and advection will transport contaminants at different rates in each stratum. Diffusive transport, on the other hand, is the process by which a contaminant in water will move from an area of greater concentration toward an area where it is less concentrated. Diffusion will occur as long as a concentration gradient exists, even if the fluid is not moving, and as a result a contaminant may spread away from the place where it is introduced into a porous medium.

In today's computer age, environmental engineers have the advantage of choosing from a wide variety of mathematical models available. These models enable environmental engineers and students with minimal computer programming skills to develop computer-based mathematical models for natural and engineered environmental systems. Commercially available syntax-free authoring software can be adapted to create customized, high-level models of environmental phenomena in groundwater, air, soil, aquatic, and atmospheric systems.

ALGORITHMS: WHAT ARE THEY?

An *algorithm* is a specific mathematical calculation procedure, a computable set of steps to achieve a desired result. More specifically, "an algorithm is any well-defined computational procedure that takes some value, or set of values, as input and produces some value, or set of values, as output" (Cormen et al., 2002). In other words, an algorithm is a recipe for an automated solution to a problem. A computer model may contain several algorithms. The word "algorithm" is derived from the name of a ninth-century Persian mathematician, al-Khomwarizmi.

Algorithms should not be confused with computations. Whereas an algorithm is a systematic method for solving problems, and computer science is the study of algorithms (although the algorithm was developed and used long before any device resembling a modern computer was available), the act of executing an algorithm—that is, manipulating data in a systematic manner—is called *computation.* For example, the following algorithm for finding the greatest common divisor of two given whole numbers (attributed to Euclid *ca.* 300 BC, thus known for millennia) may be stated as follows:

- Set a and b to the values A and B, respectively.
- Repeat the following sequence of operations until b has value 0:
  1. Let r take the value of $a \bmod b$.
  2. Let a take the value of b.
  3. Let b take the value of r.
- The greatest common divisor of A and B is the final value of a.

Note: The operation $a \bmod b$ gives the remainder obtained upon dividing a by b.

Here, the problem—finding the greatest common divisor of two numbers—is specified by stating what is to be computed; the problem statement itself does not require that any particular algorithm be used to compute the value. Such method-independent specifications can be used to define the meaning of algorithms: the meaning of an algorithm is the value that it computes.

Several methods can be used to compute the required value; Euclid's method is just one. The chosen method assumes a set of standard operations (such as basic operations on the whole number and a means to repeat an operation) and combines these operations to form an operation that computes the required value. Also, it is not at all obvious to the vast majority of people that the proposed algorithm does actually compute the required value. That is one reason why a study of algorithms is important—to develop methods that can be used to establish what a proposed algorithm achieves.

EXPRESSING ALGORITHMS

Although an in-depth discussion of algorithms is beyond the scope of this text, the analysis of algorithms often requires us to draw upon a body of mathematical operations. Some of these operations are as simple as high-school algebra, but others may be less familiar to the average environmental engineer. Along with learning how to manipulate asymptotic notations and solving recurrences, several other concepts and methods must be learned to analyze algorithms.

Methods for evaluating bounding summations, for example, occur frequently in the analysis of algorithms and are used when an algorithm contains an iterative control construct such as a *while* or *for* loop. In this case, the running time can be expressed as the sum of the times spent on each execution of the body of the loop. Many of the formulas commonly used in analyzing algorithms can be found in any calculus text. In addition, in order to analyze many algorithms, we must be familiar with the basic definitions and notations for sets, relations, functions, graphs, and trees. A basic understanding of elementary principles of counting (permutations, combinations, and the like) is important as well. Most algorithms used in environmental engineering require no probability for their analysis; however, a familiarity with these operations can be useful.

Because mathematical and scientific analyses (and many environmental engineering functions) are so heavily based on numbers, computation has tended to be associated with numbers; however, this need not be the case. Algorithms can be expressed using any formal manipulation system—that is, any system that defines a set of entities and a set of unambiguous rules for manipulating those entities. For example, **SKI** calculus consists of three combinators (entities) called, coincidentally, **S**, **K**, and **I**. The computation rules for the calculus are

1. $\mathbf{S}xyz \rightarrow fx(gx)$
2. $\mathbf{K}xy \rightarrow x$
3. $\mathbf{I}x \rightarrow x$

where f, g, x, and y are strings of the three entities. **SKI** calculus is computationally complete; that is, any computation that can be performed using any formal system can be performed using **SKI** calculus. (Equivalently, all algorithms can be expressed using **SKI** calculus.) Not all systems of computation are equally as powerful, though; some problems that can be solved using one system cannot be solved using another. Further, it is known that problems exist that cannot be solved using any formal computation system.

GENERAL ALGORITHM APPLICATIONS

Practical applications of algorithms are ubiquitous. All computer programs are expressions of algorithms, where the instructions are expressed in computer language being used to develop the program. Computer programs are described as expressions of algorithms, as an algorithm is a general technique for achieving some purpose and can be expressed in a number of different ways. Algorithms exist for many purposes and are expressed in many different ways. Examples of algorithms include recipes in cookbooks, servicing instructions in the manual of a computer, knitting patterns, digital instructions for a welding robot indicating where each weld should be made, or cyberspeak for any system used in cyberspace.

Algorithms can be used in sorting operations—for example, to reorder a list into some defined sequence. It is possible to express an algorithm as instructions given to a human who has a similar requirement to reorder some list—for example, to sort a list of tax records into a sequence determined by the date of birth on the record. These instructions could employ the *insertion sort algorithm*, the *bubble sort algorithm*, or one of many other available algorithms. Thus, an algorithm, as a general technique for expressing the process of completing a defined task, is independent of the precise manner in which it is expressed.

Sorting is by no means the only application for which algorithms have been developed. Practical applications of algorithms include the following examples:

- Internet routing (e.g., single-source shortest paths)
- Search engine (e.g., string matching)
- Public-key cryptography and digital signatures (e.g., number-theoretic algorithms)
- Allocating scarce resources in the most beneficial way (e.g., linear programming)

Algorithms are at the core of most technologies used in contemporary computers:

- Hardware design uses algorithms.
- The design of any GUI relies on algorithms.
- Routing in networks relies heavily on algorithms.
- Compilers, interpreters, and assemblers make extensive use of algorithms.

A few classic algorithms are commonly used to illustrate the function, purpose, and applicability of algorithms. One of these classics is known as the *Byzantine Generals* (Black, 2012). Briefly, this algorithm is about the problem of reaching a consensus among distributed units if some of them give misleading answers. The problem is couched in terms of generals deciding on a common plan of attack. Some traitorous generals may lie about whether they will support a particular plan and what other generals told them. What decision-making algorithm should the generals use to reach a consensus through only an exchange of messages? What percentage of liars can the algorithm tolerate and still correctly determine a consensus?

Another classic algorithm that is used to illustrate how an algorithm can be applied to real-world situations (because of its general usefulness and because it is easy to explain to just about anyone) is the *Traveling Salesman* problem. The Traveling Salesman problem is the most notorious NP-complete problem; that is, no polynomial-time algorithm has yet been discovered for an NP-complete problem, nor has anyone yet been able to prove that no polynomial-time algorithm can exist for any one of them. For the Traveling Salesman problem, imagine that a traveling salesman has to visit each of a given set of cities by car, but he can only stop in each city one time. In Figure 4.1A, find the shortest possible route that visits each city once and returns to the origin city (Figure 4.1B).

We have pointed out some of the functions that algorithms can perform, but the question arises: "Can every problem be solved algorithmically?" The simple and complex answer is *no*. For example, for some problems no generalized algorithmic solution can possibly exist (they are unsolvable). Also, some problems—*NP-complete problems*—have no known efficient solutions; that is, it is unknown if efficient algorithms exist for these problems. If an efficient algorithm exists for any one

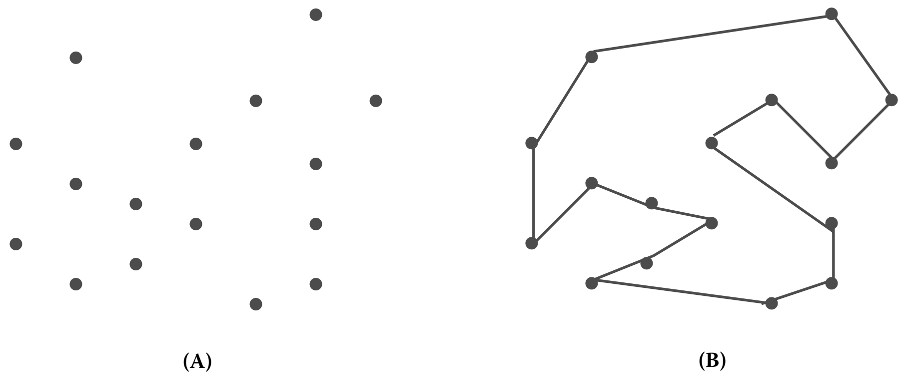
(A) (B)

FIGURE 4.1 Traveling Salesman problem.

of them, then efficient algorithms exist for all of them (e.g., Traveling Salesman problem). Finally, problems exist that we simply do not know how to solve algorithmically. From this discussion, it should be apparent that computer science is not simply about word processing and spreadsheets; it can include applications and not just software applications.

ENVIRONMENTAL PRACTICE ALGORITHM APPLICATIONS

Although algorithms can be used in transportation applications (e.g., Traveling Salesman problem), many of their most important applications are in environmental engineering functions. For example, consider a robot arm assigned to weld all the metal parts on an automobile in an assembly line. The shortest path that visits each weld point exactly once would be the most efficient one for the robot. A similar application arises in minimizing the amount of time taken by a design engineer or draftsperson to draw a given structure. Algorithms have found widespread application in all branches of environmental practice. In environmental engineering, for example, the U.S. Environmental Protection Agency (USEPA) uses computer models relying upon various algorithms to monitor chemical spill and ultimate fate data. In the following, we provide selected model summary descriptions of applications used in dispersion modeling. Specifically, we discuss how the USEPA (and others) employ preferred or recommended models (i.e., refined models that are recommended for a specific type of regulatory application) in monitoring air quality (i.e., ambient pollutant concentrations and their temporal and spatial distribution). Further information on this important topic can be found at USEPA (2003).

DISPERSION MODELS*

- *BLP* (buoyant line and point source model) is a Gaussian plume dispersion model designed to handle unique modeling problems associated with aluminum reduction plants and other industrial sources where plume rise and downwash effects from stationary line sources are important.
- *CALINE3* is a steady-state Gaussian dispersion model designed to determine air pollution concentrations at receptor locations downwind of "at-grade," fill," "bridge," and "cut section" highways located in relatively uncomplicated terrain.
- *CALPUFF* is a multilayer, multispecies, non-steady-state puff dispersion model that simulates the effects of time- and space-varying meteorological conditions on pollution transport, transformation, and removal. CALPUFF can be applied on scales of tens to hundreds of kilometers. It includes algorithms for subgrid scale effects (such as terrain impingement), as well as longer range effects (such as pollutant removal due to wet scavanging and dry deposition, chemical transformation, and visibility effects of particulate matter concentrations).
- *CTDMPLUS* (Complex Terrain Dispersion Model Plus Algorithms for Unstable Situations) is a refined point-source Gaussian air quality model for use in all stability conditions for complex terrain (i.e., terrain exceeding the height of the stack being modeled as contrasted with simple terrain, which is defined as an area where terrain features are all lower in elevation than the top of the stack of the source). The model contains, in its entirety, the technology of CTDM for stable and neutral conditions.
- *ISC3* (Industrial Source Complex Model) is a steady-state Gaussian plume model that can be used to assess pollutant concentrations from a wide variety of sources associated with an industrial complex. This model can account for the following: settling and dry

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* The algorithm-based models described in this section are currently listed in Appendix A of the *Guidelines on Air Quality Models* (Appendix W of 40 CFR Part 51).

deposition of particles; downwash; point, area, line, and volume sources; plume rise as a function of downwind distance; separation of point sources; and limited terrain adjustment. ISC3 operates in both long-term and short-term modes.

- *OCD* (Offshore and Coastal Dispersion Model) is a straight-line Gaussian model developed to determine the impact of offshore emissions from point, area, or line sources on the air quality of coastal regions. OCD incorporates overwater plume transport and dispersion as well as changes that occur as the plume crosses the shoreline. Hourly meteorological data are needed from both offshore and onshore locations.

SCREENING TOOLS

Screening tools are relatively simple analysis techniques to determine if a given source is likely to pose a threat to air quality. Concentration estimates from screening techniques precede a refined modeling analysis and are conservative. Following are some of the screening tools available:

- *CAL3QHC/CAL3QHCR* (CALINE3 with queuing and hot-spot calculations) is a CALINE3-based CO model with a traffic model to calculate delays and queues that occur at signalized intersections; CAL3QHCR requires local meteorological data.
- *COMPLEX 1* is a multiple point-source screening technique with terrain adjustment that incorporates the plume impaction algorithm of the VALLEY model.
- *CTSCREEN* (Complex Terrain Screening Model) is a Gaussian plume dispersion model designed as a screening technique for regulatory application to plume impaction assessments in complex terrain. CTSCREEN is a screening version of the CTDMPLUS model.
- *LONGZ* is a steady-state Gaussian plume formulation for both urban and rural areas in flat or complex terrain to calculate long-term (seasonal and/or annual) ground-level ambient air concentrations attributable to emissions from up to 14,000 arbitrarily placed sources (stack, buildings, and area sources).
- *SCREEN3* is a single-source Gaussian plume model that provides maximum ground-level concentrations for point, area, flare, and volume sources, as well as concentrations in the cavity zone and concentrations due to inversion break-up and shoreline fumigation. SCREEN3 is a screening version of the ISC3 model.
- *SHORTZ* is a steady-state bivariate Gaussian plume formulation model for both urban and rural areas in flat or complex terrain to calculate ground-level ambient air concentrations. It can calculate 1-hr, 2-hr, 3-hr, etc., average concentrations due to emissions from stacks, buildings, and area sources for up to 300 arbitrarily placed sources.
- *VALLEY* is a steady-state, complex-terrain, univariate Gaussian plume dispersion algorithm designed for estimating either 24-hour or annual concentrations resulting from emissions from up to 50 (total) point and area sources.
- *VISCREEN* calculates the potential impact of a plume of specified emissions for specific transport and dispersion conditions.

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5 Statistics Review[*]

There are three kinds of lies: lies, damned lies, and statistics.

—Benjamin Disraeli, British statesman

To the uninitiated it may often appear that the statistician's primary function is to prevent or at least impede the progress of research. And even those who suspect that statistical methods may be more boon than bane are at times frustrated in their efforts to make use of the statistician's wares.

Frank Freese (1967)

No aphorism is more frequently repeated in connection with field trials, than that we must ask Nature few questions, or, ideally, one question, at a time. The writer is convinced that this view is wholly mistaken.

—Ronald Fisher, biologist, geneticist, and statistician

STATISTICAL CONCEPTS

Despite the protestation of Disraeli and the wisdom of Freese, environmental practice includes the study of and use of statistical analysis of the results. The principal concept of statistics is that of variation. Variation is often found when conducting typical environmental health functions requiring the use of biostatistics, where a wide range of statistics are applied to an even wider range of topics in biology, such as toxicological or biological sampling protocols for air contamination, and other environmental functions applied to agriculture, forestry, fisheries, and other specialized areas. This chapter provides environmental practitioners with a survey of the basic statistical and data analysis techniques that can be used to address many of the problems that they will encounter on a daily basis. It covers the data analysis process, from research design to data collection, analysis, reaching conclusions, and, most importantly, the presentation of findings.

Finally, it is important to point out that statistics can be used to justify the implementation of a program, identify areas that need to be addressed, or evaluate the impact that various environmental health and safety programs might have on losses and accidents. A set of occupational health and safety data (or other data) is only useful if it is analyzed properly. Better decisions can be made when the nature of the data is properly characterized. For example, the importance of using statistical data when selling an environmental health and safety plan or some other type of environmental operation and trying to win over those who control the purse strings cannot be overemphasized.

With regard to Freese's opening statement, much of the difficulty is due to not understanding the basic objectives of statistical methods. We can boil these objectives down to two:

1. Estimation of population parameters (values that characterize a particular population)
2. Testing hypotheses about these parameters

A common example of the first is estimation of the coefficients a and b in the linear relationship $Y = a + bX$. To accomplish this objective one must first define the population involved and specify the parameters to be estimated. This is primarily the research worker's job. The statistician helps devise efficient methods of collecting the data and calculating the desired estimates.

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[*] Much of the information in this chapter is modeled after Freese, F., *Elementary Statistical Methods for Foresters*, Handbook 317, U.S. Department of Agriculture, Washington, DC, 1967.

Unless the entire population is examined, an estimate of a parameter is likely to differ to some degree from the population value. The unique contribution of statistics to research is that it provides ways of evaluating how far off the estimate may be. This is ordinarily done by computing confidence limits, which have a known probability of including the true value of the parameter. For example, the mean diameter of the trees in a pine plantation may be estimated from a sample as being 9.2 inches, with 95% confidence limits of 8.8 and 9.6 inches. These limits (if properly obtained) tell us that, unless a 1-in-20 chance has occurred in sampling, the true mean diameter is somewhere between 8.8 and 9.6 inches.

The second basic objective in statistics is to test some hypothesis about the population parameters. A common example is a test of the hypothesis that the regression coefficient in the linear model

$$Y = a + bX$$

has some specified value (say zero). Another example is a test of the hypothesis that the difference between the means of two populations is zero.

Again, it is the research worker who should formulate meaningful hypotheses to be tested, not the statistician. This task can be tricky. The beginner would do well to work with the statistician to be sure that the hypothesis is put in a form that can be tested. Once the hypothesis is set, it is up to the statistician to work out ways of testing it and to devise efficient procedures for obtaining the data (Freese, 1969).

PROBABILITY AND STATISTICS

Those who work with probabilities are commonly thought to have an advantage when it comes to knowing, for example, the likelihood of tossing coins heads up six times in a row, the chances of a crapshooter making several consecutive winning throws ("passes"), and other such useful bits of information. It is fairly well known that statisticians work with probabilities; thus, they are often associated with having the upper hand, so to speak, on predicting outcomes in games of chance. However, statisticians also know that this assumed edge they have in games of chance is often dependent on other factors.

The fundamental role of probability in statistical activities is often not appreciated. In putting confidence limits on an estimated parameter, the part played by probability is fairly obvious. Less apparent to the neophyte is the operation of probability in the testing of hypotheses. Some of them say with derision, "You can prove anything with statistics" (remember what Disraeli said about statistics). Anyway, the truth is, you can prove nothing; you can at most compute the probability of something happening and let the researcher draw his own conclusions.

Let's return to our game of chance to illustrate this point. In the game of craps, the probability of a shooter winning (making a pass) is approximately 0.493—assuming, of course, a perfectly balanced set of dice and an honest shooter. Suppose now that you run up against a shooter who picks up the dice and immediately makes seven passes in a row! It can be shown that if the probability of making a single pass is really 0.493, then the probability of seven or more consecutive passes is about 0.007 (or 1 in 141). This is where the job of statistics ends; you can draw your own conclusions about the shooter. If you conclude that the shooter is pulling a fast one, then in statistical terms you are rejecting the hypothesis that the probability of the shooter making a single pass is 0.493.

In practice, most statistical tests are of this nature. A hypothesis is formulated and an experiment is conducted or a sample is selected to test it. The next step is to compute the probability of the experimental or sample results occurring by chance if the hypothesis is true. If this probability is less than some preselected value (perhaps 0.05 or 0.01), then the hypothesis is rejected. Note that nothing has been proved—we haven't even proved that the hypothesis is false. We merely inferred this because of the low probability associated with the experiment or sample results.

Our inferences may be incorrect if we are given inaccurate probabilities. Obviously, reliable computation of these probabilities requires knowledge of how the variable we are dealing with is distributed (that is, what the probability is of the chance occurrence of different values of the variable). Accordingly, if we know that the number of beetles caught in light traps follows what is called the Poisson distribution we can compute the probability of catching X or more beetles. But, if we assume that this variable follows the Poisson distribution when it actually follows the negative binomial distribution, then our computed probabilities may be in error.

Even with reliable probabilities, statistical tests can lead to the wrong conclusions. We will sometimes reject a hypothesis that is true. If we always test at the 0.05 level, we will make this mistake on the average of 1 time in 20. We accept this degree of risk when we select the 0.05 level of testing. If we are willing to take a bigger risk, we can test at the 0.10 or the 0.25 level. If we are not willing to take this much risk, we can test at the 0.01 or 0.001 level.

Researchers can make more than one kind of error. In addition to rejecting a hypothesis that is true (a Type I error), one can make the mistake of not rejecting a hypothesis that is false (a Type II error). In crapshooting, it is a mistake to accuse an honest shooter of cheating (Type I error—rejecting a true hypothesis), but it is also a mistake to trust a dishonest shooter (Type II error—failure to reject a false hypothesis).

The difficulty is that for a given set of data, reducing the risk of one kind of error increases the risk of the other kind. If we set 15 straight passes as the critical limit for a crapshooter, then we greatly reduce the risk of making a false accusation (probability about 0.00025). But in doing so we have dangerously increased the probability of making a Type II error—failure to detect a phony. A critical step in designing experiments is the attainment of an acceptable level of probability of each type of error. This is usually accomplished by specifying the level of testing (i.e., probability of an error of the first kind) and then making the experiment large enough to attain an acceptable level of probability for errors of the second kind.

It is beyond the scope of this book to go into basic probability computations, distribution theory, or the calculation of Type II errors, but anyone who uses statistical methods should be fully aware that he or she is dealing primarily with probabilities (not necessarily lies or damnable lies) and not with immutable absolutes. Remember, 1-in-20 chances do actually occur—about one time out of twenty.

MEASURE OF CENTRAL TENDENCY

When we talk about statistics, it is usually because we are estimating something with incomplete knowledge. Maybe we can only afford to test 1% of the items we are interested in and we want to say something about the properties of the entire lot, or perhaps we must destroy the sample to test it. In that case, 100% sampling is not feasible if someone is supposed to get the items back after we are done with them. The questions we are usually trying to answer are "What is the central tendency of the item of interest?" and "How much dispersion about this central tendency can we expect?" Simply, the average or averages that can be compared are measures of central tendency or central location of the data.

SYMBOLS, SUBSCRIPTS, BASIC STATISTICAL TERMS, AND CALCULATIONS

In statistics, *symbols* such as X, Y, and Z are used to represent different sets of data. Hence, if we have data for five companies, we might let

X = Company income.
Y = Company materials expenditures.
Z = Company savings.

Subscripts are used to represent individual observations within these sets of data. Thus, X_i represents the income of the ith company, where *i* takes on the values 1, 2, 3, 4, and 5. Using this notation, X_1, X_2, X_3, X_4, and X_5 stand for the incomes of the first company, the second company, and so on. The data are arranged in some order, such as by size of income, the order in which the data were gathered, or any other way suitable to the purposes or convenience of the investigator.

The subscript *i* is a variable used to index the individual data observations; therefore, X_i, Y_i, and Z_i represent the income, materials expenditures, and savings of the *i*th company. For example, X_2 represents the income of the second company, Y_2 the materials expenditures of the second company, and Z_5 the savings of the fifth company.

Suppose that we have data for two different samples: the net worths of 100 companies and the test scores of 30 students. To refer to individual observations in these samples, we can let X_i denote the net worth of the ith company, where *i* assumes values from 1 to 100 (as indicated by the notation $i = 1, 2, 3, \ldots, 100$.) We can also let Y_j denote the test score of the *j*th student, where $j = 1, 2, 3, \ldots,$ 20. The different subscript letters make it clear that different sample are involved. Letters such as *X, Y,* and *Z* generally represent the different variables or types of measurements involved, whereas subscripts such as *i*, *j*, *k*, and *l* designate individual observations (Hamburg, 1987).

Next, we turn our attention to the method of expressing summations of sets of data. Suppose we want to add a set of four observations, denoted X_1, X_2, X_3, and X_4. A convenient way of designating this addition is

$$\sum_{i=1}^{4} X_i = X_1 + X_2 + X_3 + X_4$$

where the symbol Σ (Greek capital "sigma") means the "sum of." Thus, the following

$$\sum_{i=1}^{4} X_i$$

is read "the sum of the *X* values going from 1 to 4." For example, if $X_1 = 5$, $X_2 = 1$, $X_3 = 8$, and $X_4 = 6$, then

$$\sum_{i=1}^{4} X_i = 5 + 1 + 8 + 6 = 20$$

In general, if there are *n* observations, we write

$$\sum_{i=1}^{n} X_i = X_1 + X_2 + X_3 + \ldots + X_n$$

Basic statistical terms include mean or average, median, mode, and range. The following is an explanation of each of these terms.

MEAN

Mean is one of the most familiar and commonly estimated population parameters. It is the total of the values of a set of observations divided by the number of observations. Given a random sample, the population mean is estimated by

$$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n}$$

where X_i is the observed value of the *i*th unit in the sample, *n* is the number of units in the sample, and

$$\sum_{i=1}^{n} X_1$$

means to sum up all *n* of the *X* values in the sample.

If there are *N* units in the population, the total of the *X* values over all units in the population would be estimated by

$$\hat{T} = N\bar{X}$$

The circumflex (ˆ) over the *T* is frequently used to indicate an estimated value as opposed to the true but unknown population value. It should be noted that this estimate of the mean is used for a simple random sample. It may not be appropriate if the units included in the sample are not selected entirely at random.

MEDIAN

The median is the value of the central item when the data are arrayed in size.

MODE

The mode is the observation that occurs with the greatest frequency and thus is the most "fashionable" value.

RANGE

The range is the difference between the values of the highest and lowest terms.

■ EXAMPLE 5.1

Problem: Given the following laboratory results for the measurement of dissolved oxygen (DO) in water, find the mean, mode, median, and range.

6.5 mg/L, 6.4 mg/L, 7.0 mg/L, 6.9 mg/L, 7.0 mg/L

Solution: To find the mean:

$$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n} = \frac{6.5\text{ mg/L} + 6.4\text{ mg/L} + 7.0\text{ mg/L} + 6.0\text{ mg/L} + 7.0\text{ mg/L}}{5} = 6.58\text{ mg/L}$$

The mode is 7.0 mg/L, the number that appears most often.

Now arrange the measurements in order:

6.4 mg/L, 6.5 mg/L, 6.9 mg/L, 7.0 mg/L, 7.0 mg/L.

The median is 6.9 mg/L, the central value, and the range is 0.6 mg/L (7.0 mg/L – 6.4 mg/L).

The importance of using statistically valid sampling methods cannot be overemphasized. Several different methodologies are available. A careful review of these methods (with an emphasis on designing appropriate sampling procedures) should be made before computing analytic results. Using appropriate sampling procedures along with careful sampling techniques will provide basic data that are accurate. The need for statistics in environmental practice is driven by the discipline itself. Environmental studies often deal with entities that are variable. If there were no variation in collected data, then there would be no need for statistical methods.

Over a given time interval there will always be some variation in sampling analyses. Usually, the average and the range yield the most useful information. For example, in evaluating the indoor air quality (IAQ) in a factory, a monthly summary of air-flow measurements, operational data, and laboratory tests for the factory would be used. Another example is when a work center or organization evaluates its monthly on-the-job reports of accidents and illnesses, where a monthly summary of reported injuries, lost-time incidents, and work-caused illnesses would be used.

In the preceding section, we used the term *sample* and the sampling scenario to illustrate the use and definition of mean, mode, median, and range. Though these terms are part of the common terminology used in statistics, the term sample in statistics has its own unique meaning. There is a difference between the term sample and the term population. In statistics, we most often obtain data from a sample and use the results from the sample to describe an entire population. The population of a sample signifies that one has measured a characteristic for everyone or everything that belongs to a particular group. For example, if one wishes to measure that characteristic of the population defined as environmental professionals, one would have to obtain a measure of that characteristic for every environmental professional possible. Measuring a population is difficult, if not impossible.

We use the term *subject* or *case* to refer to a member of a population or sample. There are statistical methods for determining how many cases must be selected in order to have a credible study. *Data*, another important term, are the measurements taken for the purposes of statistical analysis. Data can be classified as either *qualitative* or *quantitative*. Qualitative data deal with characteristics of the individual or subject (e.g., gender of a person or the color of a car), whereas quantitative data describe a characteristic in terms of a number (e.g., the age of a horse or the number of lost-time injuries an organization had over the previous year). Along with common terminology, the field of statistics also generally uses some common symbols. Statistical notation uses Greek letters and algebraic symbols to convey meaning about the procedures that one should follow to complete a particular study or test. Greek letters are used as statistical notation for a population, while English letters are used for statistical notation for a sample. Table 5.1 summarizes some of the more common statistical symbols, terms and procedures used in statistical operations.

TABLE 5.1
Commonly Used Statistical Symbols and Procedures

	Symbol	
Term or Procedure	**Population Symbol**	**Sample Notation**
Mean	$\bar{\mu}$	$\bar{x}$
Standard deviation	σ	s
Variance	σ^2	s^2
Number of cases	N	n
Raw umber or value	X	x
Correlation coefficient	R	r
Procedure	**Symbol**	
Sum of	Σ	
Absolute value of x	$\lvert x \rvert$	
Factorial of n	$n!$	

DISTRIBUTION

An environmental professional conducting a research study collects data, and a group of raw data is obtained, but to make sense out of the data they must be organized into a meaningful format. The formatting begins by putting the data into some logical order, then grouping the data. Before the data can be compared to other data it must be organized. Organized data are referred to *distributions*. When confronted with masses of ungrouped data (listings of individual values), it is difficult to generalize about the information the mass es contain. However, if a frequency distribution of the figures is formed, then many features become readily discernible. A frequency distribution records the number of cases that fall into each class of the data.

■ EXAMPLE 5.2

Problem: An environmental health and safety professional gathered data on the medical costs of 24 on-the-job injury claims for a given year. The raw data collected are shown below:

$60	$1500	$85	$120
$110	$150	$110	$340
$2000	$3000	$550	$560
$4500	$85	$2300	$200
$120	$880	$1200	$150
$650	$220	$150	$4600

Solution: To develop a frequency distribution, the investigator took the values of the claims and placed them in order. Then the investigator counted the frequency of occurrences for each value as shown in Table 5.2. In order to develop a frequency distribution, groupings were formed using the values in Table 5.2, ensuring that each group had an equal range. The safety engineer grouped the data into ranges of 1000. The lowest range and highest range were determined by the data. Because it was decided to group by thousands, values fell in the ranges of $0 to $4999, and the distribution ended with this. The frequency distribution for the data appears in Table 5.3.

NORMAL DISTRIBUTION

When large amounts of data are collected on certain characteristics, the data and subsequent frequency can follow a distribution that is bell shaped in nature—the *normal distribution*. Normal distributions are a very important class of statistical distribution. As stated, all normal distributions are symmetric and have bell-shaped curves with a single peak (see Figure 5.1).

TABLE 5.2
Value and Frequency of Claims

Value	Frequency	Value	Frequency
$60	1	$650	1
$85	2	$880	1
$110	2	$1200	1
$120	2	$1500	1
$150	3	$2000	1
$200	1	$2300	1
$220	1	$3000	1
$340	1	$4500	1
$550	1	$4600	1
$560	1	Total	24

TABLE 5.3
Frequency Distribution

Range	Frequency
$0–$999	17
$1000–1999	2
$2000–2999	2
$3000–3999	1
$4000–4999	2
Total	24

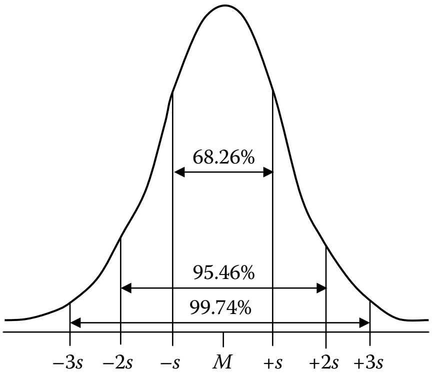

FIGURE 5.1 Normal distribution curve showing the frequency of a measurement.

To speak specifically of any normal distribution, two quantities have to be specified: the mean μ (pronounced "mu"), where the peak of the density occurs, and the standard deviation σ (sigma). Different values of μ and σ yield different normal density curves and hence different normal distributions. Although there are many normal curves, they all share an important property that allows us to treat them in a uniform fashion. All normal density curves satisfy the following property, which is often referred to as the *empirical rule*:

- 68% of the observations fall within 1 standard deviation of the mean; that is, between $\mu - \sigma$ and $\mu + \sigma$.
- 95% of the observations fall within 2 standard deviations of the mean; that is, between $\mu - 2\sigma$ and $\mu + 2\sigma$.
- 98% of the observations fall within 3 standard deviations of the mean; that is, between $\mu - 3\sigma$ and $\mu + 3\sigma$.

Thus, for a normal distribution, almost all values lie within 3 standard deviations of the mean (see Figure 5.1). It is important to stress that the rule applies to all normal distributions. Also remember that it applies *only* to normal distributions.

> ***Note:*** Before applying the empirical rule it is a good idea to identify the data being described and the value of the mean and standard deviation. A sketch of a graph summarizing the information provided by the empirical rule should also be made.

■ EXAMPLE 5.3

Problem: The scores for all high school seniors taking the math section of the Scholastic Aptitude Test (SAT) in a particular year had a mean of 490 ($\mu = 490$) and a standard deviation of 100 ($\sigma = 100$). The distribution of SAT scores is bell shaped.

1. What percentage of seniors scored between 390 and 590 on this SAT test?
2. One student scored 795 on this test. How did this student do compared to the rest of the scores?
3. A rather exclusive university admits only students who received among the highest 16% of the scores on this test. What score would a student need on this test to be qualified for admittance to this university?

The data being described are the math SAT scores for all seniors taking the test in one year. A bell-shaped curve summarizing the percentages given by the empirical rule is shown in Figure 5.2.

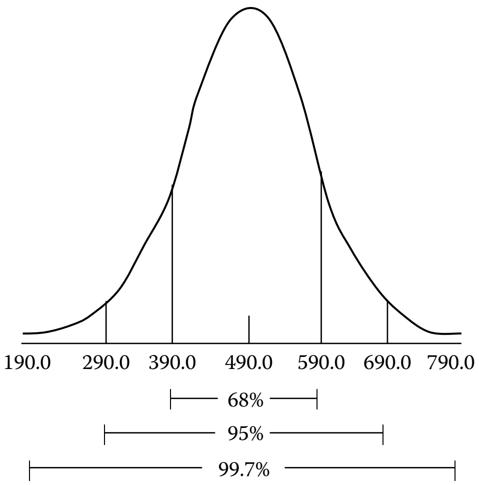

FIGURE 5.2 Sample Scholastic Aptitude Test (SAT) math percentages given by the empirical rule.

Solution:

1. From Figure 5.2, about 68% of seniors scored between 390 and 590 on this SAT test.
2. Because about 99.7% of the scores are between 190 and 790, a score of 795 is excellent. This is one of the highest scores on this test.
3. Because about 68% of the scores are between 390 and 590, this leaves 32% of the scores outside the interval. Because a bell-shaped curve is symmetric, one-half of these scores, or 16%, are on each end of the distribution.

STANDARD DEVIATION

The standard deviation, s or σ (sigma), is often used as an indicator of precision. The standard deviation is a measure of the variation (spread) in the set of observations; that is, it gives us some idea as to whether most of the individuals in a population are close to the mean or spread out. In order to gain a better understanding of the benefits derived from using statistical methods in safety engineering, it is appropriate to consider some of the basic theory of statistics. In any set of data, the true value (mean) will lie in the middle of all of the measurements taken. This is true, providing the sample size is large and only random error is present in the analysis. In addition, the measurements will show a normal distribution as shown in Figure 5.1. In Figure 5.1, 68.26% of the results fall between $M + s$ and $M - s$, 95.46% of the results lie between $M + 2s$ and $M - 2s$, and 99.74% of the results lie between $M + 3s$ and $M - 3s$. Therefore, if they are precise, then 68.26% of all the measurements should fall between the true value estimated by the mean, plus the standard deviation and the true value minus the standard deviation. The following equation is used to calculate the sample standard deviation:

$$s = \sqrt{\frac{\sum\left(X - \bar{X}\right)^2}{n-1}}$$

where

s = Standard deviation.
Σ = Means to sum the values from X to X_n.
X = Measurements from X to X_n.
$\bar{X}$ = Mean.
n = Number of samples.

TABLE 5.4
Calculations for Example 5.4

X	$X - \bar{X}$	$(X - \bar{X})^2$
9.5	–0.5	0.25
10.5	0.5	0.25
10.1	0.1	0.01
9.9	–0.1	0.01
10.6	0.6	0.36
9.5	–0.5	0.25
11.5	1.5	2.25
9.5	–0.5	0.25
10.0	0	0
9.4	–0.6	0.36
		3.99

■ EXAMPLE 5.4

Problem: Calculate the standard deviation (σ) of the following dissolved oxygen values:

$$9.5, 10.5, 10.1, 9.9, 10.6, 9.5, 11.5, 9.5, 10.0, 9.4$$

$$\bar{X} = 10.0$$

Solution: See Table 5.4.

$$\sigma = \sqrt{\frac{\sum (X - \bar{X})^2}{n - 1}} = \sqrt{\frac{3.99}{10 - 1}} = 0.67$$

COEFFICIENT OF VARIATION

In nature, populations with large means often show more variation than populations with small means. The coefficient of variation (C) facilitates comparison of variability in different sized means. It is the ratio of the standard deviation to the mean. A standard deviation of 2 for a mean coefficient of variation would be 0.20 or 20% in each case. If we have a standard deviation of 1.414 and a mean of 9.0, the coefficient of variation would be estimated by

$$C = \frac{s}{\bar{X}} = \frac{1.414}{9.0} = 0.157, \text{ or } 15.7\%$$

STANDARD ERROR OF THE MEAN

There is usually variation among the individual units of a population. Again, the standard deviation is a measure of this variation. Because the individual units vary, variation may also exist among the means (or any other estimates) computed from samples of these units. Take, for example, a population with a true mean of 10. If we were to select four units at random, they might have a sample mean of 8. Another sample of four units from the same population might have a mean of 11, another 10.5, and so forth. Clearly it would be desirable to know the variation likely to be encountered among the means of samples from this population. A measure of the variation among sample means is the standard error of the mean. It can be thought of as a standard deviation among sample means;

it is a measure of the variation among sample means, just as the standard deviation is a measure of the variation among individuals. The standard error of the mean may be used to compute confidence limits for a population mean.

The computation of the standard error of the mean (often symbolized by $s\bar{x}$) depends on the manner in which the sample was selected. For simple random sampling without replacement (i.e., a given unit cannot appear in the sample more than once) from a population having a total of N units the formula for the estimated standard error of the mean is

$$s_{\bar{x}} = \sqrt{\frac{s^2}{n}\left(1 - \frac{n}{N}\right)}$$

In a forestry example, if we had $n = 10$ and found that $s = 1.414$ and $s^2 = 2$ in the population that contains 1000 trees, then the estimated mean diameter ($\bar{X} = 9.0$) would have a standard error of

$$s_{\bar{x}} = \sqrt{\frac{2}{10}\left(1 - \frac{10}{1000}\right)} = \sqrt{0.198} = 0.445$$

Note: The term (1 – *n*/*N*) is called the *finite population correction*, or fpc. The fpc is used when the sampling fraction (the number of elements or respondents sampled relative to the population) becomes large. The fpc is used in the calculation of the standard error of the estimate. If the value of the fpc is close to 1, it will have little impact and can be safely ignored.

COVARIANCE

Very often, each unit of a population will have more than a single characteristic. In forestry practice, for example, trees may be characterized by their height, diameter, and form class (amount of taper). The covariance is a measure of the association between the magnitudes of two characteristics. If there is little or no association, the covariance will be close to zero. If the large values of one characteristic tend to be associated with the small values of another characteristic, the covariance will be negative. If the large values of one characteristic tend to be associated with the large values of another characteristic, the covariance will be positive. The population covariance of X and Y is often symbolized by σ_{xy}; the sample estimate by s_{xy}.

Let's return to a forestry practice example. Suppose that the diameter (inches) and age (years) have been obtained for a number of randomly selected trees. If we symbolize diameter by Y and age by X, then the sample covariance of diameter and age is given by

$$s_{xy} = \frac{\sum XY - \frac{\left(\sum X\right)\left(\sum Y\right)}{N}}{n-1}$$

This is equivalent to the formula

$$s_{xy} = \frac{\sum (X - \bar{X})(Y - \bar{Y})}{n-1}$$

If $n = 12$ and the Y and X values were as follows:

$$Y = 4 + 9 + 7 + 7 + 5 + 10 + 9 + 6 + 8 + 6 + 4 + 11 = 86$$

$$X = 20 + 40 + 30 + 45 + 25 + 45 + 30 + 40 + 20 + 35 + 25 + 40 = 395$$

DID YOU KNOW?

The computed value of a statistic such as the correlation efficient depends on which particular units were selected for the sample. Such estimates will vary from sample to sample. More important, they will usually vary from the population value which we try to estimate.

then

$$s_{xy} = \frac{(4)(20) + (9)(40) + \ldots + (11)(40) - \dfrac{(86)(395)}{12}}{12 - 1} = \frac{2960 - 2830.83}{11} = 11.74$$

The positive covariance is consistent with the well-known and economically unfortunate fact that larger diameters tend to be associated with older ages.

SIMPLE CORRELATION COEFFICIENT

The magnitude of the covariance, like that of the standard deviation, is often related to the size of the variables themselves. Units with large *X* and *Y* values tend to have larger covariances than units with small *X* and *Y* values. Also, the magnitude of the covariance depends on the scale of measurement; in the previous example, if the diameter had been expressed in millimeters instead of inches, the covariance would have been 298.196 instead of 11.74. The simple correlation coefficient, a measure of the degree of linear association between two variables, is free of the effects of scale of measurement. It can vary from between –1 and +1. A correlation of 0 indicates that there is no linear association (although there may be a very strong nonlinear association). A correlation of +1 or –1 would suggest a perfect linear association. As for the covariance, a positive correlation implies that the large values of *X* are associated with the large values of *Y*. If the large values of *X* are associated with the small values of *Y*, then the correlation is negative.

The population correlation coefficient is commonly symbolized by ρ (rho) and the sample-based estimate *r*. The population correlation coefficient is defined to be

$$\rho = \frac{\text{Covariance of } X \text{ and } Y}{\sqrt{(\text{Variance of } X)(\text{Variance of } Y)}}$$

For a simple random sample, the simple correlation coefficient is computed as follows:

$$r = \frac{s_{xy}}{s_x \cdot s_y} = \frac{\sum xy}{\sqrt{\left(\sum x^2\right)\left(\sum y^2\right)}}$$

where

s_{xy} = Sample covariance of *X* and *Y*.
s_x = Sample standard deviation of *X*.
s_y = Sample standard deviation of *Y*.
Σxy = Corrected sum of *XY* products:

$$\sum XY - \frac{\left(\sum X\right)\left(\sum Y\right)}{n}$$

Σx^2 = Corrected sum of squares for X:

$$\sum X^2 - \frac{\left(\sum X\right)^2}{n}$$

Σy^2 = Corrected sum of squares for Y:

$$\sum Y^2 - \frac{\left(\sum Y\right)^2}{n}$$

For the values used to illustrate the covariance we have:

$$\sum xy = (4)(20) + (9)(40) + \ldots + (11)(40) - \frac{(86)(395)}{12} = 129.1667$$

$$\sum y^2 = 4^2 + 9^2 + \ldots + 11^2 - \frac{(86)^2}{12} = 57.6667$$

$$\sum x^2 = 20^2 + 40^2 + \ldots + 40^2 - \frac{(395)^2}{12} = 922.9167$$

So,

$$r = \frac{129.1667}{\sqrt{(57.6667)(922.9167)}} = \frac{129.1667}{230.6980} = 0.56$$

VARIANCE OF A LINEAR FUNCTION

Routinely we combine variables or population estimates in a linear function. For example, if the mean timber volume per acre has been estimated as $\overline{X}$, then the total volume on M acres with be $M\overline{X}$; the estimate of total volume is a linear function of the estimated mean volume. If the estimate of cubic volume per acre in sawtimber is $\overline{X}_1$ and that of pulpwood above the sawtimber top is $\overline{X}_2$, then the estimate of total cubic foot volume per acre is $\overline{X}_1 + \overline{X}_2$. If on a given tract the mean volume per half-acre is $\overline{X}_1$ for spruce and the mean volume per quarter-acre is $\overline{X}_2$ for yellow birch, then the estimated total volume per acre of spruce and birch would be $2\overline{X} + 4\overline{X}_2$. In general terms, a linear function of three variables (say X_1, X_2, and X_3) can be written as

$$L = a_1X_1 + a_2X_2 + a_3X_3$$

where a_1, a_2, and a_3 are constants.

If the variances are s_1^2, s_2^2, and s_3^2 (for X_1, X_2 and X_3, respectively) and the covariances are $s_{1,2}$, $s_{1,3}$, and $s_{2,3}$, then the variance of L is given by

$$s_L^2 = a_1^2s_1^2 + a_2^2s_2^2 + a_3^2s_3^2 + 2\left(a_1a_2s_{1,2} + a_1a_3s_{1,3} + a_2a_3s_{2,3}\right)$$

The standard deviation (or standard error) of L is simply the square root of this. The extension of the rule to cover any number of variables should be fairly obvious.

■ EXAMPLE 5.5

Problem: The sample mean volume per forested acre for a 10,000-acre tract is $X = 5680$ board feet with a standard error of $s\bar{x} = 632$ (so = 399,424). The estimated total volume is

$$L = 10{,}000(\bar{X}) = 56{,}800{,}000 \text{ board feet}$$

The variance of this estimate would be

$$s_L^2 = (10{,}000)^2\left(s_{\bar{x}}^2\right) = 39{,}942{,}400{,}000{,}000$$

Because the standard error of an estimate is the square root of its variance, the standard error of the estimated total is

$$s_L = \sqrt{s_L^2} = 6{,}320{,}000$$

■ EXAMPLE 5.6

Problem: In 1995, a random sample of 40 1/4-acre circular plots was used to estimate the cubic foot volume of a stand of pine. Plot centers were monumented for possible relocation at a later time. The mean volume per plot was $\bar{X}_1 = 225$ ft^3. The plot variance was $s_{x1}^2 = 8281$ so that the variance of the mean was $s_{\bar{x}1}^2 = 8281/40 = 207.025$. In 2000, a second inventory was made using the same plot centers. This time, however, the circular plots were only 1/10 acre. The mean volume per plot was $\bar{X}_2 = 122$ ft^3. The plot variance was $s_{x2}^2 = 6084$, so the variance of the mean was $s_{\bar{x}2}^2 = 152.100$. The covariance of initial and final plot volumes was $s_{x1,2} = 4259$, making the covariance of the means $s_{\bar{x}1,\bar{x}2} = 4259/40 = 106.475$.

Solution: The net periodic growth per acre would be estimated as

$$G = 10\bar{X}_2 - 4\bar{X}_1 = 10(122) - 4(225) = 320 \text{ ft}^3/\text{acre}$$

By the rule for linear functions the variance of G would be

$$\begin{aligned} s_G^2 &= (10)^2 s_{\bar{x}2}^2 + (-4)^2 s_{\bar{x}1}^2 + 2(10)(-4)s_{\bar{x}1,\bar{x}2} \\ &= 100(152.100) + 16(207.025) - 80(106.475) \\ &= 10{,}004.4 \end{aligned}$$

In this example there was a statistical relationship between the 2000 and 1995 means because the same plot locations were used in both samples. The covariance of the means ($s_{\bar{x}1,\bar{x}2}$) is a measure of this relationship. If the 2000 plots had been located at random rather than at the 1995 locations, the two means would have been considered statistically independent and their covariance would have been set at zero. In this case the equation for the variance of the net periodic growth per acre (G) would reduce to

$$s_G^2 = (10)^2 s_{\bar{x}2}^2 + (-4)^2 s_{\bar{x}1}^2 = 100(152.100) + 16(207.025) = 18{,}522.40$$

SAMPLING MEASUREMENT VARIABLES

SIMPLE RANDOM SAMPLING

Most environmental practitioners are familiar with *simple random sampling.* As in any sampling system, the aim is to estimate some characteristic of a population without measuring all of the population units. In a simple random sample of size *n*, the units are selected so that every possible combination of *n* units has an equal chance of being selected. If sampling is without replacement, then at any stage of the sampling each unused unit should have an equal chance of being selected.

Sample Estimates of the Population Mean and Total

From a population of $N = 100$ units, $n = 20$ units were selected at random and measured. Sampling was without replacement—once a unit had been included in the sample it could not be selected again. The unit values were

10 9 10 9 11 16 11 7 12 12 11 3 5 11 14 8 13 12 20 10

Sum of all 20 random units = 214

From this sample we estimate the population mean as

$$\bar{X} = \frac{\sum X}{n} = \frac{214}{20} = 10.7$$

A population of $N = 100$ units having a mean of 10.7 would then have an estimated total of

$$\hat{T} = N\bar{X} = 100(10.7) = 1070$$

Standard Errors

The first step in calculating a standard error is to obtain an estimate of the population variance (σ^2) or standard deviation (σ). As noted in a previous section, the standard deviation for a simple random sample (like our example here) is estimated by

$$s = \sqrt{\frac{\sum X^2 - \frac{\left(\sum X\right)^2}{n}}{n-1}} = \sqrt{\frac{10^2 + 16^2 + \ldots + 10^2 - \frac{214^2}{20}}{19}} = \sqrt{13.4842} = 3.672$$

For sampling without replacement, the standard error of the mean is

$$s_{\bar{x}} = \sqrt{\frac{s^2}{n}\left(1 - \frac{n}{N}\right)} = \sqrt{\frac{13.4842}{20}\left(1 - \frac{20}{100}\right)} = \sqrt{0.539368} = 0.734$$

From the formula for the variance of a linear function we can find the variance of the estimated total:

$$s_{\hat{T}}^2 = N^2 s_{\bar{x}}^2$$

The standard error of the estimated total is the square root of this, or

$$s_{\hat{T}} = N s_{\bar{x}} = 100(0.734) = 73.4$$

Confidence Limits

Sample estimates are subject to variation. How much they vary depends primarily on the inherent variability of the population (Var^2) and on the size of the sample (n) and of the population (N). The statistical way of indicating the reliability of an estimate is to establish confidence limits. For estimates made from normally distributed populations, the confidence limits are given by

$$\text{Estimate} \pm t \text{ (standard error)}$$

For setting confidence limits on the mean and total we already have everything we need except for the value of t, and that can be obtained from a table of the t distribution.

In the previous example, the sample of $n = 20$ units had a mean of $\overline{X} = 10.7$ and a standard error of $s_{\overline{x}} = 0.734$. For 95% confidence limits on the mean we would use a t value (from a t table) of 0.05 and (also from a t table) 19 degrees of freedom. As $t_{0.05} = 2.093$, the confidence limits are given by

$$\overline{X} \pm (t)(s_{\overline{x}}) = 10.7 \pm (2.093)(0.734) = 9.16 \text{ to } 12.24$$

This says that, unless a 1-in-20 chance has occurred in sampling, the population mean is somewhere between 9.16 and 12.24. It does not say where the mean of future samples from this population might fall, nor does it say where the mean may be if mistakes have been made in the measurements.

For 99% confidence limits, we find $t_{0.01} = 2.861$ (with 19 degrees of freedom), so the limits are

$$10.7 \pm (2.861)(0.734) = 8.6 \text{ to } 12.8$$

These limits are wider, but they are more likely to include the true population mean. For the population total the confidence limits are

$$95\% \text{ limits} = 1070 \pm (2.093)(73.4) = 916 \text{ to } 1224$$
$$99\% \text{ limits} = 1070 \pm (2.861)(73.4) = 860 \text{ to } 1280$$

For large samples ($n > 60$), the 95% limits are closely approximated by

$$\text{Estimate} \pm 2 \text{ (standard error)}$$

and the 99% limits by

$$\text{Estimate} \pm 2.6 \text{ (standard error)}$$

Sample Size

Samples cost money. So do errors. The aim in planning a survey should be to take enough observations to obtain the desired precision—no more, no less. The number of observations needed in a simple random sample will depend on the precision desired and the inherent variability of the population being sampled. Because sampling precision is often expressed in terms of the confidence interval on the mean, it is not unreasonable in planning a survey to say that in the computed confidence interval

$$\overline{X} \pm ts_{\overline{x}}$$

we would like to have the $ts_{\overline{x}}$ equal to or less than some specified value E, unless a 1-in-20 (or 1-in-100) chance has occurred in the sample. That is, we want

$$ts_{\overline{x}} = E$$

DID YOU KNOW?

It is important for the specified error (E) and the estimated variance (s^2) to be on the same scale of measurement. We could not, for example, use a board-foot variance in conjunction with an error expressed in cubic feet. Similarly, if the error is expressed in volume per acre, the variance must be put on a per-acre basis.

or, because

$$s_{\bar{x}} = \frac{s}{\sqrt{n}}$$

we want

$$t\left(\frac{s}{\sqrt{n}}\right) = E$$

Solving this for n gives the desired sample size:

$$n = \frac{t^2 s^2}{E^2}$$

To apply this equation we need to have an estimate (s^2) of the population variance and a value for Student's t at the appropriate level of probability. The variance estimate can be a real problem. One solution is to make the sample survey in two stages. In the first state, n_1 random observations are made and from these an estimate of the variance (s^2) is computed. This value is then plugged into the sample size equation:

$$n = \frac{t^2 s^2}{E^2}$$

where t has $n_1 - 1$ degrees of freedom and is selected from the appropriate table. The computed value of n is the total size of sample needed. As we have already observed n_1 units, this means that we will have to observed ($n - n_1$) additional units.

If pre-sampling as described above is not feasible then it will be necessary to make a guess at the variance. Assuming our knowledge of the population is such that the guessed variance (s^2) can be considered fairly reliable, then the size of sample (n) needed to estimate the mean to within $\pm E$ units is approximately

$$n = \frac{4s^2}{E^2}$$

for 95% confidence and

$$n = \frac{20s^2}{3E^2}$$

for 99% confidence.

Less reliable variance estimates could be doubled (as a safety factor) before applying these equations. In many cases, the variance estimate may be so poor as to make the sample size computation just so much statistical window dressing.

When sampling is without replacement (as it is in most forest sampling situations) the sample size estimates given above apply to populations with an extremely large number (N) of units so that the sampling fraction (n/N) is very small. If the sampling fraction is not small (say $n/N = 0.05$), then the sample size estimates should be adjusted. This adjusted value of n is

$$n_a = \frac{n}{1 + \dfrac{n}{N}}$$

Suppose that we plan to use quarter-acre plots in a survey and estimate the variance among plot volumes to be $s^2 = 160{,}000$. If the error limit is $E = 5000$ feet per acre, we must convert the variance to an acre basis or the error to a quarter-acre basis. To convert a quarter-acre volume to an acre basis we multiply by 4, and to convert a quarter-acre variance to an acre variance we multiply by 16. Thus, the variance would be 2,560,000 and the sample-size formula would be

$$n = \frac{t^2(2{,}560{,}000)}{(500)^2} = t^2(10.24)$$

Alternatively, we can leave the variance alone and convert the error statement from an acre to a quarter-acre basis ($E = 125$). Then, the sample-size formula is

$$n = \frac{t^2(160{,}000)}{(125)^2} = t^2(10.24), \text{ as before}$$

STRATIFIED RANDOM SAMPLING

In stratified random sampling, a population is divided into subpopulations (strata) of known size, and a simple random sample of at least two units is selected in each subpopulation. This approach has several advantages. For one thing, if there is more variation between subpopulations than within them, the estimate of the population mean will be more precise than that given by a simple random sample of the same size. Also, it may be desirable to have separate estimates for each subpopulation (e.g., in timber types or administrative subunits). In addition, it may be administratively more efficient to sample by subpopulations.

■ EXAMPLE 5.7

Problem: A 500-acre forested area was divided into three strata on the basis of timber type. A simple random sample of 0.2-acre plots was taken in each stratum, and the means, variances, and standard errors were computed by the formulas for a simple random sample. These results, along with the size (N_h) of each stratum (expressed in number of 0.1-acre plots), are shown in Table 5.5.

Solution: The squared standard error of the mean for stratum h is computed by the formula given for the simple random sample

$$s_{\bar{x}_h}^2 = \frac{s_h^2}{n_h}\left(1 - \frac{n_h}{N_h}\right)$$

TABLE 5.5
Data for Example 5.7

Type	Stratum Number (h)	Stratum Size (N_h)	Sample Size (n_h)	Stratum Mean (X_h)	Within-Stratum Variance (s_h^2)	Squared Standard Error of the Mean ($s_{\bar{x}_h}^2$)
Pine	1	1350	30	251	10,860	353.96
Upland hardwoods	2	700	15	164	9680	631.50
Bottom-land hardwoods	3	450	10	110	3020	265.29
Sum		2500				

Thus, for stratum 1 (pine type),

$$s_{\bar{x}}^2 = \frac{10,860}{30}\left(1 - \frac{30}{1350}\right) = 353.96$$

Where the sampling fraction (n_h/N_h) is small, the fpc can be omitted.

With these data, the population mean is estimated by

$$\bar{X}_{st} = \sum \frac{N_h \bar{X}_h}{N}$$

where $N = \Sigma N_h$.

For this example we have

$$\bar{X}_{st} = \frac{N_1\bar{X}_1 + N_2\bar{X}_2 + N_3\bar{X}_4}{N} = \frac{(1350)(251) + (700)(164) + (450)(110)}{2500} = 201.26$$

The formula for the standard error of the stratified mean is cumbersome but not complicated:

$$s_{\bar{x}_{st}} = \sqrt{\frac{1}{N^2}\left[\sum N_h^2 s_{\bar{x}_h}^2\right]} = \sqrt{\frac{(1350)^2(353.96) + (700)^2(631.50) + (450)^2(295.29)}{(2500)^2}} = 12.74$$

If the sample size is fairly large, the confidence limits on the mean are given by

$$95\% \text{ confidence limits} = X_{st} \pm 2s_{\bar{x}_{st}}$$
$$99\% \text{ confidence limits} = X_{st} \pm 2.6s_{\bar{x}_{st}}$$

There is no simple way of compiling the confidence limits for small samples.

Sample Allocation

If a sample of n units is taken, how many units should be selected in each stratum? Among several possibilities, the most common procedure is to allocate the sample in proportion to the size of the stratum; in a stratum having 2/5 of the units of the population, we would take 2/5 of the samples. In the population discussed in the previous example, the proportional allocation of the 55 sample units was as follows:

Stratum	**Relative Size (N_h/N)**	**Sample Allocation**
1	0.54	29.7 or 30
2	0.28	15.4 or 15
3	0.18	9.9 or 10
Sums	1.00	55

Some other possibilities are equal allocation, allocation proportional to estimated value, and optimum allocation. In optimum allocation, an attempt is made to get the smallest standard error possible for a sample of *n* units. This is done by sampling more heavily in the state having a larger variation. The equation for optimum allocation is

$$n_h = \left(\frac{N_h s_h}{\sum N_h s_h} \right) n$$

Optimum allocation obviously requires estimates of the within-stratum variances—information that may be difficult to obtain. A refinement of optimum allocation is to take sampling cost differences into account and allocate the sample so as to get the most information per dollar. If the cost per sampling unit in stratum *h* is c_h, the equation is

$$n_h = \left[\frac{\dfrac{N_h s_h}{\sqrt{c_h}}}{\sum \left(\dfrac{N_h s_h}{\sqrt{c_h}} \right)} \right] n$$

Sample Size

To estimate the size of sample to take for a specified error at a given level of confidence, it is first necessary to decide on the method of allocation. Ordinarily, proportional allocation is the simplest and perhaps the best choice. With proportional allocation, the size of sample needed to be within ±*E* units of the true value at the 0.05 probability level can be approximated by

$$n = \frac{N\left(\sum N_h s_h^2\right)}{\dfrac{N^2 E^2}{4} + \sum N_h s_h^2}$$

For the 0.01 probability level, use 6.76 in place of 4.

■ EXAMPLE 5.8

Problem: Assume that prior to sampling a 500-acre forest we decided to estimate the mean volume per acre to within ±100 cubic feet per acre unless a 1-in-20 chance occurs in sampling. As we plan to sample with 0.2-acre plots, the error specification should be put on a 0.2-acre basis. Therefore, $E = 20$. From previous sampling, the stratum variances for 0.2-acre volumes are estimated to be

$$s_1^2 = 8000 \quad s_2^2 = 10{,}000 \quad s_3^2 = 5000$$

Therefore,

$$n = \frac{2500\left[(1350)(8000) + (700)(10{,}000) + (450)(5000)\right]}{\dfrac{(2500)^2(20)^2}{4} + \left[(1350)(8000) + (700)(10{,}000) + (450)(5000)\right]} = 77.7, \text{ or } 78$$

The 78 sample units would now be allocated to the strata by the formula

$$n_h = \left(\frac{N_h}{N}\right)n$$

giving $n_1 = 42$, $n_2 = 22$, and $n_3 = 14$.

SAMPLING—DISCRETE VARIABLES

RANDOM SAMPLING

The sampling methods discussed in the previous sections apply to data that are on a continuous or nearly continuous scale of measurement. These methods may not be applicable if each unit observed is classified as alive or dead, germinated or not germinated, infected or not infected. Data of this type may follow what is known as the binomial distribution. They require slightly different statistical techniques.

As an illustration, suppose that a sample of 1000 seeds was selected at random and tested for germination. If 480 of the seeds germinated, the estimated viability for the lot would be

$$\bar{p} = \frac{480}{1000} = 0.48, \text{ or } 48\%$$

For large samples (say, $n > 250$) with proportions greater than 0.20 but less than 0.80, approximate confidence limits can be obtained by first computing the standard error of $\bar{p}$ by the equation

$$s_{\bar{p}} = \sqrt{\frac{\bar{p}(1-\bar{p})}{(n-1)}\left(1-\frac{n}{N}\right)}$$

Then, the 95% confidence limits are given by

$$\bar{p} \pm \left[2(s_{\bar{p}}) + \frac{1}{2n}\right]$$

Applying this to the above example (and ignoring the fpc) we get

$$s_{\bar{p}} = \sqrt{\frac{(0.48)(0.52)}{999}} = 0.0158$$

And the 95% confidence interval is given by the following:

$$48 \pm \left[2(0.0158) + \frac{1}{2(1000)}\right] = 0.448 \text{ to } 0.512$$

The 99% confidence limits are approximated by

$$\bar{p} \pm \left(2.6s_{\bar{p}} + \frac{1}{2n}\right)$$

SAMPLE SIZE

An appropriate table can be used to estimate the number of units that would have to be observed in a simple random sample in order to estimate a population proportion with some specified precision. Suppose, for example, that we wanted to estimate the germination percent for a population to within ±10% (or 0.10) at the 95% confidence level. The first step is to guess about what the proportion of seed germination will be. If a good guess is not possible, then the safest course is to guess $\bar{p} = 0.59$, as this will give the maximum sample size.

Next, pick any of the sample sizes given in the appropriate table (e.g., 10, 15, 20, 30, 50, 100, 250, and 1000) and look at the confidence interval for the specified value of $\bar{p}$. Inspection of these limits will tell whether or not the precision will be met with a sample of this size or if a larger or smaller sample would be more appropriate.

Thus, if we guess $\bar{p} = 0.2$, then in a sample of $n = 50$ we would expect to observe (0.2)(50) = 10, and the table says that the 95% confidence limits on $\bar{p}$ would be 0.10 and 0.34. Since the upper limit is not within 0.10 of $\bar{p}$, a larger sample would be needed. For a sample of $n = 100$ the limits are 0.13 to 0.29. Because both of these values are within 0.10 of $\bar{p}$, a sample of 100 would be adequate.

If the table indicates the need for a sample of over 250, the size can be approximated by

$$n \approx \frac{4(\bar{p})(1-\bar{p})}{E^2}, \text{ for 95\% confidence}$$

or,

$$n \approx \frac{20(\bar{p})(1-\bar{p})}{3E^2}, \text{ for 99\% confidence}$$

where E is the precision with which $\bar{p}$ is to be estimated (expressed in same for as p̄, either percent or decimal).

CLUSTER SAMPLING FOR ATTRIBUTES

Simple random sampling of discrete variables is often difficult or impractical. When estimating tree plantation survival, for example, we could select individual trees at random and examine them, but it wouldn't make much sense to walk down a row of planted trees in order to observe a single member of that row. It would usually be more reasonable to select rows at random and observe all of the trees in the selected row.

Seed viability is often estimated by randomly selecting several lots of 100 or 200 seeds each and recording for each lot the percentage of the seeds that germinate. These are examples of *cluster sampling*; the unit of observation is th e cluster rather than the individual tree or single seed. The value attached to the unit is the proportion having a certain characteristic rather than the simple fact of having or not having that characteristic. If the clusters are large enough (say, over 100 individuals per cluster) and nearly equal in size, the statistical methods that have been described for measurement variables can often be applied. Thus, suppose that the germination percent of a seedlot is estimated by selecting $n = 10$ sets of 200 seeds each and observing the germination percent for each set:

Set	1	2	3	4	5	6	7	8	9	10	Sum
Germination percent (p)	78.5	82.0	86.0	80.5	74.5	78.0	79.0	81.0	80.5	83.5	803.5

then the mean germination percent is estimated by

$$\bar{p} = \frac{\sum p}{n} = \frac{803.5}{10} = 80.35\%$$

The standard deviation of p is

$$s_p = \sqrt{\frac{\sum p^2 - \frac{\left(\sum p\right)^2}{n}}{(n-1)}} = \sqrt{\frac{(78.5)^2 + \ldots (83.5)^2 - \frac{(803.5)^2}{10}}{9}} = \sqrt{10.002778} = 3.163$$

And the standard error for $\bar{p}$ (ignoring the fpc) is

$$s_{\bar{p}} = \sqrt{\frac{s_p^2}{n}\left(1 - \frac{n}{N}\right)} = \sqrt{\frac{10.002778}{10}} = 1.000$$

Note that n and N in these equations refer to the number of clusters, not to the number of individuals.

The 95% confidence interval, computed by the procedure for continuous variables is

$$p \pm (t_{0.05})(s_{\bar{p}}), \text{ where } t \text{ has } (n-1) = 9 \text{ degrees of freedom}$$

$$80.35 \pm (2.262)(1.000) = 78.1 \text{ to } 82.6$$

TRANSFORMATIONS

The above method of computing confidence limits assumes that the individual percentages follow something close to a normal distribution with homogeneous variance (i.e., same variance regardless of the size of the percent). If the clusters are small (say, less than 100 individuals per cluster) or some of the percentages are greater than 80 or less than 20, the assumptions may not be valid and the computed confidence limits will be unreliable. In such cases, it may be desirable to compute the transformation

$$y = \arcsin\sqrt{\text{percent}}$$

and to analyze the transformed variable.

CHI-SQUARE TESTS

TEST OF INDEPENDENCE

Individuals are often classified according to two (or more) distinct systems. A tree can be classified as to species and at the same time according to whether it is infected or not infected with some disease. A milacre plot can be classified as to whether or not it is stocked with adequate reproduction and whether it is shaded or not shaded. Given such a cross-classification, it may be desirable to know whether the classification of an individual according to one system is independent of its classification by the other system. In the species-infection classification, for example, independence of species and infection would be interpreted to mean that there is no difference in infection rate among species (i.e., infection rate does not depend on species).

The hypothesis that two or more systems of classification are independent can be tested by chi-square. The procedure can be illustrated by a test of three termite repellents. A batch of 1500 wooden stakes was divided at random into three groups of 500 each, and each group received a different termite-repellent treatment. The treated stakes were driven into the ground, with the treatment at any particular stake location being selected at random. Two years later the stakes were examined for termites. The number of stakes in each classification is shown in the following 2×3 (two rows by three columns) contingency table:

	Group I	Group II	Group III	Subtotals
Attacked by termites	193	148	210	551
Not attacked	307	352	390	949
Subtotals	500	500	500	1500

If the data in the table can be symbolized as shown below:

	Group I	Group II	Group III	Subtotals
Attacked by termites	a_1	a_2	a_3	A
Not attacked	b_1	b_2	b_3	B
Subtotals	T_1	T_2	T_3	G

then the test of independence is made by computing

$$\chi^2 = \frac{1}{(A)(B)}\sum_{i=1}^{3}\left(\frac{(a_iB - b_iA)^2}{T_i}\right)$$

$$= \frac{1}{(551)(949)}\left[\frac{((193)(949)-(307)(551))^2}{500}+\ldots+\frac{((210)(949)-(290)(551))^2}{500}\right]$$

$$= 17.66$$

The result is compared to the appropriate tabular accumulative distribution of chi-square values of χ^2 with $(c - 1)$ degrees of freedom, where c is the number of columns in the table of data. If the computed value exceeds the tabular value given in the 0.05 column, then the difference among treatments is said to be significant at the 0.05 level (i.e., we reject the hypothesis that attack classification is independent of termite-repellent treatment).

For illustrative purposes, in this example, we say that the computed value of 17.66 (2 degrees of freedom) exceeds the tabular value in the 0.01 column, so the difference in rate of attack among treatments is said to be significant at the 1% level. Examination of the data suggests that this is primarily due to the lower rate of attack on the Group II stakes.

TEST OF A HYPOTHESIZED COUNT

A geneticist hypothesized that, if a certain cross were made, the progeny would be of four types, in the following proportions:

$$A = 0.48, \quad B = 0.32, \quad C = 0.12, \quad D = 0.08$$

The actual segregation of 1225 progeny is shown below, along with the numbers expected according to the hypothesis:

Type	A	B	C	D	Total
Number (X_i)	542	401	164	118	1225
Expected (m_i)	588	392	147	98	1225

As the observed counts differ from those expected, we might wonder if the hypothesis is false. Or, can departures as large as this occur strictly by chance?

The chi-square test is

$$\chi^2 = \sum_{i=1}^{k}\left(\frac{(X_i - m_i)^2}{m_i}\right), \text{ with } (k-1) \text{ degrees of freedom}$$

where

k = Number of groups recognized.
X_i = Observed count for the ith.
m_i = Count expected in the ith group if the hypothesis is true.

For the above data,

$$\chi^2_{3dt} = \frac{(542-588)^2}{588} + \frac{(401-392)^2}{392} + \frac{(164-147)^2}{147} + \frac{(118-98)^2}{98} = 9.85$$

This value exceeds the tabular χ^2 with 3 degrees of freedom at the 0.05 level (i.e., it is greater than 7.81). Hence, the hypothesis would be rejected (if the geneticist believed in testing at the 0.05 level).

BARTLETT'S TEST OF HOMOGENEITY OF VARIANCE

Many of the statistical methods described later are valid only if the variance is homogeneous (i.e., variance within each of the populations is equal). The *t* test of the following section assumes that the variance is the same for each group, and so does the analysis of variance. The fitting of an unweighted regression as described in the last section also assumes that the dependent variable has the same degree of variability (variance) for all levels of the independent variables.

Bartlett's test offers a means of evaluating this assumption. Suppose that we have taken random samples in each of four groups and obtained variances (s^2) of 84.2, 63.8, 88.6, and 72.1 based on samples of 9, 21, 5, and 11 units, respectively. We would like to know if these variances could have come from populations all having the same variance. The quantities needed for Bartlett's test are tabulated here:

Group	Variance (s^2)	(n – 1)	Corrected Sum of Squares (SS)	1/(n – 1)	log s^2	(n – 1)(log s^2)
1	84.2	8	673.6	0.125	1.92531	15.40248
2	63.8	20	1276.0	0.050	1.80482	36.09640
3	88.6	5	443.0	0.200	1.94743	9.73715
4	72.1	10	721.0	0.100	1.85794	18.57940
Sums	—	43	3113.6	0.475	—	79.81543

where the number of groups (k) = 4, and the corrected sum of squares (SS) is

$$\left(\sum X^2 - \frac{\left(\sum X\right)^2}{n}\right) = (n-1)s^2$$

From this we compute the pooled within-group variance:

$$\bar{s}^2 = \frac{\sum SS_i}{\sum (n_i - 1)} = \frac{3113.6}{43} = 72.4093$$

and

$$\log \bar{s}^2 = 1.85979$$

Then the test for homogeneity is

$$\begin{aligned}\chi^2_{(k-1)df} &= (2.3026)\left[\left(\log \bar{s}^2\right)\left(\sum (n_i - 1)\right) - \sum (n_i - 1)\left(\log s_i^2\right)\right]\\ \chi^2_{3df} &= (2.3026)\left[(1.85979)(43) - 79.81543\right]\\ &= 0.358\end{aligned}$$

This value of χ^2 is now compared with the value of χ^2 in an accumulative distribution of chi-square for the desired probability level. A value greater than that given in the table would lead us to reject the homogeneity assumption.

> ***Note:*** The original form of this equation used natural logarithms in place of the common logarithms shown here. The natural log of any number is approximately 2.3026 times its common log—hence, the constant of 2.3026 in the equation. In computations, common logarithms are usually more convenient than natural logarithms.

The χ^2 value given by the above equation is biased upward. If χ^2 is nonsignificant, the bias is not important. However, if the computed χ^2 is just a little above the threshold value for significance, a correction for bias should be applied. The correction (C) is

$$C = \frac{3(k-1) + \left[\sum\left(\frac{1}{n_i - 1}\right) - \frac{1}{\sum (n_i - 1)}\right]}{3(k-1)}$$

The corrected value of χ^2 is then

$$\frac{3(4-1) + \left(0.475 - \frac{1}{43}\right)}{3(4-1)} = 1.0502$$

DID YOU KNOW?

According to Ernst Mayr (1970, 2002), *races* are distinct, generally divergent populations within the same species with relatively small morphological and genetic differences. The populations can be described as ecological races if they arise from adaptations to different local habitats or geographic races when they are geographically isolated. If sufficiently different, two or more races can be identified as subspecies, an official biological taxonomy unit subordinate to species. If not, they are denoted as races, which means that a formal rank should not be given to the group or taxonomists are unsure whether or not a formal rank should be given. Again, according to Mayr, "a subspecies is a geographical race that is sufficiently different taxonomically to be worthy of a separate name."

COMPARING TWO GROUPS BY THE *T* TEST

T TEST FOR UNPAIRED PLOTS

An individual unit in a population may be characterized in a number of different ways. A single tree, for example, can be described as alive or dead, hardwood or softwood, infected or not infected, and so forth. When dealing with observations of this type, we usually want to estimate the proportion of a population having a certain attribute. Or, if there are two or more different groups, we will often be interested in testing whether or not the groups differ in the proportions of individuals having the specified attribute. Some methods of handling these problems have been discussed in previous sections.

Alternatively, we might describe a tree by a measurement of some characteristic such as its diameter, height, or cubic volume. For this measurement type of observation we may wish to estimate the mean for a group as discussed in the section on sampling for measurement variables. If there are two or more groups we will frequently want to test whether or not the group means are different. Often the groups will represent types of treatment that we wish to compare. Under certain conditions, the *t* or *F* tests may be used for this purpose.

Both of these tests have a wide variety of applications. For the present we will confine our attention to tests of the hypothesis that there is no difference between treatment (or group) means. The computational routine depends on how the observations have been selected or arranged. The first illustration of a *t* test of the hypothesis that there is no difference between the means of two treatments assumes that the treatments have been assigned to the experimental units completely at random. Except for the fact that there are usually (but not necessarily) an equal number of units or "plots" for each treatment, there is no restriction on the random assignment of treatments.

In this example the "treatments" were two races of white pine which were to be compared on the basis of their volume production over a specified period of time. Twenty-two square, 1-acre plots were staked out for the study; 11 of these were selected entirely at random and planted with seedlings of race A. The remaining 11 were planted with seedlings of race B. After the prescribed time period the pulpwood volume (in cords—a stack of wood 4 ft wide by 4 ft high by 8 ft in length) was determined for each plot:

	Race A			**Race B**	
11	5	9	9	6	9
8	10	11	9	13	8
10	8	11	6	5	6
8	8		10	7	
	Sum = 99			Sum = 88	
	Average = 9.0			Average = 8.0	

To test the hypothesis that there is no difference between the race means (sometimes referred to as a null hypothesis—general or default position) we compute

$$t = \frac{\overline{X}_A - \overline{X}_B}{\sqrt{\dfrac{s^2(n_A + n_B)}{(n_A)(n_B)}}}$$

where

$\overline{X}_A$ and $\overline{X}_B$ = Arithmetic means for groups A and B.

n_A and n_B = Number of observations in groups A and B (n_A and n_B do not have to be the same).

s^2 = Pooled within-group variance (calculation shown below).

To compute the pooled within-group variance, we first get the corrected sum of squares (SS) within each group:

$$SS_{\mathrm{A}} = \sum X_{\mathrm{A}}^2 - \frac{\left(\sum X_{\mathrm{A}}\right)^2}{n_{\mathrm{A}}} = 11^2 + 8^2 + \ldots + 11^2 - \frac{(99)^2}{11} = 34$$

$$SS_{\mathrm{B}} = \sum X_{\mathrm{B}}^2 - \frac{\left(\sum X_{\mathrm{B}}\right)^2}{n_{\mathrm{B}}} = 9^2 + 9^2 + \ldots + 6^2 - \frac{(88)^2}{11} = 54$$

Then the pooled variance is

$$s^2 = \frac{SS_{\mathrm{A}} + SS_{\mathrm{B}}}{(n_{\mathrm{A}} - 1) + (n_{\mathrm{B}} - 1)} = \frac{88}{20} = 4.4$$

Hence,

$$t = \frac{9.0 - 8.0}{\sqrt{4.4\left(\frac{11+11}{(11)(11)}\right)}} = \frac{1.0}{\sqrt{0.800000}} = 1.118$$

This value of t has $(n_{\mathrm{A}} - 1) + (n_{\mathrm{B}} - 1)$ degrees of freedom. If it exceeds the tabular value (from a distribution of t table) at a specified probability level, we would reject the hypothesis. The difference between the two means would be considered significant (larger than would be expected by chance if there is actually no difference). In this case, tabular t with 20 degrees of freedom at the 0.05 level is 2.086. Since our sample value is less than this, the difference is not significant at the 0.05 levels.

One of the unfortunate aspects of the t test and other statistical methods is that almost any kind of numbers can be plugged into the equations. But, if the numbers and methods of obtaining them do not meet certain requirements, then the result may be a fancy statistical facade with nothing behind it. In a handbook of this scope it is not possible to make the reader aware of all of the niceties of statistical usage, but a few words of warning are certainly appropriate.

A fundamental requirement in the use of most statistical methods is that the experimental material must be a random sample of the population to which the conclusions are to be applied. In the t test of white pine races, the plots should be a sample of the sites on which the pine are to be grown, and the planted seedlings should be a random sample representing the particular race. A test conducted in one corner of an experimental forest may yield conclusions that are valid only for that particular area or sites that are about the same. Similarly, if the seedlings of a particle race are the progeny of a small number of parents, their performance may be representative of those parents only, rather than of the race.

In addition to assuming that the observations for a given race are a valid sample of the population of possible observations, the t test described above assumes that the population of such observations follows the normal distribution. With only a few observations, it is usually impossible to determine whether or not this assumption has been met. Special studies can be made to check on the distribution, but often the question is left to the judgment and knowledge of the research worker.

Finally, the t test of unpaired plots assumes that each group (or treatment) has the same population variance. Since it is possible to compute a sample variance for each group, this assumption can be checked with Bartlett's test for homogeneity of variance. Most statistical textbooks present variations of the t test that may be used if the group variances are unequal.

Sample Size

If there is a real difference of D feet between the two races of white pine, how many replicates (plots) would be needed to show that it is significant? To answer this, we first assume that the number of replicates will be the same for each group ($n_A = n_B = n$). The equation for t can then be written as

$$t = \frac{D}{\sqrt{\frac{2s^2}{n}}} \quad \text{or} \quad n = \frac{2t^2s^2}{D^2}$$

Next we need an estimate of the within-group variance, s^2. As usual, this must be determined from previous experiments, or by special study of the populations.

■ EXAMPLE 5.9

Suppose that we plan to test at the 0.05 level and wish to detect a true difference of $D = 1$ cord if it exists. From previous tests, we estimate $s^2 = 5.0$. Thus, we have

$$n = \frac{2t^2s^2}{D^2} = 2t^2\left(\frac{5.0}{1.0}\right)$$

Here we hit a snag. In order to estimate n we need a value for t, but the value of t depends on the number of degrees of freedom, which depends on n. The situation calls for an iterative solution, which is a mathematical procedure that generates a sequence of improving approximate solutions for a class of problems—in other words, a fancy name for trial and error. We start with a guessed value for n, say $n_0 = 20$. As t has $(n_A - 1) + (n_B - 1) = 2(n - 1)$ degrees of freedom, we'll use $t = 2.025$ (which is equal to $t_{0.05}$ with 38 degrees of freedom) and compute

$$n_1 = 2(2.025)^2\left(\frac{5.0}{1.0}\right) = 41$$

The proper value of n will be somewhere between n_0 and n_1—much closer to n_1 than to $n_{0.}$ We can now make a second guess at n and repeat the process. If we try $n_2 = 38$, t will have $2(n - 1) = 74$ degrees of freedom and $t_{0.05} = 1.992$. Thus,

$$n_3 = 2(1.992)^2\left(\frac{5.0}{1.0}\right) = 39.7$$

Thus, n appears to be over 39 and we will use $n = 40$ plots for each group, or a total of 80 plots.

T TEST FOR PAIRED PLOTS

A second test was made of the two races of white pine. It also had 11 replicates of each race, but instead of the two races being assigned completely at random over the 22 plots, the plots were grouped into 11 pairs and a different race was randomly assigned to each member of a pair. The cordwood volumes at the end of the growth period were as follows:

	Plot Pair												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Sum**	**Mean**
Race A	12	8	8	11	10	9	11	11	13	10	7	110	10.0
Race B	10	7	8	9	11	6	10	11	10	8	9	99	9.0
$d_i = A_i - B_i$	2	1	0	2	–1	3	1	0	3	2	–2	11	1.0

As before, we wish to test the hypothesis that there is no real difference between the race means. The value of t when the plots have been paired is

$$t = \frac{\bar{X}_A - \bar{X}_B}{\sqrt{\frac{s_d^2}{n}}} = \frac{\bar{d}}{\sqrt{s_{\bar{d}}^2}}, \text{ with } (n-1) \text{ degrees of freedom}$$

where

n = Number of pairs of plots.

s_d^2 = Variance of the individual differences between A and B.

$$s_d^2 = \frac{\sum d_i^2 - \frac{\left(\sum d_i\right)^2}{n}}{(n-1)} = \frac{2^2 + 1^2 + \ldots + (-2)^2 - \frac{11^2}{11}}{10} = 2.6$$

So, in this example we find

$$t_{10df} = \frac{10.0 - 9.0}{\sqrt{2.6/11}} = 2.057$$

When this value of 2.057 is compared to the tabular value of t in a distribution of t table ($t_{0.05}$ with 10 degrees of freedom = 2.228), we find that the difference is not significant at the 0.05 level. That is, a sample means difference of 1 cord or more could have occurred by chance more than one time in twenty even if there is no real difference between the race means. Usually such an outcome is not regarded as sufficiently strong evidence to reject the hypothesis.

"The method of paired observations is a useful technique. Compared with the standard two-sample t test, in addition to the advantage that we do not have to assume that the two samples are independent, we also need not assume that the variances of the two samples are equal" (Hamburg, 1987, p. 304). Moreover, the paired test will be more sensitive (capable of detecting smaller real differences) than the unpaired test whenever the experimental units (plots, in this case) can be grouped into pairs such that the variation between pairs is appreciably larger than the variation within pairs. The basis for paring plots may be geographic proximity or similarity in any other characteristic that is expected to affect the performance of the plot. In animal-husbandry studies, litter mates are often paired, and where patches of human skin are the plots, the left and right arms may constitute the pair. If the experimental units are very homogeneous, then there may be no advantage in pairing.

Number of Replicates

The number (n) of plot pairs needed to detect a true mean difference of size D is

$$n = \frac{t^2 s_d^2}{D^2}$$

COMPARISON OF TWO OR MORE GROUPS BY ANALYSIS OF VARIANCE

Complete Randomization

A planter wanted to compare the effects of five site-preparation treatments on the early height growth of planted pine seedlings. He laid out 25 plots and applied each treatment to 5 randomly selected plots. The plots were then hand planted and at the end of 5 years the height for all pines was measured and an average height computed for each plot. The plot averages (in feet) were as follows:

	Treatments					
	A	**B**	**C**	**D**	**E**	**Total**
	15	16	13	11	14	
	14	14	12	13	12	
	12	13	11	10	12	
	13	15	12	12	10	
	13	14	10	11	11	
Sums	67	72	58	57	59	313
Treatment means	13.4	14.4	11.6	11.4	11.8	12.52

Looking at the data we see that there are differences among the treatment means: A and B have higher averages than C, D, and E. Soils and planting stock are seldom completely uniform, however, so we would expect some differences even if every plot had been given exactly the same site-preparation treatment. The question is, can differences as large as this occur strictly by chance if there is actually no difference among treatments? If we decide that the observed differences are larger than might be expected to occur strictly by chance, then the inference is that the treatment means are not equal. Statistically speaking, we reject the hypothesis of no difference among treatment means.

Problems like this are neatly handled by an analysis of variance. To make this analysis, we need to fill in a table like the following:

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares
Treatments	4		
Error	20		
Total	24		

Source of Variation

There are a number of reasons why the height growth of these 25 plots might vary, but only one can be definitely identified and evaluated—that attributable to treatments. The unidentified variation is assumed to represent the variation inherent in the experimental material and is labeled error. Thus, total variation is being divided into two parts: one part attributable to treatments, and the other unidentified and called error.

Degrees of Freedom

Degrees of freedom are difficult to explain in non-statistical language. In the simpler analyses of variance, however, they are not difficult to determine. For the total, the degrees of freedom are one less than the number of observations; there are 25 plots, so the total has 24 degrees of freedom. For the sources, other than error, the degrees of freedom are one less than the number of classes or groups recognized in the source. Thus, in the source labeled "Treatments," there are five groups (five treatments), so there will be four degrees of freedom for treatments. The remaining degrees of freedom (24 – 4 = 20) are associated with the error term.

Sums of Squares

There is a sum of squares associated with every source of variation. These *SS* are easily calculated as follows. First we need what is known as a "correction term," or *CT*. This is simply

$$CT = \frac{\left(\sum^{n} X\right)^2}{n} = \frac{313^2}{25} = 3918.76, \text{ where } \sum^{n} \text{ is the sum of } n \text{ items}$$

Then the total sum of squares is

$$\text{Total } \underset{24df}{SS} = \sum^{n} X^2 - CT = \left(15^2 + 14^2 + \ldots + 11^2\right) - CT = 64.24$$

The sum of squares attributable to treatments is

$$\text{Treatment } \underset{4df}{SS} = \frac{\sum^{n} (\text{treatment totals})^2}{\text{No. of plots per treatment}} - CT$$

$$= \frac{67^2 + 72^2 + \ldots + 59^2}{5} - CT = \frac{19{,}767}{5} - CT = 34.64$$

Note that in both *SS* calculations the number of items squared and added was one more than the number of degrees of freedom associated with the sum of squares. The number of degrees of freedom just below the *SS* and the numbers of items to be squared and added over the *n* value provided a partial check as to whether the proper totals are being used in the calculation—the degrees of freedom must be one less than the number of items.

Note also that the divisor in the treatment *SS* calculation is equal to the number of individual items that go to make up each of the totals being squared in the numerator. This was also true in the calculation of total *SS*, but there the divisor was 1 and did not have to be shown. Note further that the divisor times the number over the summation sign (5 × 5 = 25 for treatments) must always be equal to the total number of observations in the test—another check.

The sum of squares for error is obtained by subtracting the treatment *SS* from total *SS*. A good habit to get into when obtaining sums of squares by subtraction is to perform the same subtraction using degrees of freedom. In the more complex designs, doing this provides a partial check on whether the right items are being used.

Mean Squares

The mean squares are now calculated by dividing the sums of squares by the associated degrees of freedom. It is not necessary to calculate the mean squares for the total. The items that have been calculated are entered directly into the analysis table, which at the present stage would look like this:

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares
Treatments	4	34.64	8.66
Error	20	29.60	1.48
Total	24	64.25	

An *F* test of treatments (used to reject the null hypothesis) is now made by dividing the mean square for treatments by the mean square for error. In this case,

$$F = \frac{8.66}{1.48} = 5.851$$

Fortunately, critical values of the *F* ratio have been tabulated for frequently used significance levels analogous to the χ^2 distribution. Thus, the result, 5.851, can be compared to the appropriate value of *F* in the table. The tabular *F* for significance at the 0.05 level is 2.87 and that for the 0.01 level is 4.43. As the calculated value of *F* exceeds 4.43, we conclude that the difference in height growth between treatments is significant at the 0.01 level. (More precisely, we reject the hypothesis that there is no difference in mean height growth between the treatments.) If *F* had been smaller than 4.43 but larger than 2.87, we would have said that the difference is significant at the 0.05 level. If *F* had been less than 2.87, we would have said that the difference between treatments is not significant at the 0.05 level. Researchers should select their own levels of significance (preferably in advance of the study), keeping in mind that significance at the α (alpha) level, for example, means this: If there is actually no difference among treatments, then the probability of getting chance differences as large as those observed is α or less.

t Test vs. the Analysis of Variance

If only two treatments are compared, the analysis of variance of a completely randomized design and the *t* test of unpaired plots lead to the same conclusion. The choice of test is strictly one of personal preference, as may be verified by applying the analysis of variance to the data used to illustrate the *t* test of unpaired plots. The resulting *F* value will be equal to the square of the value of *t* that was obtained (i.e., $F = t^2$). Like the *t* test, the *F* test is valid only if the variable observed is normally distributed and if all groups have the same variance.

MULTIPLE COMPARISONS

In the example illustrating the completely randomized design, the difference among treatments was found to be significant at the 0.01 probability level. This is interesting as far as it goes, but usually we will want to take a closer look at the data, making comparisons among various combinations of the treatments. Suppose, for example, that A and B involve some mechanical form of site preparation while C, D, and E are chemical treatments. We might want to test whether the average of A and B together differ from the combined average of C, D, and E. Or, we might wish to test whether A and B differ significantly from each other. When the number of replications (*n*) is the same for all treatments, such comparisons are fairly easy to define and test.

The question of whether the average of treatments A and B differs significantly from the average of treatments C, D, and E is equivalent to testing whether the linear contrast

$$\bar{Q} = \left(3\bar{\mathrm{A}} + 3\bar{\mathrm{B}}\right) - \left(2\bar{\mathrm{C}} + 2\bar{\mathrm{D}} + 2\bar{\mathrm{E}}\right)$$

differs significantly from zero ($\bar{\mathrm{A}}$ = the mean for treatment A, etc.). Note that the coefficients of this contrast sum to zero (3 + 3 – 2 – 2 – 2 = 0) and are selected so as to put the two means in the first group on an equal basis with the three means in the second group.

F Test with Single Degree of Freedom

A comparison specified in advance of the study (on logical grounds and before examination of the data) can be tested by an *F* test with single degree of freedom. For the linear contrast

$$\hat{Q} = a_1\bar{X}_1 + a_2\bar{X}_2 + a_3\bar{X}_3 + \ldots$$

among means based on the same number (n) of observations, the sum of squares has one degree of freedom and is computed as

$$\underset{1df}{SS} = \frac{n\hat{Q}^2}{\sum a_i^2}$$

This sum of squares divided by the mean square for error provides an F test of the comparison. Thus, in testing A and B vs. C, D, and E we have

$$\hat{Q} = 3(13.4) + 3(14.4) - 2(11.6) - 2(11.4) - 2(11.8) = 13.8$$

and

$$\underset{1df}{SS} = \frac{5(13.8)^2}{3^3 + 3^3 + (-2)^2 + (-2)^2 + (-2)^2} = \frac{952.20}{30} = 31.74$$

Then, dividing by the error mean square gives the F value for testing the contrast:

$$F = \frac{31.74}{1.48} = 21.446 \text{ with 1 and 20 degrees of freedom}$$

This exceeds the tabular value of F (4.35) at the 0.05 probability level. If this is the level at which we decided to test, we would reject the hypothesis that the mean of treatments A and B does not differ from the mean of treatments C, D, and E.

If $\hat{Q}$ is expressed in terms of the treatment totals rather than their means so that

$$\hat{Q}_T = a_1\left(\sum X_1\right) + a_2\left(\sum X_2\right) + \ldots$$

then the equation for the single degree of freedom sum of squares is

$$\underset{1df}{SS} = \frac{\hat{Q}_T^2}{n\left(\sum a_i^2\right)}$$

The results will be the same as those obtained with the means. For the test of A and B vs. C, D, and E,

$$\hat{Q}_T = 3(67) + 3(72) - 2(58) - 2(57) - 2(59) = 69$$

And,

$$\underset{1df}{SS} = \frac{69^2}{5\left[3^2 + 3^2 + (-2)^2 + (-2)^2 + (-2)^2\right]} = \frac{4761}{150} = 31.74\text{, as before}$$

Working with the totals saves the labor of computing means and avoids possible rounding errors.

Scheffe's Test

Quite often we will want to test comparisons that were not anticipated before the data were collected. If the test of treatments was significant, such unplanned comparisons can be tested by the method of Scheffe, or Scheffe's test. Named after the American statistician Henry Scheffe, the Scheffe test adjusts significant levels in a linear regression analysis to account for multiple comparisons. It is particularly useful in analysis of variance and in constructing simultaneous bands for regressions involving basic functions. When there are n replications of each treatment, k degrees of freedom for treatment, and v degrees of freedom for error, any linear contrast among the treatment means

$$\hat{Q} = a_1\bar{X}_1 + a_2\bar{X}_2 + \cdots$$

is tested by computing

$$F = \frac{n\hat{Q}^2}{k\left(\sum a_i^2\right)(\text{Error mean square})}$$

This value is then compared to the tabular value of F with k and v degrees of freedom. For example, to test treatment B against the means of treatments C and E we would have

$$\hat{Q} = \left[2\bar{\mathrm{B}} - (\bar{\mathrm{C}} + \bar{\mathrm{E}})\right] = [2(14.4) - 11.6 - 11.8] = 5.4$$

And,

$$F = \frac{5(5.4)^2}{(4)\left[2^2 + (-1)^2 + (-1)^2\right](1.48)} = 4.105, \text{ with 4 and 20 degrees of freedom}$$

This figure is larger than the tabular value of F (2.87), so in testing at the 0.05 level we would reject the hypothesis that the mean for treatment B did not differ from the combined average of treatments C and E.

For a contrast (Q_T) expressed in terms of treatment totals, the equation for F becomes

$$F = \frac{\hat{Q}_T^2}{nk\left(\sum a_i^2\right)(\text{Error mean square})}$$

Unequal Replication

If the number of replications is not the same for all treatments, then for the linear contrast

$$\hat{Q} = a_1\bar{X}_1 + a_2\bar{X}_2 + \ldots$$

The sum of squares in the single degree of freedom F test is given by

$$\underset{1df}{SS} = \frac{\hat{Q}_2}{\left(\frac{a_1^2}{n_1} + \frac{a_2^2}{n_2} + \ldots\right)}$$

where n_i is the number of replications on which $\bar{X}_i$ is based.

With unequal replication, the F value in Scheffe's test is computed by the equation

$$F = \frac{\hat{Q}^2}{k\left(\frac{a_1^2}{n_1} + \frac{a_2^2}{n_2} + \ldots\right)(\text{Error mean square})}$$

Selecting the coefficients (a_i) for such contrasts can be tricky. When testing the hypothesis that there is no difference between the means of two groups of treatments, the positive coefficients are usually

$$\text{Positive } a_i = \frac{n_i}{p}$$

where p is the total number of plots in the group of treatments with positive coefficients.

The negative coefficients are

$$\text{Negative } a_j = \frac{n_j}{m}$$

where m is the total number of plots in the group of treatments with negative coefficients.

To illustrate, if we wish to compare the mean of treatments A, B, and C with the mean of treatments D and E and there are two plots of treatment A, three of B, five of C, three of D, and two of E, then $p = 2 + 3 + 5 = 10$, $m = 3 + 2 = 5$, and the contrast would be

$$\hat{Q} = \left(\frac{2}{10}\bar{\text{A}} + \frac{3}{10}\bar{\text{B}} + \frac{5}{10}\bar{\text{C}}\right) - \left(\frac{3}{5}\bar{\text{D}} + \frac{2}{5}\bar{\text{E}}\right)$$

Randomized Block Design

There are two basic types of the two-factor analysis of variance: *completely randomized design* (discussed in the previous section) and *randomized block design*. In the completely randomized design, the error mean square is a measure of the variation among plots treated alike. It is in fact an average of the within-treatment variances, as may easily be verified by computation. If there is considerable variation among plots treated alike, the error mean square will be large and the F test for a given set of treatments is less likely to be significant. Only large differences among treatments will be detected as real and the experiment is said to be insensitive.

Often the error can be reduced (thus giving a more sensitive test) by use of a randomized block design in place of complete randomization. In this design, similar plots or plots that are close together are grouped into blocks. Usually the number of plots in each block is the same as the number of treatments to be compared, though there are variations having two or more plots per treatment in each block. The blocks are recognized as a source of variation that is isolated in the analysis. A general rule in randomized block design is to "block what you can, randomize what you can't." In other words, blocking is used to remove the effects of nuisance variables or factors. Nuisance factors are those that may affect the measured result but are not of primary interest. For example, in applying a treatment, nuisance factors might be the time of day the experiment was run, the room temperature, or the specific operator who prepared the treatment (Addelman, 1969, 1970).

As an example, a randomized block design with five blocks was used to test the height growth of cottonwood cuttings from four selected parent trees. The field layout looked like this:

D	B	B	C	A	D	B	A	C	D
C	A	A	D	B	C	C	D	A	B
I		II		III		IV		V	

DID YOU KNOW?

The term "block" derives from experimental design work in agriculture in which parcels of land are referred to as *blocks*. In a randomized block design, treatments are randomly assigned to units within each block. To test the yield of different fertilizers, for example, this design ensures that the best fertilizer is applied to all types of soil, not just the best soil (Hamburg, 1987).

Each plot consisted of a planting of 100 cuttings of the clone assigned to that plot. When the trees were 5 years old the heights of all survivors were measured and an average computed for each plot. The plot averages (in feet) by clones and blocks are summarized below:

	Clone				**Block**
Block	**A**	**B**	**C**	**D**	**Totals**
I	18	14	12	16	60
II	15	15	16	13	59
III	16	15	8	15	54
IV	14	12	10	12	48
V	12	14	9	14	49
Clone totals	75	70	55	70	270
Clone means	15	14	11	14	—

The hypothesis to be tested is that clones do not differ in mean height. In this design there are two identifiable sources of variation—that attributable to clones and that associated with blocks. The remaining portion of the total variation is used as a measure of experimental error. The outline of the analysis is therefore as follows:

Source of Variation	**Degrees of Freedom**	**Sums of Squares**	**Mean Squares**
Blocks	4		
Clones	3		
Error	12		
Total	19		

The breakdown in degrees of freedom and computation of the various sums of squares follow the same pattern as in the completely randomized design. Total degrees of freedom (19) are one less than the total number of plots. Degrees of freedom for clones (three) are one less than the number of clones. With five blocks, there will be four degrees of freedom for blocks. The remaining 12 degrees of freedom are associated with the error term.

Sums-of-squares calculations proceed as follows:

1. $CT = \dfrac{\left(\sum^{20} X\right)^2}{n} = \dfrac{270^2}{20} = 3645$

2. Total $\underset{19df}{SS} = \sum^{20} X^2 - CT = \left(18^2 + 15^2 + \ldots + 14^2\right) - CT = 3766 - 3645 = 121$

3. Clone $\underset{3df}{SS} = \dfrac{\sum^{4}(\text{Clone totals}^2)}{\text{No. of plots per clone}} - CT = \dfrac{75^2 + 70^2 + 55^2 + 70^2}{5} - CT = 3690 - 3645 = 45$

$$4.\ \text{Block}\ \underset{4df}{SS} = \frac{\sum^{5}(\text{Block totals}^2)}{\text{No. of plots per block}} - CT = \frac{60^2 + 59^2 + \ldots + 49^2}{4} - CT = 3675.5 - 3645 = 30.5$$

$$5.\ \text{Error}\ \underset{12df}{SS} = \text{Total}\ \underset{19df}{SS} - \text{Clone}\ \underset{3df}{SS} - \text{Block}\ \underset{4df}{SS} = 45.5$$

Note that in obtaining the error *SS* by subtraction, we get a partial check on ourselves by subtracting clone and block *df*'s from the total *df* to see if we come out with the correct number of error *df*. If these don't check, we have probably used the wrong sums of squares in the subtraction.

Mean squares are again calculated by dividing the sums of squares by the associated number of degrees of freedom. Tabulating the results of these computations

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares
Blocks	4	30.5	7.625
Clones	3	45.0	15.000
Error	12	45.5	3.792
Total	19	121.0	

F for clones is obtained by dividing the clone means square by the error mean square. In this case F = 15.000/3792 = 3.956. As this is larger than the tabular *F* of 3.49 (obtained from a distribution of *F* table) ($F_{0.05}$ with 3 and 12 degrees of freedom) we conclude that the difference between clones is significant at the 0.05 level. The significance appears to be due largely to the low value of C as compared to A, B, and D.

Comparisons among clone means can be made by the methods previously described. For example, to test the prespecified (i.e., before examining the data) hypothesis that there is no difference between the mean of clone C and the combined average A, B, and D we would have:

$$\underset{1df}{SS}\ \text{for}\ (\text{A} + \text{B} + \text{D vs. C}) = \frac{5\left(3\bar{\text{C}} - \bar{\text{A}} - \bar{\text{B}} - \bar{\text{D}}\right)^2}{3^2 + (-1)^2 + (-1)^2 + (-1)^2} = \frac{5(-10)^2}{12} = 41.667$$

Then,

$$F = \frac{41.667}{3.792} = 10.988$$

Tabular *F* at the 0.01 level with 1 and 12 degrees of freedom is 9.33. As calculated *F* is greater than this, we conclude that the difference between C and the average of A, B, and D is significant at the 0.01 level.

The sum of squares for this single-degree-of-freedom comparison (41.667) is almost as large as that for clones (45.0) with three degrees of freedom. This result suggests that most of the clonal variation is attributable to the low value of C, and that comparisons between the other three means are not likely to be significant.

DID YOU KNOW?

With only two treatments, the analysis of variance of a randomized block design is equivalent to the *t* test of paired replicates. The value of *F* will be equal to the value of t^2 and the inferences derived from the tests will be the same. The choice of tests is a matter of personal preference.

There is usually no reason for testing blocks, but the size of the block mean square relative to the mean square for error does give an indication of how much precision was gained by blocking. If the block mean square is large (at least two or three times as large as the error mean square) the test is more sensitive than it would have been with complete randomization. If the block mean square is about equal to or only slightly larger than the error mean square, the use of blocks has not improved the precision of the test. The block mean square should not be appreciably smaller than the error mean square. If it is, the method of conducting the study and the computations should be re-examined.

In addition to the assumption of homogeneous variance and normality, the randomized block design assumes that there is no interaction between treatments and blocks; that is, that differences among treatments are about the same in all blocks. Because of this assumption, it is not advisable to have blocks that differ greatly, as they may cause an interaction with treatments.

LATIN SQUARE DESIGN

In the randomized block design the purpose of blocking is to isolate a recognizable extraneous source of variation. If successful, blocking reduces the error mean square and gives a more sensitive test than could be obtained by complete randomization. In some situations, however, we have a two-way source of variation that cannot be isolated by blocks alone. In an agricultural field, for example, fertility gradients may exist both parallel to and at right angles to plowed rows. Simple blocking isolates only one of these sources of variation, leaving the other to swell the error term and reduce the sensitivity of the test.

When such a two-way source of extraneous variation is recognized or suspected, the Latin square design may be helpful. In this design, the total number of plots or experimental units is made equal to the square of the number of treatments. In forestry and agricultural experiments, the plots are often (but not always) arranged in rows and columns, with each row and column having a number of poles equal to the number of treatments being tested. The rows represent different levels of one source of extraneous variation while the columns represent different levels of the other source of extraneous variation. Thus, before the assignment of treatments, the field layout of a Latin square for testing five treatments might look like this:

				Columns		
		1	**2**	**3**	**4**	**5**
Rows	**1**					
	2					
	3					
	4					
	5					

Treatments are assigned to plots at random, but with the very important restriction that a given treatment cannot appear more than once in any row or any column. An example of a field layout of a Latin square for testing five treatments is given below. The letters represent the assignment of five treatments (which here are five species of hardwoods). The numbers show the average 5-year height growth by plots. The tabulation below shows the totals for rows, columns, and treatments:

	Columns				
Rows	**1**	**2**	**3**	**4**	**5**
1	C 13	A 21	B 16	E 16	D 14
2	A 18	B 15	D 17	C 17	E 15
3	D 17	C 15	E 15	A 15	B 18
4	E 18	D 18	C 16	B 14	A 16
5	B 17	E 16	A 25	D 19	C 14

Row	$\sum$	**Column**	$\sum$	**Treatment**	$\sum$	$\bar{X}$
1	80	1	83	A	95	19
2	82	2	85	B	80	16
3	80	3	89	C	75	15
4	82	4	81	D	85	16
Total	415		415		415	16.6

The partitioning of degrees of freedom, the calculation of sums of squares, and the subsequent analysis follow much the same pattern illustrated previously for randomized blocks.

$$CT = \frac{\left(\sum^{25} X\right)^2}{n} = \frac{415^2}{25} = \frac{172{,}225}{25} = 6889.0$$

$$\text{Total } \underset{24df}{SS} = \sum^{25} X^2 - CT = 7041 - CT = 152.0$$

$$\text{Row } \underset{4df}{SS} = \frac{\sum^{5}(\text{Row totals}^2)}{\text{No. of plots per row}} - CT = \frac{34{,}529}{5} - CT = 16.8$$

$$\text{Column } \underset{4df}{SS} = \frac{\sum^{5}(\text{Column totals}^2)}{\text{No. of plots per column}} - CT = \frac{34{,}525}{5} - CT = 16.0$$

$$\text{Species } \underset{4df}{SS} = \frac{\sum^{5}(\text{Species totals}^2)}{\text{No. of plots per species}} - CT = \frac{34{,}675}{5} - CT = 46.0$$

$$\text{Error } \underset{12df}{SS} = \text{Total } \underset{24df}{SS} - \text{Row } \underset{4df}{SS} - \text{Column } \underset{4df}{SS} - \text{Species } \underset{4df}{SS} = 73.2$$

The analysis of variance is as follows:

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares
Rows	4	16.8	4.2
Columns	4	16.0	4.0
Species	4	46.0	11.5
Error	12	73.2	6.1
Total	24	152.0	

$$F \text{ (for species)} = \frac{11.5}{6.1} = 1.885$$

As the computed value of F is less than the tabular value of F at the 0.05 level (with 4/12 degrees of freedom), the differences among species are considered nonsignificant.

The Latin square design can be used whenever there is a two-way heterogeneity that cannot be controlled simply by blocking. In greenhouse studies, distance from a window could be treated as a row effect while distance from the blower or heater might be regarded as a column effect. Though the plots are often physically arranged in rows or columns, this is not required. When testing the use of materials in a manufacturing process where different machines and machine operators will be involved, the variation between machines could be treated as a row effect and the variation due to operators could be treated as a column effect. The Latin square should not be used if an interaction between rows and treatments or columns and treatments is suspected.

FACTORIAL EXPERIMENTS

In environmental practice, knowledge that interactions between elements of the environment occur and an understanding of what their influence or impact on the environment is, or can be, is important. Consider a comparison of corn yields following three rates or levels of nitrogen fertilization indicating that the yields depended on how much phosphorus was used along with the nitrogen. The differences in yield were smaller when no phosphorus was used than when the nitrogen applications were accompanied by 100 lb/acre of phosphorus. In statistics, this situation is referred to as an interaction between nitrogen and phosphorus. Another example is when leaf litter was removed from the forest floor, the catch of pine seedlings was much greater than when the litter was not removed, but for red oak the reverse was true—the seedling catch was lower where litter was removed. Thus, species and litter treatment were interacting.

Interactions are important in the interpretation of study results. In the presence of an interaction between species and litter treatment it obviously makes no sense to talk about the effects of litter removal without specifying the species. The nitrogen–phosphorus interaction means that it may be misleading to recommend a level of nitrogen without mentioning the associated level of phosphorus.

Factorial experiments are aimed at evaluating known or suspected interactions. In these experiments, each factor to be studied is tested at several levels and each level of a factor is tested at all possible combinations of the levels of the other factors. In a planting test involving three species of trees and four methods of preplanting site preparation, each method will be applied to each species, and the total number of treatment combinations will be 12. In a factorial test of the effects of two nursery treatments on the survival of four species of pine planted by three different methods, there would be 24 ($2 \times 4 \times 3 = 24$) treatment combinations.

The method of analysis can be illustrated by a factorial test of the effects of three levels of nitrogen fertilization (0, 100, and 200 lb/acre) on the growth of three species (A, B, and C) of planted pine. The nine possible treatment combinations were assigned at random to nine plots in each of three blocks. Treatments were evaluated on the basis of average annual height growth in inches per year over a 3-year period. Field layout and plot data were as follows (with subscripts denoting nitrogen levels: 0 = 0, 1 = 100, 2 = 200):

C_2 17	B_2 18	C_0 37
A_0 45	B_0 24	C_1 20
B_1 21	A_2 24	A_1 17

I

B_2 23	C_2 20	A_1 18
B_1 18	A_2 14	C_0 43
A_0 40	C_1 25	B_0 35

II

C_1 19	C_2 21	A_0 37
B_1 19	A_2 17	A_1 28
B_0 29	C_0 39	B_2 15

III

Preliminary analysis of the nine combinations (temporarily ignoring their factorial nature) is made just as though this were a straight randomized block design (which is exactly what it is). (See table below.)

Summary of Plot Data

Species	Nitrogen Level	Blocks			Nitrogen Subtotals	Species Totals
		I	II	III		
A	0	45	40	37	122	
	1	17	18	28	63	
	2	24	14	17	55	
	Block subtotals	86	72	82		240
B	0	24	35	29	88	
	1	21	18	19	58	
	2	18	23	15	56	
	Block subtotals	63	76	63		202
C	0	37	43	39	119	
	1	20	25	19	64	
	2	17	20	21	58	
	Block subtotals	74	88	79		241
All species	0	106	118	105	329	
	1	58	61	66	185	
	2	59	57	53	169	
	Totals	223	236	224	**683**	

$$CT = \frac{\left(\sum^{27} X\right)^2}{27} = \frac{683^2}{27} = 17,277.3704$$

$$\text{Total } \underset{26df}{SS} = \sum^{26} X^2 - CT = (45^2 + 17^2 + \ldots + 21^2) - CT = 2275.63$$

$$\text{Block } \underset{2df}{SS} = \frac{\sum^{3} (\text{Block totals}^2)}{\text{No. of plots per block}} - CT = \frac{\left(223^2 + 236^2 + 224^2\right)}{9} - CT = 11.6296$$

$$\text{Treatment } \underset{8df}{SS} = \frac{\sum^{9}(\text{Treatment totals}^2)}{\text{No. of plots per treatment}} - CT = \frac{\left(122^2 + 63^2 + 58^2\right)}{3} - CT = 1970.2963$$

$$\text{Error } \underset{16df}{SS} = \text{Total } \underset{26df}{SS} - \text{Treatment } \underset{8df}{SS} - \text{Block } \underset{2df}{SS} = 293.7037$$

Tabulating these in the usual form:

Source of Variation	**Degrees of Freedom**	**Sums of Squares**	**Mean Squares**
Blocks	2	11.6296	5.8148
Treatments	8	1970.2963	246.2870
Error	16	293.7037	18.3565
Total	26	2275.6296	

$$F_{8/16df} = \frac{246.2870}{18.3565} = 13.417, \text{ significant at } 0.01$$

The next step is to analyze the components of the treatment variability. How do the species compare? What is the effect of fertilization? And does fertilization affect all species the same way (i.e., is there a species-nitrogen interaction)? To answer these questions we have to partition the degrees of freedom and sums of squares associated with treatments. This is easily done by summarizing the data for the nine combinations in a two-way table:

	Nitrogen Levels			
Species	**0**	**1**	**2**	**Totals**
A	122	63	55	240
B	88	58	56	202
C	119	64	58	241
Totals	329	185	169	683

The nine individual values will be recognized as those that entered into the calculation of the treatment *SS*. Keeping in mind that each entry in the body of the table is the sum of three plot values and that the species and nitrogen totals are each the sum of nine plots, the sums of squares for species, nitrogen, and the species–nitrogen interaction can be computed as follows:

$$\text{Treatment } \underset{8df}{SS} = 1970.2963, \text{ as previously calculated}$$

$$\text{Species } \underset{2df}{SS} = \frac{\sum^{3}(\text{Species totals}^2)}{\text{No. of plots per species}} - CT = \frac{\left(240^2 + 202^2 + 241^2\right)}{9} - CT$$

$$= \frac{156{,}485}{9} - CT = 109.8518$$

$$\text{Nitrogen } \underset{2df}{SS} = \frac{\sum^{3}(\text{Nitrogen totals}^2)}{\text{No. of plots per level of nitrogen}} - CT$$

$$= \frac{\left(329^2 + 185^2 + 169^2\right)}{9} - CT = \frac{171{,}027}{9} - CT = 1725.6296$$

$$\text{Species–nitrogen interation } \underset{4df}{SS} = \text{Treatment } \underset{8df}{SS} - \text{Species } \underset{2df}{SS} - \text{Nitrogen } \underset{2df}{SS} = 134.8149$$

The analysis now becomes:

Source of Variation	**Degrees of Freedom**	**Sums of Squares**	**Mean Squares**	***F***
Blocks	2	11.6296	5.8148	—
Treatments	8	1970.2963	246.2870	13.417[b]
Species	2[a]	109.8518[a]	54.9259	2.992[c]
Nitrogen	2[a]	1725.6296[a]	862.8148	47.003[b]
Species-nitrogen	4[a]	134.8149[a]	33.7037	1.836[c]
Error	16	293.7037	18.3565	—
Total	26	2275.6296	—	—

[a] These figures are a partitioning of the degrees of freedom and sums of squares for treatments and are therefore not included in the total at the bottom of the table.

[b] Significant at the 0.01 level.

[c] Not significant.

The degrees of freedom for simple interactions can be obtained in two ways. The first way is by subtracting the degrees of freedom associated with the component factors (in this case, two for species and two for nitrogen levels) from the degrees of freedom associated with all possible treatment combinations (eight in this case). The second way is to calculate the interaction degrees of freedom as the product of the component factor degrees of freedom (in this case, 2 × 2 = 4). Do it both ways as a check. The *F* values for species, nitrogen, and the species–nitrogen interaction are calculated by dividing their mean squares by the mean square for error. The analysis indicates a significant difference among levels of nitrogen, but no difference between species and no species–nitrogen interaction.

As before, a prespecified comparison among treatment means can be tested by breaking out the sum of squares associated with that comparison. To illustrate the computations, we will test nitrogen vs. no nitrogen and also 100 lb vs. 200 lb of nitrogen.

$$\text{Nitrogen vs. no nitrogen } \underset{1df}{SS} = \frac{9\left[2\left(\frac{329}{9}\right) - 1\left(\frac{185}{9}\right) - 1\left(\frac{169}{9}\right)\right]^2}{2^2 + 1^2 + 1^2}$$

$$= \frac{[2(329) - 185 - 169]^2}{9(6)} = 1711.4074$$

In the numerator, the mean for the zero level of nitrogen is multiplied by 2 to give it equal weight with the mean of levels 1 and 2 with which it is compared. The 9 is the number of plots on which each mean is based. The $(2^2 + 1^2 + 1^2)$ in the denominator is the sum of squares of the coefficients used in the numerator.

$$\text{100 lb vs. 200 lb } \underset{1df}{SS} = \frac{9\left[1\left(\dfrac{189}{9}\right) - 1\left(\dfrac{169}{9}\right)\right]^2}{1^2 + 1^2}$$

$$= \frac{[185 - 169]^2}{9(2)} = 14.2222$$

Note that these two sums of squares (1711.4075 and 14.2222), each with one degree of freedom, add up to the sum of squares for nitrogen (1,725.6296) with two degrees of freedom. This additive characteristic holds true only if the individual degree of freedom comparisons selected are orthogonal (i.e., independent). When the number of observations is the same for all of the treatments, then the orthogonality of any two comparisons can be checked in the following manner.

First, tabulate the coefficients and check to see that for each comparison the coefficients sum to zero:

	Nitrogen Level			
Comparison		**1**	**2**	**Sum**
$2N_0$ vs. $N_1 + N_2$	2	–	–	0
N_1 vs. N_2	0	+	–	0
Product of coefficients	0	–	–	0

Then, for two comparisons to be orthogonal the sum of the products of corresponding coefficients must be zero. Any sum of squares can be partitioned in a similar manner, with the number of possible orthogonal individual degree of freedom comparisons being equal to the total number of degrees of freedom with which the sum of squares is associated.

The sum of squares for species can also be partitioned into two orthogonal single-degree-of-freedom comparisons. If the comparisons were specified before the data were examined, we might make single degree of freedom tests of the difference between B and the average of A and C and also of the difference between A and C. The method is the same as that illustrated in the comparison of nitrogen treatments. The calculations are as follows:

$$\text{2B vs. (A + C) } \underset{1df}{SS} = \frac{9\left[1\left(\dfrac{240}{9}\right) + 1\left(\dfrac{241}{9}\right) - 2\left(\dfrac{202}{9}\right)\right]^2}{1^2 + 1^2 + 2^2}$$

$$= \frac{[240 + 241 - 2(202)]^2}{9(6)} = 109.7963$$

$$\text{A vs. C } \underset{1df}{SS} = \frac{9\left[1\left(\dfrac{241}{9}\right) - 1\left(\dfrac{240}{9}\right)\right]^2}{1^2 + 1^2} = \frac{[241 - 240]^2}{9(2)} = 0.0555$$

These comparisons are orthogonal, so the sums of squares each with one degree of freedom add up to the species *SS* with two degrees of freedom.

Note that in computing the sums of squares for the single-degree-of-freedom comparisons, the equations have been restated in terms of treatment totals rather than means. This often simplifies the computations and reduces the errors due to rounding.

With the partitioning the analysis has become:

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Square	*F*
Blocks	2	11.6296	5.8148	—
Species	2	109.8518	54.9259	2.992[a]
2B vs. (A + C)	1	109.7963	109.7963	5.981[b]
A vs. C	1	0.0555	0.0555	—
Nitrogen	2	1725.6296	862.8148	47.003[c]
$2N_0$ vs. $(N_1 + N_2)$	1	1711.4074	1711.4074	93.232[c]
N_1 vs. N_2	1	14.2222	14.2222	—
Species × nitrogen interaction	4	134.8149	33.7037	1.836[a]
Error	16	293.7037	18.3565	—
Total	26	2275.6296		—

[a] Not significant.

[b] Significant at the 0.05 level.

[c] Significant at the 0.01 level.

We conclude that species B is poorer than A or C and that there is no difference in growth between A and C. We also conclude that nitrogen adversely affected growth and that 100 lb was about as bad as 200 lb. The nitrogen effect was about the same for all species (i.e., no interaction).

It is worth repeating that the comparisons to be made in an analysis should, whenever possible, be planned and specified prior to an examination of the data. A good procedure is to outline the analysis, putting in all the times that are to appear in the first two columns (source of variation and degrees of freedom) of the table.

The factorial experiment, it will be noted, is not an experimental design. It is, instead, a way of selecting treatments; given two or more factors each at two or more levels, the treatments are all possible combinations of the levels of each factor. If we have three factors with the first at four levels, the second at two levels, and the third at three levels, we will have 4 × 2 × 3 = 24 factorial combinations or treatments. Factorial experiments may be conducted in any of the standard designs. The randomized block and split plot design are the most common for factorial experiments in forest research.

SPLIT-PLOT DESIGN

When two or more types of treatment are applied in factorial combinations, it may be that one type can be applied on relatively small plots while the other type is best applied to larger plots. Rather than make all plots of the size needed for the second type, a split-plot design can be employed. In this design, the major (large-plot) treatments are applied to a number of plots with replication accomplished through any of the common designs (such as complete randomization, randomized blocks, Latin square). Each major plot is then split into a number of subplots, equal to the number of minor (small-plot) treatments. Minor treatments are assigned at random to subplots within each major plot.

As an example, a test was to be made of direct seeding of loblolly pine at six different dates on burned and unburned seedbeds. To get typical burn effects, major plots 6 acres in size were selected. There were to be four replications of major treatments in randomized blocks. Each major plot was divided into six 1-acre subplots for seeding at six dates. The field layout was somewhat as follows (blocks denoted by Roman numerals, burning treatment by capital letters, day of seeding by lowercase letters):

A	f	b	c
	a	d	e
B	e	a	f
	d	c	b

I

A	c	e	b
	a	d	f
B	a	f	d
	e	b	c

II

B	b	f	c
	a	d	e
A	c	b	d
	f	a	e

III

A	c	a	f
	d	b	e
B	b	e	d
	c	f	a

IV

One pound of seed was sowed on each 1-acre subplot. Seedling counts were made at the end of the first growing season. Results were as follows:

	I		**II**		**III**		**IV**		**Date Subtotals**		**Date Totals**
Date	**A**	**BA**	**BA**		**BA**		**BA**		**B**		
a	900	880	810	1100	760	960	1040	1040	3510	3980	7490
b	880	1050	1170	1240	1060	1110	910	1120	4020	4520	8540
c	1530	1140	1160	1270	1390	1320	1540	1080	5620	4810	10430
d	1970	1360	1890	1510	1820	1490	2140	1270	7820	5630	13450
e	1960	1270	1670	1380	1310	1500	1480	1450	6420	5600	12020
f	830	150	420	380	570	420	760	270	2580	1220	3800
Major plot totals	8070	5850	7120	6880	6910	6800	7870	6230	29,970	25,760	—
Block totals	13,920		14,000		13,710		14,100		—		55,730

The correction term and total sum of squares are calculated using the 48 subplot values:

$$CT = \frac{(\text{Grand total of all subplots})^2}{\text{Total number of subplots}} = \frac{55,730^2}{48} = 64,704,852$$

$$\text{Total } \underset{47df}{SS} = \sum^{48} (\text{Subplot values})^2 - CT = \left(900^2 + 880^2 + \ldots + 270^2\right) - CT = 9,339,648$$

Before partitioning the total sum of squares into its components, it may be instructive to ignore subplots for the moment, and examine the major plot phase of the study. The major phase can be viewed as a straight randomized block design with two burning treatments in each of four blocks. The analysis would be as follows:

Source of Variation	**Degrees of Freedom**
Blocks	3
Burning	1
Error (major plots)	3
Major plots	7

Now, looking at the subplots, we can think of the major plots as blocks. From this standpoint, we would have a randomized block design with six dates of treatment in each of eight blocks (major plots) for which the analysis is as follows:

Source of Variation	Degrees of Freedom
Major plots	7
Dates	5
Remainder	35
Subplots (= Total)	47

In this analysis, the remainder is made up of two components. One of these is the burning–date interaction, with five degrees of freedom. The rest, with 30 degrees of freedom, is called the *subplot error*. Thus, the complete breakdown of the split-plot design is as follows:

Source of Variation	Degrees of Freedom	
Blocks	3	
Burning	1	
Major plot error	3	
Total major plot		7
Date	5	
Total date		5
Burning *X* date	5	
Subplot error	30	
Total remainder		35
Total		47

The various sums of squares are obtained in an analogous manner. We first compute the following:

$$\text{Major plot } \underset{7df}{SS} = \frac{\sum^{8}(\text{Major plot totals}^2)}{\text{No. of subplots per major plot}} - CT$$

$$= \frac{\left(8070^2 + \ldots + 6230^2\right)}{6} - CT = 647{,}498$$

$$\text{Block } \underset{3df}{SS} = \frac{\sum^{4}(\text{Block totals}^2)}{\text{No. of subplots per block}} - CT$$

$$= \frac{\left(13{,}920^2 + \ldots + 14{,}100^2\right)}{12} - CT = 6856$$

$$\text{Burning } \underset{1df}{SS} = \frac{\sum^{2}(\text{Burning treatment totals}^2)}{\text{No. of subplots per burning treatment}} - CT$$

$$= \frac{\left(29{,}970^2 + 25{,}760^2\right)}{24} - CT = 369{,}252$$

$$\text{Major plot error } \underset{3df}{SS} = \text{Major plot } \underset{7df}{SS} - \text{Block } \underset{3df}{SS} - \text{Burning } \underset{1df}{SS} = 271{,}390$$

$$\text{Subplot } \underset{40df}{SS} = \text{Total } \underset{47df}{SS} - \text{Major plot } \underset{7df}{SS} = 8{,}692{,}150$$

$$\text{Date } \underset{5df}{SS} = \frac{\sum^{6}(\text{Date totals}^2)}{\text{No. of subplots per date}} - CT = \frac{\left(7490^2 + \ldots + 3800^2\right)}{8} - CT = 7{,}500{,}086$$

To get the sum of squares for the interaction between date and burning we resort to a factorial experiment device—the two-way table of the treatment combination totals:

	Date						**Burning**
Burning	**a**	**b**	**c**	**d**	**e**	**f**	**Subtotals**
A	3510	4020	5620	7820	6420	2580	29,970
B	3980	4520	4810	5630	5600	1220	25,760
Date subtotals	7490	8540	10,430	13,450	12,020	3800	55,730

$$\text{Date–burning subclass } \underset{11df}{SS} = \frac{\sum^{12}(\text{Date–burning combination totals}^2)}{\text{No. of subplots per date–burning combination}} - CT$$

$$= \frac{\left(3510^2 + \ldots + 1220^2\right)}{4} - CT = 8{,}555{,}723$$

$$\text{Date–burning interaction } \underset{5df}{SS} = \text{Date–burning subclass } \underset{11df}{SS} - \text{Date } \underset{5df}{SS} - \text{Burning } \underset{1df}{SS} = 686{,}385$$

$$\text{Subplot error } \underset{30df}{SS} = \text{Subplot } \underset{40df}{SS} - \text{Date } \underset{5df}{SS} - \text{Date–burning interaction } \underset{5df}{SS} = 505{,}679$$

Thus the completed analysis table is

Source of Variation	**Degrees of Freedom**	**Sums of Squares**	**Mean Squares**
Blocks	3	6856	—
Burning	1	369,252	369,252
Major plot error	3	271,390	90,463
Date	5	7,500,086	1,500,017
Date–burning interaction	5	686,385	137,277
Subplot error	30	505,679	16,856
Total	47	9,339,648	

The F test for burning is

$$F_{1/3df} = \frac{\text{Burning mean square}}{\text{Major plot error mean square}} = \frac{369{,}252}{90{,}463} = 4.082 \text{ (not significant at 0.05 level)}$$

The *F* test for dates is

$$F_{5/30df} = \frac{\text{Date mean square}}{\text{Subplot error mean square}} = \frac{1{,}500{,}017}{16{,}856} = 88.99 \text{ (significant at 0.01 level)}$$

And for the date–burning interaction,

$$F_{5/30df} = \frac{\text{Date–burning interaction mean square}}{\text{Subplot error mean square}} = \frac{137{,}277}{16{,}856} = 8.14 \text{ (significant at 0.01 level)}$$

Note that the major plot error is used to test the sources above the dashed line in the table, while the subplot error is used for the sources below the line. Because the subplot error is a measure of random variation *within* major plots it will usually be smaller than the major plot error, which is a measure of the random variation between major plots. In addition to being smaller, the subplot error will generally have more degrees of freedom than the major plot error, and for these reasons the sources below the dashed line will usually be tested with greater sensitivity than the sources above the line. This fact is important; when planning a split-plot experiment the designer should try to get the items of greatest interest below the line rather than above. Rarely will the major plot error be appreciably smaller than the subplot error. If it is, the conduct of the study and the computations should be carefully examined. If desired, the subplots can also be split for a third level of treatment, producing a split-split-plot design. The calculations follow the same general pattern but are more involved. A split-split-plot design has three separate error terms. For comparisons among major or subplot treatments, *F* tests with a single degree of freedom may be made in the usual manner. Comparisons among major plot treatments should be tested against the major plot error mean square, while subplot treatment comparisons are tested against the subplot error. In addition, it is sometimes desirable to compare the means of two treatment combinations. This can get tricky, for the variation among such means may contain more than one source of error. A few of the more common cases are discussed below.

In general, the *t* test for comparing two equally replicated treatment means is

$$t = \frac{\text{Mean difference}}{\text{Standard error of the mean difference}} = \frac{\bar{D}}{s_{\bar{D}}}$$

1. For the difference between two major treatment means:

$$s_{\bar{D}} = \sqrt{\frac{2(\text{Major plot error mean square})}{(m)(R)}}$$

where *R* is the number of replications of major treatments, and *m* is the number of subplots per major plot; *t* has degrees of freedom equal to the degree of freedom for the major plot error.

2. For the difference between two minor treatment means:

$$s_{\bar{D}} = \sqrt{\frac{2(\text{Subplot error mean square})}{(R)(M)}}$$

where *M* is the number of major plot treatments; *t* has degrees of freedom equal to the degree of freedom for the subplot error.

3. For the difference between two minor treatments within a single major treatment:

$$s_{\bar{D}} = \sqrt{\frac{2(\text{Subplot error mean square})}{R}}$$

where the degrees of freedom for t are equal to the degrees of freedom for the subplot error.

4. For the difference between the means of two major treatments at a single level of a minor treatment, or between the means of two major treatments at different levels of a minor treatment:

$$s_{\bar{D}} = \sqrt{2\left[\frac{(m-1)(\text{Subplot error mean square}) + (\text{Major plot error mean square})}{(m)(R)}\right]}$$

In this case, t will not follow the t distribution. A close approximation to the value of t required for significance at the a level is given by

$$t = \frac{(m-1)(\text{Subplot error mean square})t_m + (\text{Major plot error mean square})t_M}{(m-1)(\text{Subplot error mean square}) + (\text{Major plot error mean square})}$$

where

t_m = Tabular value of t at the α level for degrees of freedom equal to the degrees of freedom for the subplot error.

t_M = Tabular value of t at the α level for degrees of freedom equal to the degrees of freedom for the major plot error.

Other symbols are as previously defined.

MISSING PLOTS

A mathematician who had developed a complex electronic computer program for analyzing a wide variety of experimental designs was asked how he handled missing plots. His disdainful reply was, "We tell our research workers not to have missing plots." This is good advice. But it is sometimes hard to follow, and particularly so in forest, environmental, and ecological research, where close control over experimental material is difficult and studies may run for several years. The likelihood of plots being lost during the course of a study should be considered when selecting an experimental design. Lost plots are least troublesome in the simple designs. For this reason, complete randomization and randomized blocks may be preferable to the more intricate designs when missing data can be expected.

In the complete randomization design, loss of one or more plots causes no computational difficulties. The analysis is made as though the missing plots never existed. Of course, a degree of freedom will be lost from the total and error terms for each missing plot and the sensitivity of the test will be reduced. If missing plots are likely, the number of replications should be increased accordingly. In the randomized block design, completion of the analysis will usually require an estimate of the values for the missing plots. A single missing value can be estimated by

$$X = \frac{bB + tT - G}{(b-1)(t-1)}$$

where

b = Number of blocks.

B = Total of all other units in the block with a missing plot.

t = Number of treatments.

T = Total of all other units that received the same treatment as the missing plot.

G = Total of all observed units.

If more than one plot is missing, the customary procedure is to insert guessed values for all but one of the missing units, which is then estimated by the above formula. This estimate is used in obtaining an estimated value for one of the guessed plots, and so on through each missing unit. Then the process is repeated, with the first estimates replacing the guessed values. The cycle should be repeated until the new approximations differ little from the previous estimates.

The estimated values are now applied in the usual analysis-of-variance calculations. For each missing unit one degree of freedom is deducted from the total and from the error term.

A similar procedure is used with the Latin square design, but the formula for a missing plot is

$$X = \frac{r(R + C + T) - 2G}{(r-1)(r-2)}$$

where

r = Number of rows.

R = Total of all observed units in the row with the missing plot.

C = Total of all observed units in the column with the missing plot.

T = Total of all observed units in the missing plot treatment.

G = Grand total of all observed units.

With the split-plot design, missing plots can cause trouble. A single missing subplot value can be estimated by the following equation:

$$X = \frac{rP + m\left(T_{ij}\right) - (T_i)}{(r-1)(m-1)}$$

where

r = Number of replications of major plot treatments.

P = Total of all observed subplots in the major plot having a missing subplot.

m = Number of subplot treatments.

T_{ij} = Total of all subplots having the same treatment combination as the missing unit.

T_i = Total of all subplots having the same major plot treatment as the missing unit.

For more than one missing subplot the iterative process described for randomized blocks must be used. In the analysis, one degree of freedom will be deducted from the total and subplot error terms for each missing subplot.

When data for missing plots are estimated, the treatment mean square for all designs is biased upwards. If the proportion of missing plots is small, the bias can usually be ignored. Where the proportion is large, adjustments can be made as described in the standard references on experimental designs.

REGRESSION

Simple Linear Regression

An environmental researcher had an idea that she could tell how well a loblolly pine was growing from the volume of the crown. Very simple: big crown—good growth, small crown—poor growth. But she couldn't say how big and how good, or how small and how poor. What she needed was regression analysis, which would allow her to express a relationship between tree growth and crown volume in an equation. Given a certain crown volume, she could use the equation to predict what the tree growth was. To gather data, she ran parallel survey lines across a large tract that was representative of the area in which she was interested. The lines were 5 chains apart. At each 2-chain mark along the lines, she measured the nearest loblolly pine of at least 5.6 inches diameter at breast height (d.b.h.; 4.5 ft above the forest floor on the uphill side of the tree) for crown volume and basal area growth over the past 10 years.

A portion of the data is printed below to illustrate the methods of calculation. Crown volume in hundreds of cubic feet is labeled *X* and basal area growth in square feet is labeled *Y*. Now, what can we tell the environmental researcher about the relationship?

X Crown Volume	**Y Growth**	**X Crown Volume**	**Y Growth**	**X Crown Volume**	**Y Growth**
22	0.36	53	0.47	51	0.41
6	0.09	70	0.55	75	0.66
93	0.67	5	0.07	6	0.18
62	0.44	90	0.69	20	0.21
84	0.72	46	0.42	36	0.29
14	0.24	36	0.39	50	0.56
52	0.33	14	0.09	9	0.13
69	0.61	60	0.54	2	0.10
104	0.66	103	0.74	21	0.18
100	0.80	43	0.64	17	0.17
41	0.47	22	0.50	87	0.63
85	0.60	75	0.39	97	0.66
90	0.51	29	0.30	33	0.18
27	0.14	76	0.61	20	0.06
18	0.32	20	0.29	96	0.58
48	0.21	29	0.38	61	0.42
37	0.54	30	0.53		
67	0.70	59	0.58		
56	0.67	70	0.62		
31	0.42	81	0.66		
17	0.39	93	0.69		
7	0.25	99	0.71		
2	0.06	14	0.14		
Totals				3050	26.62
Means ($n = 62$)				49.1935	0.42935

Often, the first step is to plot the field data on coordinate paper (see Figure 5.3). This is done to provide some visual evidence of whether the two variables are related. If there is a simple relationship, the plotted points will tend to form a pattern (a straight line or curve). If the relationship is very strong, the pattern will generally be distinct. If the relationship is weak, the points will be more spread out and the pattern less definite. If the points appear to fall pretty much at random, there may be no simple relationship or one that is so very poor as to make it a waste of time to fit any regression.

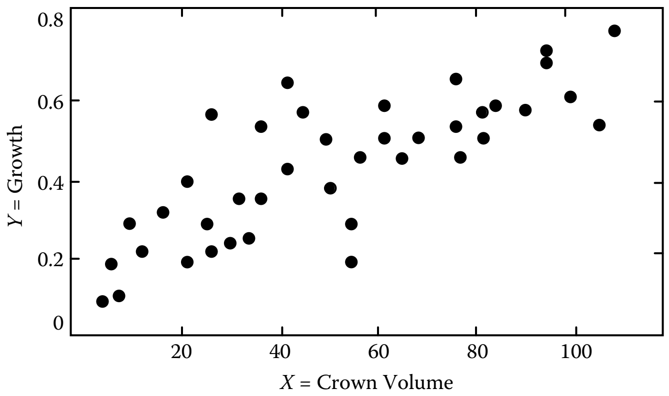

FIGURE 5.3 Plotting of growth (Y) over crown volume (X).

The type of pattern (straight line, parabolic curve, exponential curve, etc.) will influence the regression model to be fitted. In this particular case, we will assume a simple straight-line relationship. After selecting the model to be fitted, the next step will be to calculate the corrected sums of squares and products. In the following equations, capital letters indicate uncorrected values of the variables; lowercase letters will be used for the corrected values.

The corrected sum of squares for Y is

$$\sum y^2 = \sum^n Y^2 - \frac{\left(\sum^n Y\right)^2}{n} = \left(0.36^2 + 0.09^2 + \ldots + 0.42^2\right) - \frac{26.62^2}{62} = 2.7826$$

The corrected sum of squares for X is

$$\sum x^2 = \sum^n X^2 - \frac{\left(\sum^n X\right)^2}{n} = \left(22^2 + 6^2 + \ldots + 61^2\right) - \frac{3050^2}{62} = 59{,}397.6775$$

The corrected sum of products is

$$\sum xy = \sum^n (XY) - \frac{\left(\sum^n X\right)\left(\sum^n Y\right)}{n} = \left[(22)(0.36) + (6)(0.09) + \ldots + (61)(0.42)\right] - \frac{(3050)(26.62)}{62}$$
$$= 354.1477$$

The general form of equation for a straight line is $Y = a + bX$. In this equation, a and b are constants or regression coefficients that must be estimated. According to the principle of least squares, the best estimates of these coefficients are

$$b = \frac{\sum xy}{\sum x^2} = \frac{354.1477}{59{,}397.6775} = 0.005962$$

$$a = \bar{Y} - b\bar{X} = 0.42935 - (0.005962)(49.1935) = 0.13606$$

Substituting these estimates in the general equation gives

$$\hat{Y} = 0.13606 + 0.005962X$$

where $\hat{Y}$ is used to indicate that we are dealing with an estimated value of Y.

With this equation we can estimate the basal area growth for the past 10 years ($\hat{Y}$) from the measurements of the crown volume X. Because Y is estimated from a known value of X, it is called the dependent variable and X is the independent variable. In plotting on graph paper, the values of Y are usually (purely by convention) plotted along the vertical axis (ordinate) and the values of x along the horizontal axis (abscissa).

HOW WELL DOES THE REGRESSION LINE FIT THE DATA?

A regression line can be thought of as a moving average. It gives an average value of Y associated with a particular value of X. Of course, some values of Y will be above the regression line (moving average) and some below, just as some values of Y are above or below the general average of Y. The corrected sum of squares for Y (i.e., Σy^2) estimates the amount of variation of individual values of Y about the mean value of Y. A regression equation is a statement that part of the observed variation in Y (estimated by Σy^2) is associated with the relationship of Y to X. The amount of variation in Y that is associated with the regression on X is the reduction or regression sum of squares:

$$\text{Reduction } SS = \frac{\left(\sum xy\right)^2}{\sum x^2} = \frac{(354.1477)^2}{59{,}397.6775} = 2.1115$$

As noted above, the total variation in Y is estimated by $\Sigma y^2 = 2.7826$ (as previously calculated). The part of the total variation in Y that is not associated with the regression is the residual sum of squares:

$$\text{Residual } SS = \sum y^2 - \text{Reduction } SS = 2.7826 - 2.1115 = 0.6711$$

In analysis of variance we used the unexplained variation as a standard for testing the amount of variation attributable to treatments. We can do the same in regression. What's more, the familiar F test will serve.

Source of Variation	**Degrees of Freedom**[a]	**Sums of Squares**	**Mean Squares**[b]
Due to regression $\left[= \frac{(\Sigma xy)^2}{\Sigma x^2}\right]$	1	2.1115	2.1115
Residual (unexplained)	60	0.6711	0.01118
Total (= Σy^2)	61	2.7826	

[a] As there are 62 values of Y, the total sum of squares has 61 degrees of freedom. The regression of Y on X has one degree of freedom. The residual degrees of freedom are obtained by subtraction.

[b] Mean square is, as always, equal to sum of squares/degrees of freedom.

The regression is tested by

$$F = \frac{\text{Regression mean square}}{\text{Residual mean square}} = \frac{2.1115}{0.01118} = 188.86$$

Because the calculated F is much greater than tabular $F_{0.01}$ with 1/60 degree of freedom, the regression is deemed significant at the 0.01 level.

Before we fitted a regression line to the data, Y had a certain amount of variation about its mean ($\bar{Y}$). Fitting the regression was, in effect, an attempt to explain part of this variation by the linear association of Y with X. But even after the line had been fitted, some variation was unexplained—that of Y about the regression line. When we tested the regression line above, we merely showed that the part of the variation in Y that is explained by the fitted line is significantly greater than the part that the line left unexplained. The test did not show that the line we fitted gives the best possible description of the data (a curved line might be even better), nor does it mean that we have found the true mathematical relationship between the two variables. There is a dangerous tendency to ascribe more meaning to a fitted regression than is warranted.

It might be noted that the residual sum of squares is equal to the sum of the squared deviations of the observed values of Y from the regression line. That is,

$$\text{Residual } SS = \sum\left(Y - \hat{Y}\right)^2 = \sum(Y - a - bX)^2$$

The principle of least squares says that the best estimates of the regression coefficients (a and b) are those that make this sum of squares a minimum.

Coefficient of Determination

The coefficient of determination, denoted R^2, is used in the context of statistical models whose main purpose is the prediction of future outcomes on the basis of other related information. Stated differently, the coefficient of determination is a ratio that measures how well a regression fits the sample data:

$$\text{Coefficient of determination} = \frac{\text{Reduction } SS}{\text{Total } SS} = \frac{2.1115}{2.7826} = 0.758823$$

When someone says, "76% of variation in Y was associated with X," she means that the coefficient of determination was 0.76. Note that R^2 is most often seen as a number between 0 and 1.0, used to describe how well a regression line fit a set of data. An R^2 near 1.0 indicates that a regression line fits the data well, while an R^2 closer to 0 indicates that a regression line does not fit the data very well.

The coefficient of determination is equal to the square of the correlation coefficient:

$$\frac{\text{Reduction } SS}{\text{Total } SS} = \frac{\left(\sum xy\right)^2 / \sum x^2}{\sum y^2} = \frac{\left(\sum xy\right)^2}{\left(\sum x^2\right)\left(\sum y^2\right)} = r^2$$

In fact, most present-day users of regression refer to R^2 values rather than to coefficients of determination.

Confidence Intervals

Because it is based on sample data, a regression equation is subject to sample variation. Confidence limits (i.e., a pair of numbers used to estimate a characteristic of a population) on the regression line can be obtained by specifying several values over the range of X and computed by

$$\hat{Y} \pm t\sqrt{(\text{Residual mean square})\left(\frac{1}{n} + \frac{\left(X_0 - \bar{X}\right)^2}{\sum x^2}\right)}$$

where X_0 = a selected value of X, and degrees of freedom for t equal the degrees of freedom for residue mean square. In the example we had

$$\hat{Y} = 0.13606 + 0.005962X$$

$$\text{Residual mean square} = 0.01118 \text{ with 60 degrees of freedom}$$

$$n = 62$$

$$\bar{X} = 49.1935$$

$$\sum x^2 = 59{,}397.6775$$

So, if we pick $X_0 = 28$ we have $\hat{Y} = 0.303$, and 95% confidence limits

$$\hat{Y} \pm t\sqrt{(\text{Residual mean square})\left(1 + \frac{1}{n} + \frac{(X_0 - \bar{X})^2}{\sum x^2}\right)}$$

For other values of X_0 we would get:

		95% Limits	
X_0	$\hat{Y}$	**Lower**	**Upper**
8	0.184	0.139	0.229
49.1935	0.429	0.402	0.456
70	0.553	0.521	0.585
90	0.673	0.629	0.717

Note that these are confidence limits for the regression of Y on X (see Figure 5.4). They indicate the limits within which the true mean of Y for a given X will lie unless a 1-in-20 chance has occurred. The limits do not apply to a single predicted value of Y. The limits within which a single Y might lie are given by

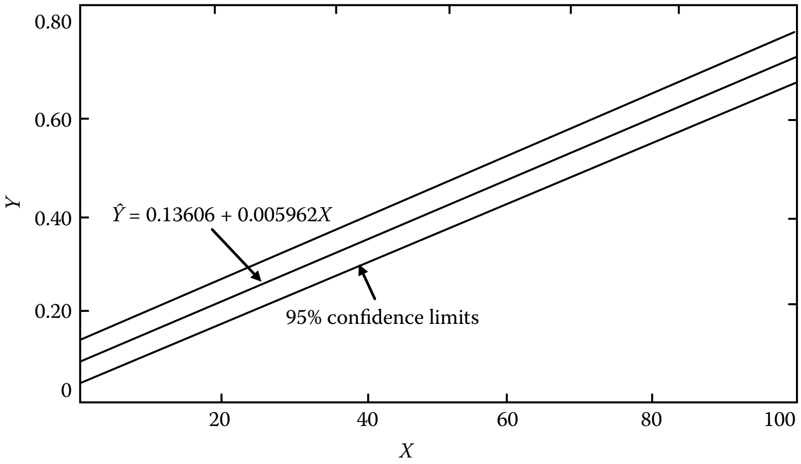

FIGURE 5.4 Confidence limits for the regression of Y on X.

$$\hat{Y} \pm t\sqrt{(\text{Residual mean square})\left(1+\frac{1}{n}+\frac{\left(X_0-\bar{X}\right)^2}{\sum x^2}\right)}$$

In addition to assuming that the relationship of Y to X is linear, the above method of fitting assumes that the variance of Y about the regression line is the same at all levels of X (the assumption of homogeneous variance or *homoscedasticity*—that is, the property of having equal variances). The fitting does not assume nor does it require that the variation of Y about the regression line follow the normal distribution. However, the F test does assume normality, and so does the use of t for the computation of confidence limits.

There is also an assumption of independence of the errors (departures from regression) of the sample observations. The validity of this assumption is best ensured by selecting the sample units at random. The requirements of independence may not be met if successive observations are made on a single unit or if the units are observed in clusters. For example, a series of observations of tree diameter made by means of a growth band would probably lack independence.

Selecting the sample units so as to get a particular distribution of the X values does not violate any of the regression assumptions, provided the Y values are a random sample of all Y values associated with the selected values of X. Spreading the sample over a wide range of X values will usually increase the precision with which the regression coefficients are estimated. This device must be used with caution, however, for if the Y values are not random then the regression coefficients and mean square residual may be improperly estimated.

MULTIPLE REGRESSION

It frequently happens that a variable (Y) in which we are interested is related to more than one independent variable. If this relationship can be estimated, it may enable us to make more precise predictions of the dependent variable than would be possible by a simple linear regression. This brings us up against multiple regression, which describes the changes in a dependent variable associated with changes in one or more independent variables; it is a little more work but no more complicated than a simple linear regression.

The calculation methods can be illustrated with the following set of hypothetical data from an environmental study relating the growth of even-aged loblolly–shortleaf pine stands to the total basal area (X_1), the percentage of the basal area in loblolly pine (X_2), and loblolly pine site index (X_3).

Y	X_1	X_2	X_3
65	41	79	75
78	90	48	83
85	53	67	74
50	42	52	61
55	57	52	59
59	32	82	73
82	71	80	72
66	60	65	66
113	98	96	99
86	80	81	90
104	101	78	86
92	100	59	88
96	84	84	93
65	72	48	70
81	55	93	85

	77	77	68	71
	83	98	51	84
	97	95	82	81
	90	90	70	78
	87	93	61	89
	74	45	96	81
	70	50	80	77
	75	60	76	70
	75	68	74	76
	93	75	96	85
	76	82	58	80
	71	72	58	68
	61	46	69	65
Sums	2206	1987	2003	2179
Means ($n = 28$)	78.7857	70.9643	71.5387	77.8214

With these data we would like to fit an equation of the form

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3$$

According to the principle of least squares, the best estimates of the X coefficients can be obtained by solving the set of least squares normal equations.

$$b_1 \text{ equation: } \left(\sum x_1^2\right)b_1 + \left(\sum x_1x_2\right)b_2 + \left(\sum x_1x_3\right)b_3 = \sum x_1y$$

$$b_2 \text{ equation: } \left(\sum x_1x_2\right)b_1 + \left(\sum x_2^2\right)b_2 + \left(\sum x_2x_3\right)b_3 = \sum x_2y$$

$$b_3 \text{ equation: } \left(\sum x_1x_3\right)b_1 + \left(\sum x_2x_3\right)b_2 + \left(\sum x_3^2\right)b_3 = \sum x_3y$$

where

$$\sum x_ix_j = \sum X_iY_j - \frac{\left(\sum X_i\right)\left(\sum X_j\right)}{n}$$

Having solved for the X coefficients (b_1, b_2, and b_3), we obtain the constant term by solving

$$a = \bar{Y} - b_1\bar{X}_1 + b_2\bar{X}_2 - b_3\bar{X}_3$$

Derivation of the least squares normal equations requires a knowledge of differential calculus. However, for the general linear mode with a constant term

$$Y = a + b_1X_1 + b_2X_2 + \ldots b_kX_k$$

the normal equations can be written quite mechanically once their pattern has been recognized. Every term in the first row contains an x_1, every term in the second row an x_2, and so forth down to the kth row, every term of which will have an x_k. Similarly, every term in the first column has an x_1 and a b_1, every term in the second column has an x_2 and a b_2, and so on through the kth column, every term of which has an x_k and a b_k. On the right side of the equations, each term has a y times the x that is appropriate for a particular row. So, for the general linear model given above, the normal equations are

$$b_1 \text{ equation: } \left(\sum x_1^2\right)b_1 + \left(\sum x_1x_2\right)b_2 + \left(\sum x_1x_3\right)b_3 + \ldots + \left(\sum x_1x_k\right)b_k = \sum x_1y$$

$$b_2 \text{ equation: } \left(\sum x_1x_2\right)b_1 + \left(\sum x_2^2\right)b_2 + \left(\sum x_2x_3\right)b_3 + \ldots + \left(\sum x_2x_k\right)b_k = \sum x_2y$$

$$b_3 \text{ equation: } \left(\sum x_1x_3\right)b_1 + \left(\sum x_2x_3\right)b_2 + \left(\sum x_3^2\right)b_3 + \ldots + \left(\sum x_3x_k\right)b_k = \sum x_3y$$

$$\vdots$$

$$b_k \text{ equation: } \left(\sum x_1x_k\right)b_1 + \left(\sum x_2x_k\right)b_2 + \left(\sum x_3x_k\right)b_3 + \ldots + \left(\sum x_k^2\right)b_k = \sum x_ky$$

Given the X coefficients, the constant term can be computed as

$$a = \bar{Y} - b_1\bar{X}_1 - b_2\bar{X}_2 - \ldots - b_k\bar{X}_k$$

Note that the normal equations for the general linear model include the solution for the simple linear regression

$$\left(\sum x_1^2\right)b_1 = \sum x_1y$$

Hence,

$$b_1 = \left(\sum x_1y\right) \Big/ \sum x_1^2$$

In fact, all of this section on multiple regression can be applied to the simple linear regression as a special case.

The corrected sums of squares and products are computed in the familiar manner:

$$\sum y^2 = \sum Y^2 - \frac{\left(\sum Y\right)^2}{n} = \left(65^2 + \ldots + 61^2\right) - \frac{(2206)^2}{28} = 5974.7143$$

$$\sum x_1^2 = \sum X_1^2 - \frac{\left(\sum X_1\right)^2}{n} = \left(41^2 + \ldots + 46^2\right) - \frac{(1987)^2}{28} = 11{,}436.9643$$

$$\sum x_1y = \sum X_1Y - \frac{\left(\sum X_1\right)\left(\sum Y\right)}{n} = (41)(65) + \ldots + (46)(61) - \frac{(1987)(2206)}{28} = 6428.7858$$

Similarly,

$$\sum x_1x_2 = -1171.4642$$

$$\sum x_1x_3 = 3458.8215$$

$$\sum x_2^2 = 5998.9643$$

$$\sum x_2x_3 = 1789.6786$$

$$\sum x_2y = 2632.2143$$

$$\sum x_3^2 = 2606.1072$$

$$\sum x_3y = 3327.9286$$

Putting these values in the normal equations gives:

$$
\begin{aligned}
11{,}436.9643b_1 - 1171.4642b_2 + 3458.8215b_3 &= 6428.7858\\
-1171.4642b_1 + 5998.9643b_2 + 1789.6786b_3 &= 2632.2143\\
3458.8215b_1 - 1789.6786b_2 + 2606.1072b_3 &= 3327.9286
\end{aligned}
$$

These equations can be solved by any of the standard procedures for simultaneous equations. One approach (applied to the above equations) is as follows:

1. Divide through each equation by the numerical coefficient of b_1.

$$
\begin{aligned}
b_1 - 0.102{,}427{,}897b_2 + 0.302{,}424{,}788b_3 &= 0.562{,}105{,}960\\
b_1 - 5.120{,}911{,}334b_2 - 1.527{,}727{,}949b_3 &= -2.246{,}943{,}867\\
b_1 + 0.517{,}424{,}389b_2 + 0.753{,}466{,}809b_3 &= 0.962{,}156{,}792
\end{aligned}
$$

2. Subtract the second equation from the first and the third from the first so as to leave two equations in b_2 and b_3.

$$5.018{,}483{,}437b_2 + 1.830{,}152{,}737b_3 = 2.809{,}049{,}827$$

$$-0.619{,}852{,}286b_2 - 0.451{,}042{,}021b_3 = -0.400{,}050{,}832$$

3. Divide through each equation by the numerical coefficient of b_2.

$$b^2 + 0.364{,}682{,}430b_3 = 0.559{,}740{,}779$$

$$b^2 + 0.727{,}660{,}494b_2 = 0.645{,}397{,}042$$

4. Subtract the second of these equations from the first, leaving one equation in b_3.

$$-0.362{,}978{,}064b_3 = -0.085{,}656{,}263$$

5. Solve for b_3.

$$b_3 = \frac{-0.085{,}656{,}263}{-0.326{,}978{,}064} = 0.235{,}981{,}927$$

6. Substitute this value of b_3 in one of the equations (the first one, for example) of step 3 and solve for b_2.

$$b_2 + (0.364{,}682{,}43)(0.381{,}927) = 0.59{,}740{,}779$$

$$b_2 = 0.473{,}682{,}316$$

7. Substitute the solutions for b_2 and b_3 in one of the equations (the first one, for example) of step 1, and solve for b_1.

$$b_1 - (0.102{,}427{,}897)(0.473{,}682{,}316) + (0.302{,}424{,}788)(0.235{,}981{,}927) = 0.562{,}105{,}960$$

$$b_1 = 0.539{,}257{,}459$$

8. As a check, add up the original normal equations and substitute the solutions for b_1, b_2, and b_3.

$$13{,}724.3216b_1 + 6{,}617.1787b_2 + 7{,}854.6073b_3 = 12{,}388.9287$$

$$12{,}388.92869 \approx 12{,}388.9287$$

Given the values of b_1, b_2, and b_3 we can now compute

$$a = \bar{Y} - b_1\bar{X}_1 - b_2\bar{X}_2 - b_3\bar{X}_3 = -11.7320$$

Thus, after rounding of the coefficients, the regression equation is

$$\hat{Y} = -11.732 + 0.539X_1 + 0.474X_2 + 0.236X_3$$

It should be noted that in solving the normal equations more digits have been carried than would be justified by the rules for number of significant digits. Unless this is done, the rounding errors may make it difficult to check the computations.

Tests of Significance

Tests of significance refer to the methods of inference used to support or reject claims based on sample data. To test the significance of the fitted regression, the outline for the analysis of variance is

Source of Variation	Degrees of Freedom
Reduction due to regression on X_1, X_2, and X_3	3
Residuals	24
Total	27

The degrees of freedom for the total are equal to the number of observations minus 1. The total sum of squares is

$$\text{Total } SS = \sum y^2 = 5974.7143$$

The degrees of freedom for the reduction are equal to the number of independent variables fitted, in this case 3. The reduction sum of squares for any least squares regression is

$$\text{Reduction } SS = \sum \text{(Estimated coefficients) (right side of their normal equations)}$$

In this example there are three coefficients estimated by the normal equations, and so

$$\begin{aligned}\text{Reduction } \underset{3df}{SS} &= b_1\left(\sum x_1y\right) + b_2\left(\sum x_2y\right) + b_3\left(\sum x_3y\right)\\ &= (0.53926)(6428.7858) + (0.47368)(2632.2143) + (0.23598)(3327.9286)\\ &= 5498.9389\end{aligned}$$

The residual *df* and sum of squares are obtained by subtraction. Thus, the analysis becomes

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares
Reduction due to X_1, X_2, and X_3	3	5498.9389	1832.9796
Residuals	24	475.7754	19.8240
Total	27	5974.7143	

To test the regression we compute

$$F_{3/24df} = \frac{1832.9696}{19.8240} = 92.46$$

which is significant at the 0.01 level.

Often we will want to test individual terms of the regression. In the previous example we might want to test the hypothesis that the true value of b_3 is zero. This would be equivalent to testing whether the viable X_3 makes any contribution to the prediction of Y. If we decide a b_3 may be equal to zero, we might rewrite the equation in terms of X_1 and X_2. Similarly, we could test the hypothesis that b_1 and b_3 are both equal to zero.

To test the contribution of any set of the independent variables in the presence of the remaining variables:

1. Fit all independent variables and compute the reduction and residual sums of squares.
2. Fit a new regression that includes only the variables not being tested. Compute the reduction due to this regression.
3. The reduction obtained in the first step minus the reduction in the second step is the gain due to the variables being tested.
4. The mean square for the gain (step 3) is tested against the mean square residual from the first step.

Coefficient of Multiple Determination

As a measure of how well the regression fits the data it is customary to compute the ratio of the reduction sum of squares to the total sum of squares. This ratio is symbolized by R^2 and is sometimes called the coefficient of determination:

$$R^2 = \frac{\text{Reduction } SS}{\text{Total } SS}$$

For the regression of Y on X_1, X_2, and X_3,

$$R^2 = \frac{5498.9389}{5974.7143} = 0.92$$

The R^2 value is usually referred to by saying that a certain percentage (92 in this case) of the variation in Y is associated with regression. The square root (R) of the ratio is the multiple correlation coefficient.

c-Multipliers

Putting confidence limits on a multiple regression requires computation of the Gauss or *c*-multipliers. The *c*-multipliers are the elements of the inverse of the matrix of corrected sums of squares and products as they appear in the normal equations.

CURVILINEAR REGRESSIONS AND INTERACTIONS

Curves

Many forms of curvilinear relationships can be fitted by the regression methods that have been described in the previous sections. If the relationship between height and age is assumed to be hyperbolic so

$$\text{Height} = a + \frac{b}{\text{Age}}$$

then we could let Y = height and X_1 = 1/age and fit

$$Y = a + b_1X_1$$

Similarly, if the relationship between Y and X is quadratic,

$$Y = a + bX + cX^2$$

then we can let $X = X_1$ and $X^2 = X_2$ and fit

$$Y = a + b_1X_1 + b_2X_2$$

Functions such as

$$Y = aX^b$$

$$Y = a(b^x)$$

$$10^Y = aX^{\mathrm{b}}$$

which are nonlinear in the coefficients can sometimes be made linear by a logarithmic transformation. The equation

$$Y = aX^b$$

would become

$$\log Y = \log a + b(\log X)$$

which could be fitted by

$$Y' = a + b_1X_1$$

where $Y' = \log Y$, and $X_1 = \log X$.

The second equation transforms to

$$\log Y = \log a + (\log b)\, X$$

The third becomes

$$Y = \log a + b(\log X)$$

Both can be fitted by the linear model.

When making these transformations, the effect on the assumption of homogeneous variance must be considered. If Y has homogeneous variance, then log Y probably will not—and *vice versa*. Some curvilinear models cannot be fitted by the methods that have been described, including

$$Y = a + b^x$$
$$Y = a(X - b)^2$$
$$Y = a(X_1 - b)(X_2 - c)$$

Fitting these models requires more cumbersome procedures.

Interactions

Suppose that there is a simple linear relationship between Y and X_1. If the slope (b) of this relationship varies, depending on the level of some other independent variable (X_2), then X_1 and X_2 are said to interact. Such interactions can sometimes be handled by introducing interaction variables. To illustrate, suppose that we know that there is a linear relationship between Y and X_1:

$$Y = a + bX_1$$

Suppose further that we know or suspect that the slope (b) varies linearly with Z:

$$b = a' + b'Z$$

This implies the relationship

$$Y = a + (a' + b'Z)X_1$$

or

$$Y = a + a'X_1 + b'X_1Z$$

where $X_2 = X_1Z$, an interaction variable.

If the Y-intercept is also a linear function of Z, then

$$a = a'' + b''Z$$

and the form of relationship is

$$Y = a'' + b''Z + a'X_1 + b'X_1Z$$

Group Regressions

Linear regressions of Y on X were fitted for each of two groups:

Group A										**Sum**	**Mean**
Y	3	7	9	6	8	13	10	12	14	82	9.111
X	1	4	7	7	2	9	10	6	12	58	6.444

where

$$n = 9, \quad \sum Y^2 = 848, \quad \sum XY = 609, \quad \sum X^2 = 480, \quad \sum y^2 = 100.8889$$

$$\sum xy = 80.5556, \quad \sum x^2 = 106.2222, \quad \hat{Y} = 4.224 + 0.7584X$$

Residual $SS = 39.7980$, with 7 degrees of freedom

Group B													**Sum**	**Mean**
Y	4	6	12	2	8	7	0	5	9	2	11	3	10	79	6.077
X	4	9	14	6	9	12	2	7	5	5	11	2	13	99	7.616

where

$$n = 13, \quad \sum Y^2 = 653, \quad \sum XY = 753, \quad \sum X^2 = 951, \quad \sum y^2 = 172.9231$$

$$\sum xy = 151.3846, \quad \sum x^2 = 197.0796, \quad \hat{Y} = 0.228 + 0.7681X$$

Residual $SS = 56.6370$, with 11 degrees of freedom

Now, we might ask, are these really different regressions? Or could the data be combined to produce a single regression that would be applicable to both groups? If there is no significant difference between the mean square residuals for the two groups (this matter may be determined by Bartlett's test), the test described below helps to answer the question.

Testing for Common Regressions

Simple linear regressions may differ either in their slope or in their level. When testing for common regressions the procedure is to test first for common slopes. If the slopes differ significantly, the regressions are different and no further testing is needed. If the slopes are not significantly different, the difference in level is tested. The analysis table is

						Residuals		
Line	**Group**	***df***	Σy^2	Σxy	Σx^2	***df***	***SS***	**MS**
1	A	8	100.8889	80.5556	106.2222	7	39.7980	—
2	B	12	172.9231	151.3846	97.0769	11	56.6370	—
3	Pooled residuals					18	96.4350	5.3575
4	Difference for testing common slopes					1	0.0067	0.0067
5	Common slope	20	273.8120	231.9402	303.2991	19	5.0759	96.4417
6	Difference for testing trends					1	80.1954	80.1954
7	Single regression	21	322.7727	213.0455	310.5909	20	176.6371	—

The first two lines in this table contain the basic data for the two groups. To the left are the total degrees of freedom for the groups (8 for A and 12 for B). In the center are the corrected sums of squares and products. The right side of the table gives the residual sum of squares and degrees of freedom. Since only simple linear regressions have been fitted, the residual degrees of freedom of each group are one less than the total degrees of freedom. The residual sum of squares is obtained by first computing the reduction sum of squares for each group.

$$\text{Reduction } SS = \frac{\left(\sum xy\right)^2}{\sum x^2}$$

This reduction is then subtracted from the total sum of squares (Σy^2) to give the residuals.

Line 3 is obtained by pooling the residual degrees of freedom and residual sums of squares for the groups. Dividing the pooled sum of squares by the pooled degrees of freedom gives the pooled mean square. The left side and center of line (we will skip line 4 for the moment) is obtained by pooling the total degrees of freedom and the corrected sums of squares and products for the groups. These are the values that are obtained under the assumption of no difference in the slopes of the group regressions. If the assumption is wrong, the residuals about this common slope regression will be considerably larger than the mean square residual about the separate regressions. The residual degrees of freedom and sum of squares are obtained by fitting a straight line to these pooled data. The residual degrees of freedom are, of course, one less than the total degrees of freedom. The residual sum of squares is, as usual,

$$\text{Reduction } SS = 273.8120 - \frac{(231.9402)^2}{303.2991} = 96.4417$$

Now, the difference between these residuals (line 4 = line 5 – line 3) provides a test of the hypothesis of common slopes. The error term for this test is the pooled mean square from line 3:

$$\text{Test of common slopes: } F_{1/13df} = \frac{0.0067}{5.3575}$$

The difference is not significant.

If the slopes differed significantly, the groups would have different regressions, and we would stop here. Because the slopes did not differ, we now go on to test for a difference in the levels of the regression.

Line 7 is what we would have if we ignored the groups entirely, lumped all the original observations together, and fitted a single linear regression. The combined data are as follows:

1. $n = (9+13) = 22,$ so the degrees of freedom $= 21$
2. $\sum Y = (82+79) = 161$
3. $\sum Y^2 = (848+653) = 1501$
4. $\sum y^2 = 1501 - \frac{(161)^2}{22} = 322.7727$
5. $\sum X = (58+99) = 157$
6. $\sum X^2 = (480+951) = 1431$
7. $\sum x^2 = 1431 - \frac{(157)^2}{22} = 310.5909$
8. $\sum XY = (609+753) = 1362$
9. $\sum xy = 1362 - \frac{(157)(161)}{22} = 213.0455$

From this we obtain the residual values on the right side of line 7.

$$\text{Residual } SS = 322.7727 - \frac{(213.0455)^2}{310.5909} = 176.6371$$

If there is a real difference among the levels of the groups, the residuals about this single regression will be considerably larger than the mean square residual about the regression that assumed the same slopes but different levels. This difference (line 6 = line 7 – line 5) is tested against the residual mean square from line 5.

$$\text{Test of levels: } F_{1/18df} = \frac{80.1954}{5.0759} = 15.80$$

As the levels differ significantly, the groups do not have the same regressions.

The test is easily extended to cover several groups, though there may be a problem in finding which groups are likely to have separate regressions and which can be combined. The test can also be extended to multiple regressions.

Analysis of Covariance in a Randomized Block Design

A test was made of the effect of three soil treatments on the height growth of 2-year-old seedlings. Treatments were assigned at random to the three plots within each of 11 blocks. Each plot was made up of 50 seedlings. Average 5-year height growth was the criterion for evaluating treatments. Initial heights and 5-year growths, all in feet, were as follows:

	Treatment A		Treatment B		Treatment C		Block Totals	
Block	**Height**	**Growth**	**Height**	**Growth**	**Height**	**Growth**	**Height**	**Growth**
1	3.6	8.9	3.1	10.7	4.7	12.4	11.4	32.0
2	4.7	10.1	4.9	14.2	2.6	9.0	12.2	33.3
3	2.6	6.3	0.8	5.9	1.5	7.4	4.9	19.6
4	5.3	14.0	4.6	12.6	4.3	10.1	14.2	36.7
5	3.1	9.6	3.9	12.5	3.3	6.8	10.3	28.9
6	1.8	6.4	1.7	9.6	3.6	10.0	7.1	26.0
7	5.8	12.3	5.5	12.8	5.8	11.9	17.1	37.0
8	3.8	10.8	2.6	8.0	2.0	7.5	8.4	26.3
9	2.4	8.0	1.1	7.5	1.6	5.2	5.1	20.7
10	5.3	12.6	4.4	11.4	5.8	13.4	15.5	37.4
11	3.6	7.4	1.4	8.4	4.8	10.7	9.8	26.5
Sums	42.0	106.4	34.0	113.6	40.0	104.4	116.0	324.4
Means	3.82	9.67	3.09	10.33	3.64	9.49	3.52	9.83

The analysis of variance of growth is

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares
Blocks	10	132.83	—
Treatment	2	4.26	2.130
Error	20	68.88	3.444
Total	32	205.97	—

$$F(\text{for testing treatments})_{2/20df} = \frac{2.130}{3.444}$$

which is not significant at the 0.05 level.

There is no evidence of a real difference in growth due to treatments. There is, however, reason to believe that, for young seedlings, growth is affected by initial height. A glance at the block totals seems to suggest that plots with greatest initial height had the greatest 5-year growth. The possibility that effects of treatment are being obscured by differences in initial heights raises the question of how the treatments would compare if adjusted for differences in initial heights.

If the relationship between height growth and initial height is linear and if the slope of the regression is the same for all treatments, the test of adjusted treatment means can be made by an analysis of covariance as described below. In this analysis, the growth will be labeled Y and initial height X.

Computationally the first step is to obtain total, block, treatment, and error sums of squares of X (SS_x) and sums of products of X and Y (SP_{xy}), just as has already been done for Y.

For X:

$$CT_x = \frac{(116.0)^2}{33} = 407.76$$

$$\text{Total } SS_x = \left(3.6^2 + \ldots + 4.8^2\right) - CT_x = 73.26$$

$$\text{Block } SS_x = \left(\frac{11.4^2 + \ldots + 9.8^2}{3}\right) - CT_x = 54.31$$

$$\text{Treatment } SS_x = \left(\frac{42.0^2 + 34.0^2 + 40.0^2}{11}\right) - CT_x = 3.15$$

$$\text{Error } SS_x = \text{Total } SS_x - \text{Block } SS_x - \text{Treatment } SS_x = 15.80$$

For XY:

$$CT_{xy} = \frac{(116.0)(324.4)}{33} = 1140.32$$

$$\text{Total } SP_{xy} = (3.6)(8.9) + \ldots + (4.8)(10.7) - CT_{xy} = 103.99$$

$$\text{Block } SP_{xy} = \left(\frac{(11.4)(32.0) + \ldots + (9.8)(26.5)}{3}\right) - CT_{xy} = 82.71$$

$$\text{Treatment } SP_{xy} = \left(\frac{(42.0)(106.4) + (34.0)(113.6) + (40.0)(104.4)}{11}\right) - CT_{xy} = -3.30$$

$$\text{Error } SP_{xy} = \text{Total } SP_{xy} - \text{Block } SP_{xy} - \text{Treatment } SP_{xy} = 24.58$$

These computed terms are arranged in a manner similar to that for the test of group regressions (which is exactly what the covariance analysis is). One departure is that the total line is put at the top.

					Residuals		
Source of Variation	***df***	***SS*** $_y$	***SP*** $_{xy}$	***SS*** $_x$	***df***	***SS***	**MS**
Total	32	205.97	103.99	73.26			
Blocks	10	132.83	82.71	54.31			
Treatment	2	4.26	–3.30	3.15			
Error	20	68.88	24.58	15.80	19	30.641	1.613

On the error line, the residual sum of squares after adjusting for a linear regression is

$$\text{Residual } SS = SS_y - \frac{\left(SP_{xy}\right)^2}{SS_x} = 68.88 - \frac{(24.58)^2}{15.80} = 30.641$$

This sum of squares has one degree of freedom less than the unadjusted sum of squares.

To test treatments we first pool the unadjusted degree of freedom and sums of squares and products for treatment and error. The residual terms for this pooled line are then computed just as they were for the error line:

					Residuals	
Source of Variation	***df***	***SS*** $_y$	***SP*** $_{xy}$	***SS*** $_x$	***df***	***SS***
Treatment plus error	22	73.14	21.28	18.95	21	49.244

Then to test for a difference among treatments after adjustment for the regression of growth on initial height, we compute the difference in residuals between the error and the treatment + error lines:

Source of Variation	**Degrees of Freedom**	**Sums of Squares**	**Mean Squares**
Difference for testing adjusted treatments	2	18.603	9.302

The mean square for the difference in residual is now tested against the residual mean square for error.

$$F_{2/19df} = \frac{9.302}{1.613} = 5.77$$

Thus, after adjustment, the difference in treatment means is found to be significant at the 0.05 level. It may also happen that differences that were significant before adjustment are not significant afterwards.

If the independent variable has been affected by treatments, interpretation of a covariance analysis requires careful thinking. The covariance adjustment may have the effect of removing the treatment differences that are being tested. On the other hand, it may be informative to know that treatments are or are not significantly different in spite of the covariance adjustment. The beginner who is uncertain of the interpretations would do well to select as covariates only those that have not been affected by treatments.

The covariance test may be made in a similar manner for any experimental design and, if desired (and justified), adjustment may be made for multiple or curvilinear regressions.

The entire analysis is usually presented in the following form:

					Adjusted		
Source	***df***	***SS$_y$***	***SP$_y$***	***SS$_x$***	***df***	***SS***	***MS***
Total	32	205.97	103.99	73.26			
Blocks	10	132.83	82.71	54.31			
Treatment	2	4.26	–3.30	3.15			
Error	20	68.88	24.58	15.80	19	30.641	1.613
Treatment + error	22	73.14	21.28	18.95	21	49.244	—
Difference for testing adjusted treatment means					2	18.603	9.302

$$\text{Unadjusted treatments: } F_{2/20dt} = \frac{2.130}{3.444}, \text{ not significant}$$

$$\text{Adjusted treatments: } F_{2/19dt} = \frac{9.302}{1.613} = 5.77, \text{ significant at 0.05 level}$$

Adjusted Means

If we wish to know what the treatment means are after adjustment for regression, the equation is

$$\text{Adjusted } \overline{Y}_i = \overline{Y}_i - b\left(\overline{X}_i - \overline{X}\right)$$

where

$\overline{Y}_i$ = Unadjusted mean for treatment *i*.

b = Coefficient of the linear regression = (Error SP_{xy})/(Error SS_x)

$\overline{X}_i$ = Mean of the independent variable for treatment *i*.

$\overline{X}$ = Mean of X for all treatments.

In the example, we had $\overline{X}_A = 3.82$, $\overline{X}_B = 3.09$, $\overline{X}_C = 3.64$, $\overline{X} = 3.52$, and

$$b = \frac{24.58}{15.80} = 1.56$$

So, the unadjusted and adjusted mean growths are

	Mean Growth	
Treatment	**Unadjusted**	**Adjusted**
A	9.67	9.20
B	10.33	11.00
C	9.49	9.30

Tests among Adjusted Means

In an earlier section we encountered methods of making further tests among the means. Ignoring the covariance adjustment, we could, for example, make an F test for pre-specified comparisons such as A + C vs. B, or A vs. C. Similar tests can also be made after adjustment for covariance, through they involve more labor. The F test will be illustrated for the comparison B vs. A + C after adjustment.

As might be suspected, to make the F test we must first compute sums of squares and products of X and Y for the specified comparison:

$$SS_y = \frac{\left[2\left(\sum Y_B\right)-\left(\sum Y_A+\sum Y_C\right)\right]^2}{(2^2+1^2+1^2)(11)} = \frac{[2(113.6)-(106.4+104.4)]^2}{66} = 4.08$$

$$SS_x = \frac{\left[2\left(\sum X_B\right)-\left(\sum X_A+\sum X_C\right)\right]^2}{(2^2+1^2+1^2)(11)} = \frac{[2(34.0)-(42.0+40.0)]^2}{66} = 2.97$$

$$SP_{xy} = \frac{\left[2\left(\sum X_B\right)-\left(\sum X_A+\sum X_C\right)\right]^2}{(2^2+1^2+1^2)(11)} = \frac{[2(34.0)-(42.0+40.0)]^2}{66} = -3.48$$

From this point on, the F test of A + B vs. C is made in exactly the same manner as the test of treatments in the covariance analysis.

					Residuals		
Source	***df***	***SS***$_y$	***SP***$_{xy}$	***SS***$_x$	***df***	***SS***	**MS**
2B – (A + C)	1	4.08	–3.48	2.97	—	—	—
Error	20	68.88	24.58	15.80	19	30.641	1.613
Sum	21	72.96	21.10	18.77	20	49.241	—
Difference for testing adjusted comparison					1	18.600	18.600

$F_{1/19df} = 11.531$, which is significant at the 0.01 level.

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6 Fundamental Engineering Concepts

The mountain, and the deep and gloomy wood,
Their colours and their forms, were then to me
An appetite; a feeling and a love,
That had no need of remoter charm, …

—William Wordsworth (1798)

INTRODUCTION

Education can only go so far in preparing environmental engineers for on-the-job experience. A person who wishes to become an environmental engineer is greatly assisted by two personal factors. First, well-rounded, broad development of experience in many areas is required and results in the production of the classic generalist. Although environmental engineers cannot possibly gain in-depth knowledge about all areas, they must have the desire and the aptitude to do so. They must be interested in—and well informed about—many widely differing fields of study. The necessity for this in environmental applications is readily apparent, as the range of problems encountered is so immense that a narrow education will not suffice. Environmental engineers must handle situations that call upon skills ranging from the ability to understand the psychological and sociological problems of people to the ability to perform calculations required for mechanics and structures. The would-be practicing environmental engineer can come from just about any background, and a narrow educational focus does not preclude students and others from broadening their expertise later; however, quite often those who are very specialized lack appreciation for other disciplines, as well as the adaptability necessary for environmental engineering.

A second requirement calls for an educational emphasis upon quantitative and logical problem solving. A student whose mathematical ability is limited to simple algebra is not likely to acquire the necessary quantitative expertise without great effort. Along with mathematics, environmental engineers must have a good foundation in mechanics and structures. An education that does not include a foundation in the study of forces that act on buildings, machines, and processes leaves the environmental practitioner in the same position as a thoracic surgeon with incomplete knowledge of gross anatomy—both will have to feel their way to the target, which leaves a lot to be desired (especially in the case of the surgery patient).

Although individual learning style is important when choosing a career as an environmental engineer, again it must be stressed that generalized education is the key ingredient in the mix that produces an adequately educated environmental professional. Along with an education in the basic and applied sciences of mathematics, natural science, and behavioral science (which are applied to solve technological, biological, and behavioral problems), further study in engineering and technology is a must. Topics such as applied mechanics, properties of materials, electrical circuits and machines, fire science hydraulics, principles of engineering design, and computer science fall into this category.

In this chapter, the focus is on applied mechanics and, in particular, forces and the resolution of forces. Many accidents and resulting injuries are caused by forces of too great a magnitude for a machine, material, or structure to withstand. To design and inspect systems, devices, or products to ensure their safety, environmental engineers must account for the forces that act or might act on them. Environmental engineers must also account for forces from objects that may act on the human body (an area of focus that is often overlooked). Important subject areas that are part of or that interface with applied mechanics are the properties of materials, electrical circuits and machines, and engineering design considerations. We cannot discuss all engineering aspects related to these areas in this text; instead, our goal is to look at some fundamental concepts and their relationships to environmental engineering.

RESOLUTION OF FORCES

With regard to the environmental and occupational health aspects of environmental engineering, we tend to focus our attention on those forces that are likely to cause failure or damage to some device or system, resulting in an occurrence that is likely to produce secondary and tertiary damage to other devices or systems and harm to individuals. Typically, large forces are more likely to cause failure or damage than small ones. Environmental engineers must understand force and how a force acts on a body, particularly (1) the direction of force, (2) point of application (location) of force, (3) the area over which force acts, (4) the distribution or concentration of forces that act on bodies, and (5) how essential these elements are in evaluating the strength of materials. For example, a 40-lb force applied to the edge of a sheet of plastic and parallel to it probably will not break it. If a sledgehammer strikes the center of the sheet with the same force, the plastic will probably break. A sheet metal panel of the same size undergoing the same force will not break.

Practice tells us that different materials have different strength properties. Striking a plastic panel will probably cause it to break, whereas striking a sheet metal panel will cause a dent. The strength of a material and its ability to deform are directly related to the force applied. Important physical, mechanical, and other properties of materials include the following:

- Crystal structure
- Strength
- Melting point
- Density
- Hardness
- Brittleness
- Ductility
- Modulus of elasticity
- Wear properties
- Coefficient of expansion
- Contraction
- Conductivity
- Shape
- Exposure to environmental conditions
- Exposure to chemicals
- Fracture toughness

Note: All of these properties can vary, depending on whether the force is crushing, corroding, cutting, pulling, or twisting.

The forces an object can encounter are often different from the forces that an object can withstand. An object may be designed to withstand only minimal force before it fails (a toy doll may be designed of very soft, pliable materials or designed to break or give way in certain places when a child falls on it, thus preventing injury). Other devices may be designed to withstand the greatest possible load and shock (e.g., a building constructed to withstand an earthquake).

When working with any material that will go in an area with a concern for safety, a safety factor (SF) is often introduced. As defined by ASSE (1988), a safety factor is the ratio allowed for in the design between the ultimate breaking strength of a member, material, structure, or equipment and the actual working stress or safe permissible load placed on it during ordinary use. Simply put, including a factor of safety—into the design of a machine, for example—makes an allowance for many unknowns (e.g., inaccurate estimates of real loads or irregularities in materials) related to the materials used to make the machine, related to the machine's assembly, and related to the use of the machine. Safety factors can be determined in several ways. One of the most commonly used ways is

$$\text{Safety factor} = (\text{Failure-producing load})/(\text{Allowable stress}) \tag{6.1}$$

Forces on a material or object are classified by the way they act on the material. For example, a force that pulls a material apart is called the *tensile force*. Forces that squeeze a material or object are called *compression forces*. *Shear forces* cut a material or object. Forces that twist a material or object are *torsional forces*. Forces that cause a material or object to bend are *bending forces*. A *bearing force* occurs when one material or object presses against or bears on another material or body.

So, what is force? *Force* is typically defined as any influence that tends to change the state of rest or the uniform motion in a straight line of a body. The action of an unbalanced or resultant force results in the acceleration of a body in the direction of action of the force, or it may (if the body is unable to move freely) result in its deformation. Force is a vector quantity, possessing both magnitude and direction (see Figure 6.1); its SI unit is the newton (equal to 3.6 ounces, or 0.225 lb).

According to Newton's second law of motion, the magnitude of a resultant force is equal to the rate of change of momentum of the body on which it acts. Force F producing acceleration a (m/s^2) on a body of mass m (kg) is therefore given by

$$F = m \times a \times SF \tag{6.2}$$

With regard to environmental engineering, a key relationship between force F and a body on which it acts is

$$F = s \times A \tag{6.3}$$

where

s = Force or stress per unit area (e.g., pounds per square inch).

A = Area (e.g., square inches, square feet) over which a force acts.

Note: The stress a material can withstand is a function of the material and the type of loading.

Frequently, two or more forces act together to produce the effect of a single force, called a *resultant*. This resolution of forces can be explained by either the triangle law or the parallelogram law. The *triangle law* provides that if two concurrent forces are laid out vectorially with the beginning of the second force at the end of the first, the vector connecting the beginning and the end of the

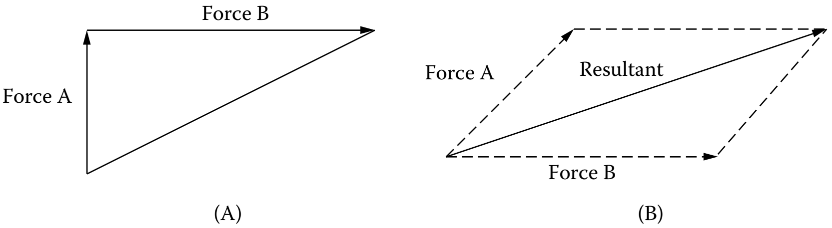

FIGURE 6.1 Force is a vector quantity.

forces represents the resultant of the two forces (see Figure 6.1A). The *parallelogram law* provides that if two concurrent forces are laid out vectorially, with either forces pointing toward or both away from their point of intersection, a parallelogram represents the resultant of the force. The concurrent forces must have both direction and magnitude if their resultant is to be determined (see Figure 6.1B). If the individual forces are known or if one of the individual forces and the resultant are known, the resultant force may be simply calculated by either the trigonometric method (sines, cosines, and tangents) or the graphic method (which involves laying out the known force, or forces, at an exact scale and in the exact directions in either a parallelogram or triangle and then measuring the unknown to the same scale).

SLINGS

Let's take a look at a few example problems involving forces that the environmental engineer might be called upon to calculate. In our examples, we use lifting slings under different conditions of loading.

> ***Note:*** Slings are commonly used between cranes, derricks, or hoists and the load, so the load may be lifted and moved to a desired location. For the safety engineer, the properties and limitations of the sling, the type and condition of material being lifted, the weight and shape of the object being lifted, the angle of the lifting sling to the load being lifted, and the environment in which the lift is to be made are all important considerations to be evaluated—before the transfer of material can take place safely.

■ EXAMPLE 6.1

Problem: Let us assume a load of 2000 lb supported by a two-leg sling; the legs of the sling make an angle of 60° with the load. What force is exerted on each leg of the sling?

Solution: When solving this type of problem, always draw a rough diagram as shown in Figure 6.2. A resolution of forces provides the answer. We will use the trigonometric method to solve this problem, but remember that it may also be solved using the graphic method. Using the trigonometric method with the parallelogram law, the problem could be solved as described below. Again, make a drawing to show a resolution of forces similar to that shown in Figure 6.3.

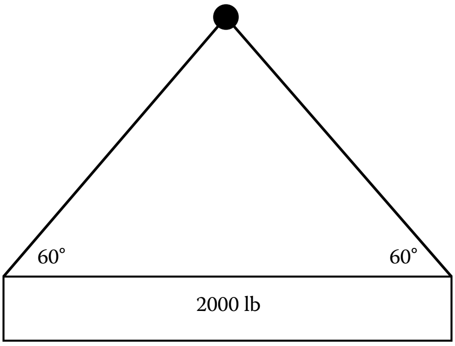

FIGURE 6.2 Illustration for Example 6.1.

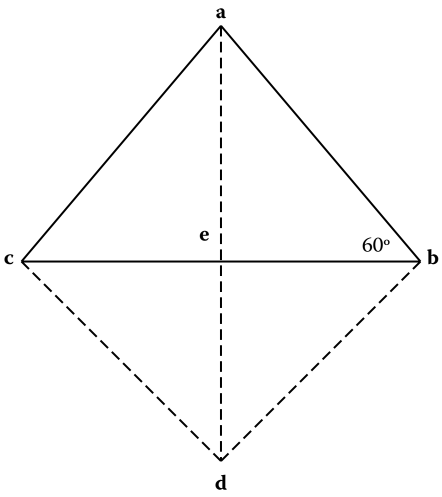

FIGURE 6.3 Illustration for Example 6.1

We could consider the load (2000 lb) as being concentrated and acting vertically, which can be indicated by a vertical line. The legs of the slings are at a 60° angle, which can be shown as **ab** and **ac**. The parallelogram can now be constructed by drawing lines parallel to **ab** and **ac**, intersecting at **d**. The point where **cb** and **ad** intersect can be indicated as **e**. The force on each leg of the sling (**ab**, for example) is the resultant of two forces, one acting vertically (**ae**), the other horizontally (**be**), as shown in the force diagram. Force **ae** is equal to one-half of **ad** (the total force acting vertically, 2000 lb), so **ae** = 1000. This value remains constant regardless of the angle **ab** makes with **bd,** because as the angle increases or decreases, **ae** also increases or decreases. But **ae** is always **ad**/2. The force **ab** can be calculated by trigonometry using the right triangle **abe**:

$$\text{Sine of an angle} = (\text{Opposite side})/(\text{Hypotenuse})$$

therefore,

$$\sin 60^\circ = (\mathbf{ae})/(\mathbf{ab})$$

transposing,

$$\mathbf{ab} = (\mathbf{ae})/(\sin 60^\circ)$$

substituting known values,

$$\mathbf{ab} = (1000)/(0.866) = 1155$$

The total weight on each leg of the sling at a 60° angle from the load is 1155 lb. Note that the weight is more than half the load, because the load is made up of two forces—one acting vertically, the other horizontally. An important point to remember is that the smaller the angle, the greater the load (force) on the sling. For example, at a 15° angle, the force on each leg of a 2000-lb load increases to 3864 lb.

Let's take a look at what the force would be on each leg of a 2000-lb load at various angles that are common for lifting slings (Figure 6.4) and work a couple of example problems.

■ EXAMPLE 6.2

Problem: We have a 3000-lb load to be lifted with a two-leg sling whose legs are at a 30° angle from the load. What is the load (force) on each leg of the sling?

Solution: We know that the sin $A = a/c$, and sin 30° = 0.5. Thus,

$$a = (3000\ \text{lb})/(2) = 1500\ \text{lb}$$

$$c = (a)/(\sin A) = 1500\ \text{lb}/0.5 = 3000\ \text{lb}$$

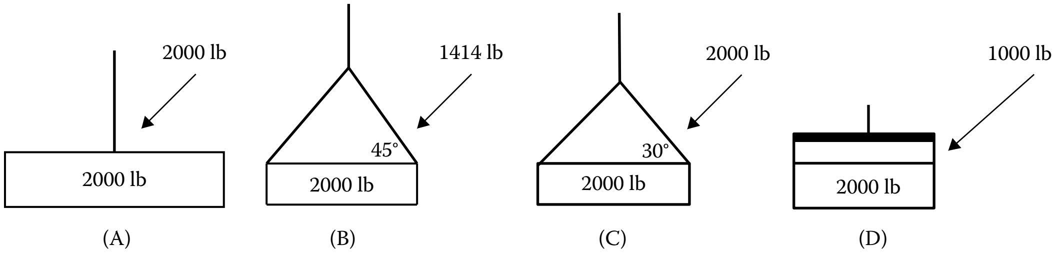

FIGURE 6.4 Sling angle and load examples for Example 6.2.

■ EXAMPLE 6.3

Problem: Given a two-rope sling supporting 10,000 lb, what is the load (force) on the left sling? Sling angle to load is 60°.

Solution: We know that the $\sin A = a/c$, and $\sin 60° = 0.866$. Thus,

$$a = (10{,}000 \text{ lb})/(2) = 5000 \text{ lb}$$

$$c = (a)/(\sin A) = 5000 \text{ lb}/0.866 = 5774 \text{ lb}$$

INCLINED PLANE

Another common problem encountered by environmental engineers involves the resolution of forces that occurs in material handling operations when moving a load (e.g., a cart) up an inclined plane (or ramp). The safety implications in this type of work activity should be obvious. The forces acting on an inclined plane are shown in Figure 6.5. Let's take a look at a typical example of how to determine the force required to pull a fully loaded cart up a ramp (an inclined plane).

■ EXAMPLE 6.4

Problem: We assume that a fully loaded cart weighing 400 lb is to be pulled up a ramp that has a 5-ft rise for each 12 ft, measured along the horizontal direction (make a rough drawing; see Figure 6.6). What force is required to pull it up the ramp?

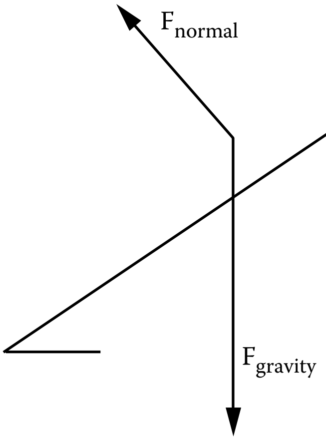

FIGURE 6.5 Forces acting on an inclined plane.

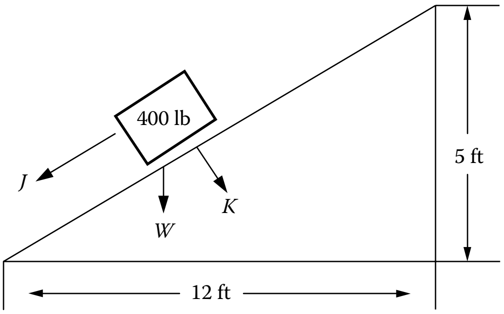

FIGURE 6.6 Inclined plane for Example 6.4.

> ***Note:*** For illustrative purposes, we will assume no friction. Without friction, of course, the work done in moving the cart in a horizontal direction would be zero; once the movement of the cart was started, it would move with constant velocity—the only work required is that necessary to get it started. However, a force equal to *J* is necessary to pull the cart up the ramp or to maintain the car at rest (in equilibrium). As the angle (slope) of the ramp is increased, greater force is required to move it, because the load is being raised as it moves along the ramp, thus doing work. Remember that this is not the case when the cart is moved along a horizontal plane without friction; however, in actual practice friction can never be ignored, and some work is accomplished in moving the cart.

Solution: To determine the actual force involved, we can again use a resolution of forces. The first step is to determine the angle of the ramp. This can be calculated by the formula:

$$\text{Tangent (angle of ramp)} = (\text{Opposite side})/(\text{Adjacent side}) = (5)/(12) = 0.42$$

and arctan 0.42 = 22.8°.

Now we need to draw a force parallelogram (see Figure 6.7) and apply the trigonometric method. The weight of the cart (W) (shown as force acting vertically) can be resolved into two components: force J parallel to the ramp and force K perpendicular to the ramp. Component K, being perpendicular to the inclined ramp, does not hinder movement up the ramp. Component J represents a force that would accelerate the cart down the ramp. To pull the cart up the ramp, a force equal to or greater than J is necessary.

Applying the trigonometric method, angle WOK is the same as the angle of the ramp.

$$OJ = WK + OW = 400 \text{ lb}$$

$$\text{Sine of angle } WOK\ (22.8^\circ) = (\text{Opposite side, } WK)/(\text{Hypotenuse, } OW)$$

Transposing,

$$WK = OW \times \sin 22.8^\circ = 400 \times 0.388 = 155.2$$

Thus, a force of 155.2 lb is necessary to pull the cart up the 22.8° angle of the ramp (with friction ignored). Note that the total amount of work is the same, whether the cart is lifted vertically (400 lb × 5 ft = 2000 ft-lb) or is pulled up the ramp (155.2 lb × 13 ft = 2000 ft-lb). The advantage gained in using a ramp instead of a vertical lift is that less force is required—but through a greater distance.

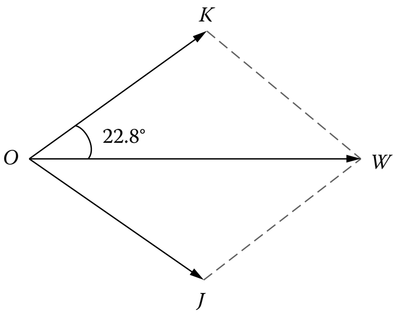

FIGURE 6.7 Force parallelogram.

PROPERTIES OF MATERIALS AND PRINCIPLES OF MECHANICS

To be able to recognize hazards and to select and implement appropriate controls, an environmental engineer must have a good understanding of the properties of materials and principles of mechanics. In this section, we begin with a discussion of the properties of materials then address the wide spectrum that is mechanics, beginning with statics and ending with electrical machines. The intent is to clearly illustrate the wide scope of knowledge required in areas germane to the properties of materials, the principles of mechanics, and other relevant topics that will help to produce well-rounded, knowledgeable environmental engineers.

PROPERTIES OF MATERIALS

When we speak of the properties of materials or a material's properties, what are we referring to and why should we concern ourselves with this topic? The best way to answer this question is to consider an environmental engineer working with design engineers in a preliminary design conference. The engineer might typically be exposed to engineering design data, parameters, and specifications related to the properties of a particular construction material to be used in the fabrication of, for example, a large mezzanine in a warehouse. To construct this particular mezzanine, consideration must be given to the fact that it will be used to store large, heavy equipment components. The demands placed on the finished mezzanine create the need for the mezzanine to be built using materials that can safely support a heavy load.

For illustration, let's say that the design engineers plan to use an aluminum alloy (structural, No. 17ST). Before they decide upon using No. 17ST and determining the quantity necessary to build the mezzanine, they must examine the material's mechanical properties to ensure that it will be able to handle the intended load (they will also factor in, many times over, for safety, the use of a material that will handle a load much greater than expected). Using a table on the mechanical properties of engineering materials in Urquhart's *Civil Engineering Handbook*, they found the information for No. 17ST shown in Table 6.1.

Is this information important to an environmental engineer? Not particularly, but what is important to an environmental engineer is that (1) professional engineers in this case actually took the time to determine the correct materials to use to construct the mezzanine, and (2) when exposed to this type of information, to specific terms, the environmental engineer must know enough about the language used to know what the design engineers are talking about and to understand its significance. (Remember Voltaire: "If you wish to converse with me, define your terms.")

Let's take a look at a few essential engineering terms and their definitions. Keep in mind that many of these definitions are defined exactly and precisely in mathematical formulas and computations. These exact and precise mathematical definitions are beyond the scope of this text, but we do include a few here that are pertinent to the environmental profession. Many of the engineering terms defined below are from Heisler (1998), Tapley (1990), and Giachino and Weeks (1985), all highly recommended texts and ones that should serve as standard reference texts for environmental engineers.

TABLE 6.1
Properties of Engineering Materials No. 17ST

Ultimate strength (defined as the ultimate strength in compression for ductile materials, which is usually taken as the yield point)	Tension = 58,000 psi Compression strength = 35,000 psi Shear strength = 35,000 psi
Yield point tension	35,000 psi.
Modulus of elasticity, tension or compression	10,000,000
Modulus of elasticity, shear	3,750,000
Weight	0.10 lb/in.^{3}

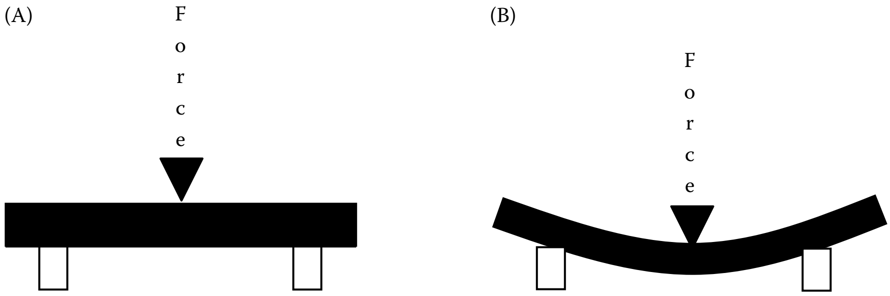

FIGURE 6.8 (A) Stress is measured in terms of the load applied over the area. (B) Strain is expressed in terms of amount of deformation per square inch.

Stress—The internal resistance a material offers to being deformed; it is measured in terms of the applied load over the area (see Figure 6.8A)

Strain—Deformation that results from a stress; it is expressed in terms of the amount of deformation per square inch (see Figure 6.8B).

Intensity of stress—Stress per unit area, usually expressed in pounds per square inch; it is the result of a force of *P* pounds producing tension, compression, or shear on an area of *A* square inches, over which it is uniformly distributed. The simple term *stress* is normally used to indicate intensity of stress.

Ultimate stress—The greatest stress that can be produced in a body before rupture occurs.

Allowable stress or working stress—The intensity of stress that the material of a structure or a machine is designed to resist.

Elastic limit—The maximum intensity of stress to which a material may be subjected and return to its original shape upon the removal of stress (see Figure 6.9).

Yield point—The intensity of stress beyond which the change in length increases rapidly with little (if any) increase in stress.

Modulus of elasticity—Ratio of stress to strain, for stresses below the elastic limit. By checking the modulus of elasticity, the comparative stiffness of different materials can readily be ascertained. Rigidity and stiffness are very important considerations for many machine and structural applications.

Poisson's ratio—Ratio of the relative change of diameter of a bar to its unit change of length under an axial load that does not stress it beyond the elastic limit.

Tensile strength—Resistance to forces acting to pull the metal apart, a very important factor in the evaluation of a metal (see Figure 6.10).

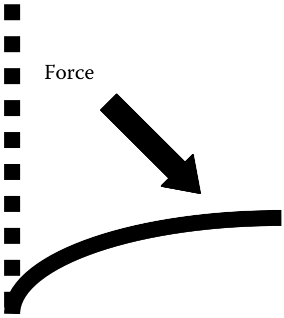

FIGURE 6.9 Elasticity and elastic limit; a metal has the ability to return to its original shape after being elongated or distorted, unless it reaches its maximum stress point.

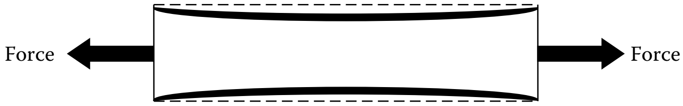

FIGURE 6.10 A metal with tensile strength resists pulling forces.

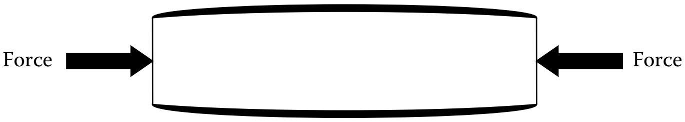

FIGURE 6.11 Compressive strength is the ability of a metal to resist crushing forces.

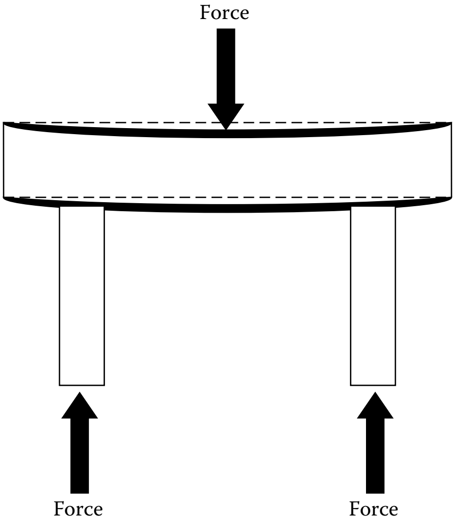

FIGURE 6.12 Bending strength (stress) is a combination of tensile strength and compressive strength.

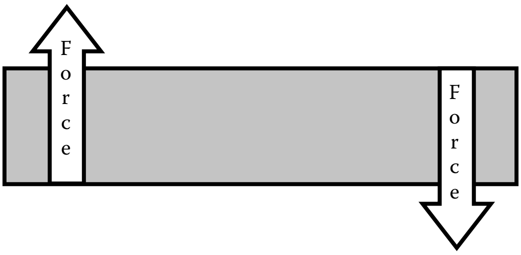

FIGURE 6.13 Torsional strength is the ability of a metal to withstand twisting forces.

Compressive strength—Ability of a material to resist being crushed (see Figure 6.11).

Bending strength—Resistance to forces causing a member to bend or deflect in the direction in which the load is applied; it is actually a combination of tensile and compressive stresses (see Figure 6.12).

Torsional strength—Resistance to forces causing a member to twist (see Figure 6.13).

Shear strength—Resistance to two equal forces acting in opposite directions (see Figure 6.14).

Fatigue strength—Resistance to various kinds of rapidly alternating stresses.

Impact strength—Resistance to loads that are applied suddenly and often at high velocity.

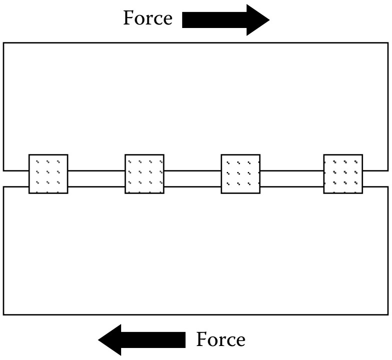

FIGURE 6.14 Sheer strength determines how well a member can withstand two equal forces acting in opposite directions.

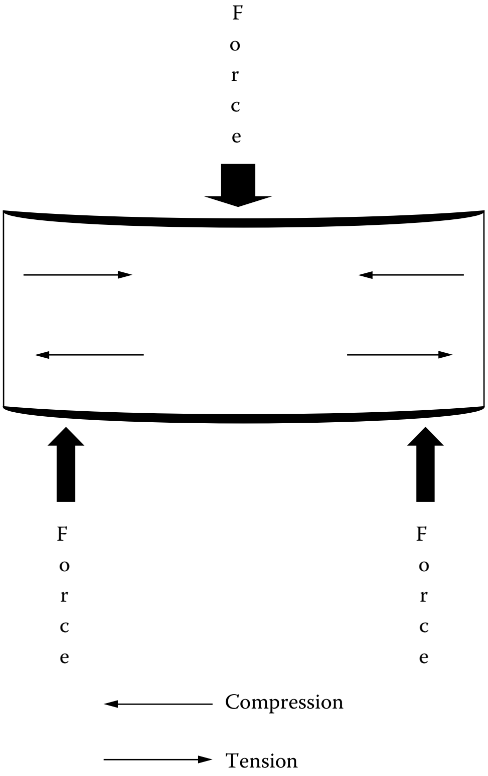

FIGURE 6.15 Distribution of stress in a beam cross-section during bending.

Ductility—Ability of a metal to stretch, bend, or twist without breaking or cracking (see Figure 6.15).

Hardness—Property in steel that resists indentation or penetration.

Brittleness—A condition whereby a metal will easily fracture under low stress.

Toughness—May be considered as strength, together with ductility. A tough material can absorb large amounts of energy without breaking.

Malleability—Ability of a metal to be deformed by compression forces without developing defects, such as forces encountered in rolling, pressing, or forging.

Friction

Earlier, in the discussion on the principle of the inclined plane, the effect of friction was ignored. In actual use, friction cannot be ignored and we must have some understanding of its characteristics and applications. Friction results when an object on the verge of sliding, rotating, rolling, or spinning, or in the process of any of these, is in contact with another body. Friction allows us to walk, ski, drive vehicles, and power machines, among other things. Whenever one object slides over another, frictional forces opposing the motion are developed between them. Friction force is the force tangent to the contact surface that resists motion. If motion occurs, the resistance is due to kinetic friction, which is normally lower than the value for static friction. Contrary to common perception, the degree of smoothness of a surface area is not responsible for these frictional forces; instead, the molecular structure of the materials is responsible. The coefficient of friction (M) (which differs among different materials) is the ratio of the frictional force (F) to the normal force (N) between two bodies:

$$M = F/N \tag{6.4}$$

For dry surfaces, the coefficient of friction remains constant, even if the weight of an object (i.e., force N) is changed. The force of friction (F) required to move the block changes proportionally. Note that the coefficient of friction is independent of the area of contact, which means that pushing a brick across the floor requires the same amount of force whether it is on end, on edge, or flat. The coefficient of friction is useful in determining the force necessary to do a certain amount of work. Temperature changes only slightly affect friction. Friction causes wear. To overcome this wear problem, lubricants are used to reduce friction.

Pressure

Pressure, in mechanics, is defined as the force per unit of area or

$$\text{Pressure} = (\text{Total force})/(\text{Area}) \tag{6.5}$$

Pressure is usually expressed in terms of force per unit of area, as in pounds per square inch when dealing with gases or in pounds per square foot when dealing with weight on a given floor area. The pressure exerted on a surface is the perpendicular force per unit area that acts upon it. Gauge pressure is the difference between total pressure and atmospheric pressure.

Specific Gravity

Specific gravity is the ratio of the weight of a liquid or solid substance to the weight of an equal volume of water, a number that can be determined by dividing the weight of a body by the weight of an equal volume of water. Because the weight of any body per unit of volume is its density, then

$$\text{Specific gravity} = (\text{Density of body})/(\text{Density of water}) \tag{6.6}$$

■ EXAMPLE 6.5

Problem: The density of a particular material is 0.24 lb/in.^{3}, and the density of water is 0.0361 lb/in.^{3}. What is the specific gravity?

Solution:

$$\text{Specific gravity} = (\text{Density of body})/(\text{Density of water}) = 0.24/0.0361 = 6.6$$

The material is 6.6 times as heavy as water. This ratio does not change, regardless of the units that may be used, which is an advantage for two reasons: (1) the ratio will always be the same for the same material, and (2) specific gravity is less confusing than the concept of density, which changes as the units change.

Force, Mass, and Acceleration

According to Newton's second law of motion:

> The acceleration produced by unbalanced force acting on a mass is directly proportional to the unbalanced force, in the direction of the unbalanced force, and inversely proportional to the total mass being accelerated by the unbalanced force.

If we express Newton's second law mathematically, it is greatly simplified and becomes

$$F = ma \tag{6.7}$$

where F is force, m is mass, and a is acceleration; 1 Newton = 1 kg · m/s^2. This equation is extremely important in physics and engineering. It simply relates acceleration to force and mass. Acceleration is defined as the change in velocity divided by the time taken. This definition tells us how to measure acceleration. $F = ma$ tells us what causes the acceleration—an unbalanced force. Mass may be defined as the quotient obtained by dividing the weight of a body by the acceleration caused by gravity. Because gravity is always present, we can, for practical purposes, think of mass in terms of weight, making the necessary allowance for gravitational acceleration.

Centrifugal and Centripetal Forces

Two terms with which the environmental professional should be familiar are *centrifugal force* and *centripetal force*. Centrifugal force is a concept based on an apparent (but not real) force. It may be regarded as a force that acts radially outward from a spinning or orbiting object (a ball tied to a string whirling about), thus balancing a real force, the centripetal force (the force that acts radially inward). This concept is important in environmental engineering, because many of the machines encountered on the job may involve rapidly revolving wheels or flywheels. If the wheel is revolving fast enough, and if the molecular structure of the wheel is not strong enough to overcome the centrifugal force, it may fracture and pieces of the wheel would fly off tangent to the arc described by the wheel. The safety implications are obvious. Any worker using such a device, or near it, may be severely injured when the rotating member ruptures. This is what happens when a grinding wheel on a pedestal grinder "bursts." Rim speed determines the centrifugal force, and rim speed involves both the speed (rpm) of the wheel and the diameter of the wheel.

Stress and Strain

In materials, stress is a measure of the deforming force applied to a body. Strain (which is often erroneously used as a synonym for stress) is really the resulting change in its shape (deformation). For perfectly elastic material, stress is proportional to strain. This relationship is explained by Hooke's law, which states that the deformation of a body is proportional to the magnitude of the deforming force, provided that the body's elastic limit is not exceeded. If the elastic limit is not reached, the body will return to its original size once the force is removed. For example, if a spring is stretched 2 cm by a weight of 1 N, it will be stretched 4 cm by a weight of 2 N, and so on; however, once the load exceeds the elastic limit for the spring, Hooke's law will no longer be obeyed, and each successive increase in weight will result in a greater extension until the spring finally breaks.

Stress forces are categorized in three ways:

1. Tension (or tensile stress), in which equal and opposite forces that act away from each other are applied to a body; tends to elongate a body
2. Compression stress, in which equal and opposite forces that act toward each other are applied to a body; tends to shorten a body
3. Shear stress, in which equal and opposite forces that do not act along the same line of action or plane are applied to a body; tends to change the shape of a body without changing its volume

PRINCIPLES OF MECHANICS

This section discusses the mechanical principles of statics, dynamics, soils, beams, floors, columns, electric circuits, and machines. Field safety engineers should have at least some familiarity with all of these. Note that safety engineers whose function is to verify design specifications (with safety in mind) should have more than just a familiarity with these topics.

Statics

Statics is the branch of mechanics concerned with the behavior of bodies at rest and forces in equilibrium and is distinguished from dynamics (concerned with the behavior of bodies in motion). Forces acting on statics do not create motion. Static applications are bolts, welds, rivets, load-carrying components (ropes and chains), and other structural elements. A common example of a static situation is shown in the bolt-and-plate assembly. The bolt is loaded in tension and holds two elements together.

Welds

Welding is a method of joining metals to achieve a more efficient use of the materials and faster fabrication and erection. Welding also permits the designer to develop and use new and aesthetically appealing designs, and it saves weight because connecting plates are not needed and allowances need not be made for reduced load-carrying ability due to holes for rivets, bolts, and so on (Heisler, 1998). Simply put, the welding process joins two pieces of metal together by establishing a metallurgical bond between them. Most processes use a fusion technique; the two most widely used are arc welding and gas welding. In the welding process, where two pieces of metal are joined together, the mechanical properties of metals are important, of course. The mechanical properties of metals primarily determine how materials behave under applied loads—in other words, how strong a metal is when it comes in contact with one or more forces. The important point is that if you apply knowledge about the strength properties of a metal, you can build a structure that is both safe and sound. The welder must know the strength of his weld as compared with the base metal to produce a weldment that is strong enough to do the job. Thus, the welder is just as concerned with the mechanical properties of metals as is the engineer.

Dynamics

Dynamics (kinetics in mechanics) is the mathematical and physical study of the behavior of bodies under the action of forces that produce changes of motion in them. In dynamics, certain properties are important: displacement, velocity, acceleration, momentum, kinetic energy, potential energy, work, and power. Environmental engineers work with these properties to determine, for example, if rotating equipment will fly apart and cause injury to workers or to determine the distance required to stop a vehicle in motion.

Hydraulics and Pneumatics—Fluid Mechanics

Hydraulics (liquids only) and pneumatics (gases only) make up the study of fluid mechanics, which in turn is the study of forces acting on fluids (both liquids and gases). Environmental engineers encounter many fluid mechanics problems and applications of fluid mechanics. Environmental engineers working in chemical industries, or in or around processes using or producing chemicals, particularly need to have an understanding of flowing liquids or gases to be able to predict and control their behavior.

Soil Mechanics

When dealing with soil, nature's building material, engineers should keep the following statement in mind:

> "Observe always that everything is the result of change, and get used to thinking that there is nothing Nature loves so well as to change existing forms and to make new ones like them."
>
> **—Marcus Aurelius (*Meditations*)**

Soil for Construction

By the time most students reach the third or fourth year of elementary school, they are familiar with the Leaning Tower of Pisa, and many are also familiar with Galileo's experiments with gravity and the speed of falling objects dropped from the top of the tower. This 12th-century bell tower has been a curiosity for literally millions of people from the time it was first built to the present. Eight stories high and 180 feet tall, with a base diameter of 52 feet, the tower began to lean by the time the third story was completed, and leans about 1/25 inch further each year.

How many people know why the tower is leaning in the first place—and who would be more than ordinarily curious about why the Leaning Tower leans? If you are a soil scientist or an engineer, this question has real significance and requires an answer. In fact, the Leaning Tower of Pisa should never have acquired the distinction of being a leaning tower in the first place. The problem is that the Leaning Tower of Pisa rests on a non-uniform consolidation of clay, and the ongoing process of leaning may eventually lead to failure of the building.

As you might have guessed, the mechanics of why the Leaning Tower of Pisa leans is what this section is all about. More specifically, it is about the mechanics and physics of the soil—important factors in making the determination as to whether a particular building site is viable for building. Simply put, these two factors are essential in answering the question "Will the soils present support buildings?"

Soil Characteristics

When we refer to the characteristics of soils, we are referring to the mechanical characteristics, physical factors important to environmental engineers. Environmental engineers focus on the characteristics of the soil related to its suitability as a construction material and its ability to be excavated. Simply put, the environmental engineer must understand the response of a particular volume of soil to internal and external mechanical forces. Obviously, it is important to be able to determine the soil's ability to withstand the load applied by structures of various types and its ability to remain stable when excavated. From a purely engineering point of view, soil is any surficial (near the surface) material that is unconsolidated enough to be excavated with tools (from bulldozers to shovels). The engineer takes into consideration both the advantages and disadvantages of using soil for engineering purposes. The obvious key advantage of using soil for engineering is that there is (in many places) no shortage of it—it may already be on the construction site, thus avoiding the expense of hauling it from afar. Another advantage of using soil for construction is its ease of manipulation; it may be easily shaped into almost any desired form. Soil also allows for the passage of moisture, or, as needed, it can be made impermeable.

The environmental engineer looks at both the advantages and disadvantages of using soil for construction projects. The most obvious disadvantage of using soil is its variability from place to place and from time to time. Soil is not a uniform material for which reliable data related to strength can be compiled or computed. Cycles of wetting and drying and freezing and thawing affect the engineering properties of soil. A particular soil may be suitable for one purpose but not for another. Stamford clay in Texas, for example, is rated as "very good" for sealing of farm ponds but "very poor" for use as base for roads and buildings (Buol et al., 1980).

To determine whether a particular soil is suitable for use as a base for roads or buildings, the environmental engineer studies soil survey maps and reports. The environmental engineer also checks with soil scientists and other engineers familiar with the region and the soil types of that region. Any good engineer will also want to conduct field sampling to ensure that the soil product he or she will be working with possesses the soil characteristics required for its intended purpose.

Important characteristics of soils for environmental engineering purposes include the following:

- Soil texture
- Kinds of clay present
- Depth to bedrock
- Soil density

- Erodibility
- Corrosivity
- Surface geology
- Plasticity
- Content of organic matter
- Salinity
- Depth to seasonal water table

The environmental engineer will also want to know the soil's density, space–volume and weight–volume relationships, stress and strain, slope stability, and compaction. Because these concepts are of paramount importance to the engineer, these concepts are discussed in the following sections.

Soil Weight–Volume or Space–Volume Relationships

The proportions of the components vary dramatically between and within various soil types, because water that is not chemically attached is a void filler, and the relationship between it and the void areas is dependent on how much water (moisture) is available. The volume of the soil mass is the sum of the volumes of the three components:

$$V_T = V_a + V_w + V_s \tag{6.8}$$

where
V_T = Total volume.
V_a = Air volume.
V_w = Water volume.
V_s = Solids volume.

The volume of the voids is the sum of V_a and V_w. However, because the weighing of air in the soil voids would be done within the Earth's atmosphere as with other weighings, the weight of the solids is determined on a different basis. We consider the weight of air in the soil to be zero and the total weight is expressed as the sum of the weights of the soil solids and the water:

$$W_T = W_s + W_w \tag{6.9}$$

where
W_T = Total weight.
W_s = Solids weight.
W_w = Water weight.

The relationship between weight and volume can be expressed as

$$W_m = V_m G_{m-w} \tag{6.10}$$

where
W_m = Weight of the material (solid, liquid, or gas).
V_m = Volume of the material.
G_m = Specific gravity of the material (dimensionless).
w = Unit weight of water.

With the relationships described above, a few useful problems can be solved. When an environmental engineer determines that, within a given soil, the proportions of the three major components need to be mechanically adjusted, this can be accomplished by reorienting the mineral grains by compaction or tilling. The environmental engineer may want to blend soil types to alter the proportions, such as increasing or decreasing the percentage of void space.

How do we go about doing this? Relationships between volumes of soil and voids are described by the void ratio (e) and porosity (η). To accomplish this, we must first determine the void ratio (the ratio of the void volume to the volume of solids):

$$e = V_v/V_s \tag{6.11}$$

We must also determine the ratio of the volume of void spaces to the total volume. This can be accomplished by determining the porosity (η) of the soil, which is the ratio of void volume to total volume. Porosity is usually expressed as a percentage:

$$\eta = (V_v/V_T) \times 100\% \tag{6.12}$$

where

V_v = Void space volume.

V_T = Total volume.

Two additional relationships, moisture content (w) and degree of saturation (S), relate the water content of the soil and the volume of the water in the void space to the total void volume:

$$w = (W_w/W_s) \times 100\% \tag{6.13}$$

and

$$S = (V_w/V_v) \times 100\% \tag{6.14}$$

Soil Particle Characteristics

The size and shape of particles in the soil, as well as density and other characteristics, relate to sheer strength, compressibility, and other aspects of soil behavior. Engineers use these index properties to form engineering classifications of soil. Simple classification tests are used to measure index properties (see Table 6.2) in the lab or the field. From Table 6.2, we see that an important division of soils (from the engineering point of view) is the separation of the cohesive (fine-grained) from the incohesive (coarse-grained) soils. Let's take a closer look at these two important terms.

TABLE 6.2
Index Property of Soils

Soil Type	Index Property
Cohesive (fine-grained)	Water content Sensitivity Type and amount of clay Consistency Atterberg limits
Incohesive (coarse-grained)	Relative density In-place density Particle-size distribution Clay content Shape of particles

Source: Adapted from Kehew, A.E., *Geology for Engineers and Environmental Scientists*, 2nd ed., Prentice Hall, Englewood Cliffs, NJ, 1995, p. 284.

Cohesion indicates the tendency of soil particles to stick together. Cohesive soils contain silt and clay. The clay and water content makes these soils cohesive through the attractive forces between individual clay and water particles. The influence of the clay particles makes the index properties of cohesive soils somewhat more complicated than the index properties of cohesionless soils. The resistance of a soil at various moisture contents to mechanical stresses or manipulations depends on the soil's *consistency*, the arrangement of clay particles, and is the most important characteristic of cohesive soils.

Another important index property of cohesive soils is *sensitivity*. Simply defined, sensitivity is the ratio of unconfined compressive strength in the undisturbed state to strength in the remolded state (see Equation 6.15). Soils with high sensitivity are highly unstable.

$$\text{Sensitivity} = (\text{Strength in undisturbed condition})/(\text{Strength in remolded condition}) \qquad (6.15)$$

Soil water content is an important factor that influences the behavior of the soil. The water content values of soil are known as the *Atterburg limits*, a collective designation of so-called limits of consistency of fine-grained soils which are determined with simple laboratory tests. They are usually presented as the *liquid limit* (LL), *plastic limit* (PL), and *shrinkage limit* (SL). The plastic limit is the water level at which soil begins to be malleable in a semisolid state, but molded pieces crumble easily when a little pressure is applied. When the volume of the soil becomes nearly constant (solid) with further decreases in water content, the soil has reached the shrinkage limit. The liquid limit is the water content at which the soil–water mixture changes from a liquid to a semifluid (or plastic) state and tends to flow when jolted. Obviously, an engineer charged with building a highway or building would not want to choose a soil for the foundation that tends to flow when wet. The difference between the liquid limit and the plasticity limit is the range of water content over which the soil is plastic and is called the *plasticity index*. Soils with the highest plasticity indices are unstable in bearing loads.

Several systems for classifying the stability of soil materials have been devised, but the best known (and probably the most useful) system is called the Unified System of Classification. This classification gives each soil type (14 classes) a two-letter designation, primarily based on particle-size distribution, liquid limit, and plasticity index.

Cohesionless coarse-grained soils behave much differently than cohesive soils and are based on (from index properties) the size and distribution of particles in the soil. Other index properties (particle shape, in-place density, and relative density, for example) are important in describing cohesionless soils, because they relate to how closely particles can be packed together.

Soil Stress and Strain

If the reader is familiar with water pressure and its effect as you go deeper into the water (as when diving deep into a lake), it should come as no surprise that the same concept applies to soil and pressure. Like water, pressure within the soil increases as the depth increases. A soil, for example, that has a unit weight of 75 lb/ft^3 exerts a pressure of 75 psi at a 1-foot depth and 225 psi at 3 feet, etc. As you might expect, as the pressure on a soil unit increases, the soil particles reorient themselves structurally to support the cumulative load. This consideration is important, because the elasticity of the soil sample retrieved from beneath the load may not be truly representative once it has been delivered to the surface. The importance of taking representative samples cannot be overstated. The response of a soil to pressure (stress) is similar to what occurs when a load is applied to a solid object; the stress is transmitted throughout the material. The load subjects the material to pressure, which equals the amount of load divided by the surface area of the external face of the object over which it is applied. The response to this pressure or stress is called *displacement* or *strain*. *Stress* (like pressure), at any point within the object, can be defined as force per unit area.

Soil Compressibility

When a vertical load such as a building or material stockpile is placed above a soil layer, some settlement can be expected. Settlement is the vertical subsidence of the building (or load) as the soil is compressed. Compressibility refers to the tendency of soil to decrease in volume under load. This compressibility is most significant in clay soils because of the inherent high porosity. Although the mechanics of compressibility and settlement are quite complex and beyond the scope of this text, the reader should know something about the actual evaluation process for these properties, which is accomplished in the consolidation test. This test subjects a soil sample to an increasing load. The change in thickness is measured after the application of each load increment.

Soil Compaction

The goal of compaction is to reduce void ratio and thus increase the soil density, which, in turn, increases the shear strength. This is accomplished by working the soil to reorient the soil grains into a more compact state. If water content is within a limited range (sufficient enough to lubricate particle movement), efficient compaction can be obtained. The most effective compaction occurs when the soil placement layer (commonly called *lift*) is approximately 8 inches. At this depth, the most energy is transmitted throughout the lift. Note that more energy must be dispersed, and the effort required to accomplish maximum density is greatly increased when the lift is greater than 10 inches in thickness. For cohesive soils, compaction is best accomplished by blending or kneading the soil using sheepsfoot rollers and pneumatic tire rollers. These devices work to turn the soil into a denser state. To check the effectiveness of the compactive effort, the in-place dry density of the soil (weight of solids per unit volume) is tested by comparing the dry density of field-compacted soil to a standard prepared in an environmental laboratory. Such a test allows a percent compaction comparison to be made.

Soil Failure

Construction, environmental, and design engineers must be concerned with soil structural implications involved with natural processes (such as frost heave, which could damage a septic system) and changes applied to soils during remediation efforts (e.g., when excavating to mitigate a hazardous materials spill in soil). Soil failure occurs whenever it cannot support a load. Failure of an overloaded foundation, collapse of the sides of an excavation, or slope failure on the sides of a dike, hill, or similar feature is termed *structural failure*. The type of soil structural failure that probably occurs more frequently than any other is slope failure (commonly known as a *cave-in*). A Bureau of Labor Statistics review of on-the-job mishaps found that cave-ins occur in construction excavations more frequently than you might think, even considering the obvious dangers inherent in excavation.

What is an excavation? How deep does an excavation have to be to be considered dangerous? The answers to these questions could save your life or help you protect others when you become an engineer involved with safety. An excavation is any manmade cut, cavity, trench, or depression in the Earth's surface formed by earth removal. This can include excavations for anything from a remediation dig to sewer line installation. No excavation activity should be accomplished without keeping personnel safety in mind. Any time soil is excavated, care and caution are advised. As a rule of thumb (and as law under 29 CFR 1926.650–652), the Occupational Safety and Health Administration (OSHA) requires trench protection in any excavation 5 feet or more in depth. Before digging begins, proper precautions must be taken. The responsible party in charge (the competent person, according to OSHA) must

- Contact utility companies to ensure that underground installations are identified and located.
- Ensure that underground installations are protected, supported, or removed as necessary to safeguard workers.

- Remove or secure any surface obstacles (trees, rocks, and sidewalks, for example) that may create a hazard for workers.
- Classify the type of soil and rock deposits at the site as stable rock, type A, type B, or type C soil. One visual and at least one manual analysis must be performed to make the soil classification.

Let's take a closer look at the requirement to classify the type of soil to be excavated. Before an excavation can be accomplished, the soil type must be determined. The soil must be classified as stable rock, type A, type B, or type C soil. Remember, commonly you will find a combination of soil types at an excavation site. In this case, soil classification is used to determine the need for a protective system. Following is a description of the various soil classifications:

- *Stable rock* is a natural solid mineral material that can be excavated with vertical sides. Stable rock will remain intact while exposed, but keep in mind that, even though solid rock is generally stable, it may become very unstable when excavated (in practice you never work in this kind of rock).
- *Type A soil*, the most stable soil, includes clay, silty clay, sandy clay, clay loam, and sometimes silty clay loam and sandy clay loam.
- *Type B soil*, moderately stable, includes silt, silt loam, sandy loam, and sometimes silty clay loam and sand clay loam.
- *Type C soil*, the least stable, includes granular soils such as gravel, sand, loamy sand, submerged soil, soil from which water is freely seeping, and submerged rock that is not stable.

To test and classify soil for excavation, both visual and manual tests should be conducted. Visual soil testing looks at soil particle size and type. Of course, a mixture of soils will be visible. If the soil clumps when dug it could be clay or silt. Type B or C soil can sometimes be identified by the presence of cracks in walls and spalling (breaks up into chips or fragments). If you notice layered systems with adjacent hazardous areas—buildings, roads, and vibrating machinery—a professional engineer may be required for classification. Standing water or water seeping through trench walls automatically classifies the soil as type C.

Manual soil testing is required before a protective system (e.g., shoring or shoring box) is selected. A sample taken from soil dug out into a spoil pile should be tested as soon as possible to preserve its natural moisture. Soil can be tested either onsite or offsite. Manual soil tests include a sedimentation test, wet shaking test, thread test, and ribbon test.

A sedimentation test determines how much silt and clay are in sandy soil. Saturated sandy soil is placed in a straight-sided jar with about 5 inches of water. After the sample is thoroughly mixed (by shaking it) and allowed to settle, the percentage of sand is visible. A sample containing 80% sand, for example, will be classified as type C. The wet shaking test is another way to determine the amount of sand vs. clay and silt in a soil sample. This test is accomplished by shaking a saturated sample by hand to gauge soil permeability based on the following facts: (1) shaken clay resists water movement through it, and (2) water flows freely through sand and less freely through silt.

The thread test is used to determine cohesion (remember, cohesion relates to stability—how well the grains hold together). After a representative soil sample is taken, it is rolled between the palms of the hands to about 1/8-inch diameter and several inches in length (any child who has played in dirt has accomplished this at one time or another—nobody said soil science has to be boring). The rolled piece is placed on a flat surface and then picked up. If a sample holds together for 2 inches, it is considered cohesive. The ribbon test is used as a backup for the thread test. It also determines cohesion. A representative soil sample is rolled out (using the palms of your hands) to a 3/4-inch diameter and several inches in length. The sample is then squeezed between the thumb and forefinger into a flat unbroken ribbon 1/8 to 1/4 inch thick that is allowed to fall freely over the fingers. If the ribbon does not break off before several inches are squeezed out, the soil is considered cohesive.

TABLE 6.3
Maximum Safe Side Slopes in Excavations

Soil Type	Side Slope (Vertical to Horizontal)	Side Slope (Degrees from Horizontal)
A	75:1	53°
B	1:1	45°
C	1.5:1	34°

Source: OSHA Excavation Standard 29 CFR 1926.650–652.

Once soil has been properly classified, the correct protective system can be chosen. This choice is based on both soil classification and site restrictions. The two main types of protective systems are (1) *sloping* or *benching*, and (2) *shoring* or *shielding*. Sloping and benching are excavation protective measures that cut the walls of an excavation back at an angle to its floor. The angle used for sloping or benching is a ratio based on soil classification and site restrictions. In both systems, the flatter the angle, the greater the protection for workers. Reasonably safe side slopes for each of these soil types are presented in Table 6.3.

Shoring and shielding are two protective measures that add support to an existing excavation; they are generally used in excavations with vertical sides but can be used with sloped or benched soil. Shoring is a system designed to prevent cave-ins by supporting walls with vertical shores called *uprights* or *sheeting*. Wales are horizontal members along the sides of a shoring structure. Cross braces are supports placed horizontally between trench walls. Shielding is a system that employs a trench box or trench shield. These can be premanufactured or built onsite under the supervision of a licensed engineer. Shields are usually portable steel structures placed in the trench by heavy equipment. For deep excavations, trench boxes can be stacked and attached to each other with stacking lugs.

Soil Physics

Soil is a dynamic, heterogeneous body that is non-isotropic; that is, it does not have the same properties in all directions. As you might expect, because of these properties various physical processes are active in soil at all times. This important point was made clear by Winegardner (1996, p. 63): "All of the factors acting on a particular soil, in an established environment, at a specified time, are working from some state of imbalance to achieve a balance." Most soil specialists have little difficulty in understanding why soils are very important to the existence of life on Earth. They know, for example, that soil is necessary (in a very direct sense) to sustain plant life and thus other life forms that depend on plants, and they know that soil functions to store and conduct water, serves a critical purpose in soil engineering involved with construction, and acts as a sink and purifying medium for waste disposal systems. The environmental practitioner involved with soil management activities must be well versed in the physical properties of soil. Specifically, he or she must have an understanding of those physical processes that are active in soil. These factors include physical interactions related to soil water, soil grains, organic matter, soil gases, and soil temperature. To gain this knowledge, the environmental engineer must have training in basic geology, soil science, and engineering construction.

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7 Air Pollution

> The difference between science and the fuzzy subjects is that science requires reasoning, while those other subjects merely require scholarship.
>
> **Heinlein (1973)**

INTRODUCTION TO AIR

Engineers always seem to have definitions for just about anything and everything (most of which cannot be easily understood by many of us). An engineer might refer to air as a fluid, because it is. Like water, air is fluid and it can be poured. Engineers are primarily interested in air as a fluid because they deal with fluid mechanics, the study of the behavior of fluids (including air) at rest or in motion. Fluids may be either gases or liquids. You are probably familiar with the physical difference between gases and liquids, as exhibited by air and water, but for the study of fluid mechanics (and the purposes of this text) it is convenient to classify fluids according to their compressibility.

- Gases are very readily compressible (as in the familiar compressed air).
- Liquids are only slightly compressible (not likely the reader has heard much about compressed water).

What is air? Air is a mixture of gases that constitutes the Earth's atmosphere. The approximate composition of dry air is, by volume at sea level, nitrogen (78%); oxygen (21%), which is necessary for life as we know it; argon (0.93%); and carbon dioxide (0.03%), together with very small amounts of numerous other constituents, including water vapor (see Table 7.1). The water vapor content is highly variable and depends on atmospheric conditions. Air is said to be pure when none of the minor constituents is present in sufficient concentration to be injurious to the health of human beings or animals, to damage vegetation, or to cause loss of amenity (e.g., through the presence of dirt, dust, or odors or by diminution of sunshine).

Where does air come from? Genesis 1:2 states that God separated the water environment into the atmosphere and surface waters on the second day of creation. Many scientists believe that 4.6 billion years ago a cloud of dust and gases forged the Earth and also created a dense molten core enveloped in cosmic gases. This was the *proto-atmosphere* or *proto-air*, composed mainly of carbon dioxide, hydrogen, ammonia, and carbon monoxide, but it was not long before it was stripped away by a tremendous outburst of charged particles from the Sun. As the outer crust of Earth began to solidify, a new atmosphere began to form from the gases outpouring from gigantic hot springs and volcanoes. This created an atmosphere of air composed of carbon dioxide, nitrogen oxides, hydrogen, sulfur dioxide, and water vapor. As the Earth cooled, water vapor condensed into highly acidic rainfall, which collected to form oceans and lakes.

For much of Earth's early existence (the first half), only trace amounts of free oxygen were present, but then green plants evolved in the oceans, and they began to add oxygen to the atmosphere as a waste gas. Eventually, oxygen increased to about 1% of the atmosphere and with time to its current 21%.

TABLE 7.1
Composition of Air/Earth's Atmosphere

Gas	Chemical Symbol	Volume (%)
Nitrogen	N_2	78.08
Oxygen	O_2	20.94
Carbon dioxide	CO_2	0.03
Argon	Ar	0.093
Neon	Ne	0.0018
Helium	He	0.0005
Krypton	Kr	Trace
Xenon	Xe	Trace
Ozone	O_3	0.00006
Hydrogen	H_2	0.00005

How do we know for sure about the evolution of air on Earth? Are we guessing, using voodoo science? There is no guessing or voodoo involved in the historical geological record. Consider, for example, geological formations that are dated to 2 billion years ago. In these early sediments there is a clear and extensive band of red sediment (red-bed sediments), sands colored with oxidized (ferric) iron. Earlier, ferrous formations had been laid down showing no oxidation. But, there is more evidence. We can look at the time frame of 4.5 billion years ago, when carbon dioxide in the atmosphere was beginning to be lost in sediments. The vast amounts of carbon deposited in limestone, oil, and coal indicate that carbon dioxide concentrations must once have been many times greater than today, when it stands at only 0.03%. The first carbonated deposits appeared about 1.7 billion years ago, the first sulfate deposits about 1 billion years ago. The decreasing carbon dioxide was balanced by an increase in the nitrogen content of the air. The forms of *respiration* practiced advanced from fermentation 4 billion years ago to anaerobic *photosynthesis* 3 billion years ago to aerobic photosynthesis 1.5 billion years ago. The aerobic respiration that is so familiar today only began to appear about 500 million years ago.

Fast-forward to the present. The atmosphere itself continues to evolve, but human activities—with their highly polluting effects—have now overtaken Nature's role in determining the changes. If we cannot live without air, if air is so precious and so necessary for sustaining life, then two questions arise: (1) Why do we ignore air? and (2) Why do we abuse it by polluting it? We tend to ignore air (like we do water) because it is so common, usually so accessible, so inexpensive, and so unexceptional.

Is air pollution really that big of a deal, though? Isn't pollution relative? That is, isn't pollution dependent on your point of view—a judgment call? Well, if it were possible to ask the victims of the incidents listed in Table 7.2 their opinion on how big a deal pollution is, they would say big, very big.

Beyond the fact that air is an essential resource that sustains life, it also stimulates and pleases the senses. Although invisible to the human eye, it makes possible such sights as beautiful and dazzling rainbows, heart-pinching sunsets and sunrises, the Northern Lights, and, on occasion, a clear view of that high alpine meadow sprinkled throughout with the colors of spring. Air is more than this, though—for example, have you ever felt the light touch of a cool, soothing breeze against your skin? But air is capable of more, much more. It carries thousands of scents—both pungent and subtle: salty ocean breezes, approaching rain, fragrances from blooming flowers, and others. It is the others that concern us here: the sulfurous gases from industrial processes with their typical rotten egg odor; the stink of garbage, refuse, and trash; the toxic poison remnants from pesticides, herbicides, and all the other "-cides." We are surrounded by air but seldom think about it until it displeases us. It is pollution, the discarded, sickening leftovers of the heavy hand of humans, that causes the problem.

TABLE 7.2
Mortality Occurring during Air Pollution Events

Location	Year	Deaths Reported as a Result of a Pollution Event
Meuse Valley, Belgium	1930	63
Donora, Pennsylvania	1948	20
London	1948	700–800
London	1952	4000
London	1956	1000
London	1957	700–800
London	1959	200–250
London	1962	700
London	1963	700
New York	1963	200–400
New York	1966	168
Bhopal, India	1984	12,000
Graniteville, South Carolina	2004	8

DEFINITION OF KEY TERMS

In order to work at even the edge of air science and the science disciplines closely related to air science, it is necessary for the reader to acquire a familiarity with the vocabulary used in air pollution control activities.

Absolute pressure—The total pressure in a system, including both the pressure of a substance and the pressure of the atmosphere (about 14.7 psi, at sea level).

Acid—Any substance that releases hydrogen ions (H^+) when it is mixed into water.

Acid precipitation—Rain, snow, or fog that contains higher than normal levels of sulfuric or nitric acid, which may damage forests, aquatic ecosystems, and cultural landmarks.

Acid surge—A period of short, intense acid deposition in lakes and streams as a result of the release (by rainfall or spring snowmelt) of acids stored in soil or snow.

Acidic solution—A solution that contains significant numbers of (H^+) ions.

Airborne toxins—Hazardous chemical pollutants that have been released into the atmosphere and are carried by air currents.

Albedo—Reflectivity, or the fraction of incident light that is reflected by a surface.

Arithmetic mean—A measurement of average value, calculated by summing all terms and dividing by the number of terms.

Arithmetic scale—A scale is a series of intervals (marks or lines), usually made along the side or bottom of a graph, that represents the range of values of the data. When the marks or lines are equally spaced, it is called an arithmetic scale.

Atmosphere—A 500-km-thick layer of colorless, odorless gases known as air that surrounds the Earth and is composed of nitrogen, oxygen, argon, carbon dioxide, and other gases in trace amounts.

Atom—The smallest particle of an element that still retains the characteristics of that element.

Atomic number—The number of protons in the nucleus of an atom.

Atomic weight—The sum of the number of protons and the number of neutrons in the nucleus of an atom.

Base—Any substance that releases hydroxyl ions (OH^-) when it dissociates in water.

Chemical bond—The force that holds atoms together within molecules. A chemical bond is formed when a chemical reaction takes place. Two types of chemical bonds are ionic bonds and covalent bonds.

Chemical reaction—A process that occurs when atoms of certain elements are brought together and combine to form molecules, or when molecules are broken down into individual atoms.

Climate—The long-term weather pattern of a particular region.

Covalent bond—A type of chemical bond in which electrons are shared.

Density—The weight of a substance per unit of its volume (e.g., pounds per cubic foot).

Dewpoint—The temperature at which a sample of air becomes saturated; that is, it has a relative humidity of 100%.

Element—Any of more than 100 fundamental substances that consist of atoms of only one kind and that constitute all matter.

Emission standards—The maximum amount of a specific pollutant permitted to be legally discharged from a particular source in a given environment.

Emissivity—The relative power of a surface to reradiate solar radiation back into space in the form of heat, or long-wave infrared radiation.

Energy—The ability to do work, to move matter from place to place, or to change matter from one form to another.

First law of thermodynamics—During physical or chemical change, energy is neither created not destroyed, but it may be changed in form and moved from place to place.

Global warming—The increase in global temperature predicted to arise from increased levels of carbon dioxide, methane, and other greenhouse gases in the atmosphere.

Greenhouse effect—The prevention of the reradiation of heat waves to space by carbon dioxide, methane, and other gases in the atmosphere. The greenhouse effect makes possible the conditions that enable life to exist on Earth.

Insolation—Solar radiation received by the Earth and its atmosphere (incoming solar radiation).

Ion—An atom or radical in solution carrying an integral electrical charge either positive (cation) or negative (anion).

Lapse rate—The rate of temperature change with altitude. In the troposphere, the normal lapse rate is –3.5°F per 1000 ft.

Matter—Anything that exists in time, occupies space, and has mass.

Mesosphere—A region of the atmosphere based on temperature that is between approximately 35 and 60 miles in altitude.

Meteorology—The study of atmospheric phenomena.

Mixture—Two or more elements, compounds, or both, mixed together with no chemical reaction occurring.

Ozone—The compound O_3. It is found naturally in the atmosphere in the ozonosphere and is also a constituent of photochemical smog.

pH—A means of expressing hydrogen ion concentration in terms of the powers of 10; measurement of how acidic or basic a substance is. The pH scale runs from 0 (most acidic) to 14 (most basic). The center of the range (7) indicates that the substance is neutral.

Photochemical smog—An atmospheric haze that occurs above industrial sites and urban areas resulting from reactions, which take place in the presence of sunlight, between pollutants produced in high temperature and pressurized combustion processes (such as the combustion of fuel in a motor vehicle). The primary component of smog is ozone.

Photosynthesis—The process of using the sun's light energy by chlorophyll-containing plants to convert carbon dioxide (CO_2) and water (H_2O) into complex chemical bonds forming simple carbohydrates such as glucose and fructose.

Pollutant—A contaminant at a concentration high enough to endanger the environment.

Pressure—The force pushing on a unit area. Normally, in air applications, pressure is measured in atmospheres (atm), Pascals (Pa), or pounds per square inch (psi).

Primary pollutants—Pollutants that are emitted directly into the atmosphere where they exert an adverse influence on human health or the environment. The six primary pollutants are carbon dioxide, carbon monoxide, sulfur oxides, nitrogen oxides, hydrocarbons, and particulates. All but carbon dioxide are regulated in the United States.

Radon—A naturally occurring radioactive gas arising from the decay of uranium 238, which may be harmful to human health in high concentrations.

Rain shadow effect—The phenomenon that occurs as a result of the movement of air masses over a mountain range. As an air mass rises to clear a mountain, the air cools and precipitation forms. Often, both the precipitation and the pollutant load carried by the air mass will be dropped on the windward side of the mountain. The air mass is then devoid of most of its moisture; consequently, the lee side of the mountain receives little or no precipitation and is said to lie in the rain shadow of the mountain range.

Raleigh scattering—The preferential scattering of light by air molecules and particles that accounts for the blueness of the sky. The scattering is proportional to $1/\lambda^4$.

Relative humidity—The concentration of water vapor in the air. It is expressed as the percentage that its moisture content represents of the maximum amount that the air could contain at the same temperature and pressure. The higher the temperature the more water vapor the air can hold.

Second law of thermodynamics—Natural law that dictates that with each change in form some energy is degraded to a less useful form and given off to the surroundings, usually as low-quality heat.

Secondary pollutants—Pollutants formed from the interaction of primary pollutants with other primary pollutants or with atmospheric compounds such as water vapor.

Solute—The substance dissolved in a solution.

Solution—A liquid containing a dissolved substance.

Specific gravity—The ratio of the density of a substance to a standard density. For gases, the density is compared with the density of air (= 1).

Stratosphere—Atmospheric layer extending from 6 to 30 miles above the Earth's surface.

Stratospheric ozone depletion—The thinning of the ozone layer in the stratosphere; occurs when certain chemicals (such as chlorofluorocarbons) capable of destroying ozone accumulate in the upper atmosphere.

Thermosphere—An atmospheric layer that extends from 56 miles to outer space.

Troposphere—The atmospheric layer that extends from the Earth's surface to 6 to 7 miles above the surface.

Weather—The day-to-day pattern of precipitation, temperature, wind, barometric pressure, and humidity.

Wind—Horizontal air motion.

COMPONENTS OF AIR: CHARACTERISTICS AND PROPERTIES*

As pointed out earlier, air is a combination of component parts: gases and other matter (suspended minute liquid or particulate matter). In this section, we discuss each of these components.

Atmospheric Nitrogen

Nitrogen (N_2) makes up the major portion of the atmosphere (78.03% by volume, 75.5% by weight). It is a colorless, odorless, tasteless, nontoxic, and almost totally inert gas. Nitrogen is nonflammable, will not support combustion, and is not life supporting. Nitrogen is part of Earth's atmosphere

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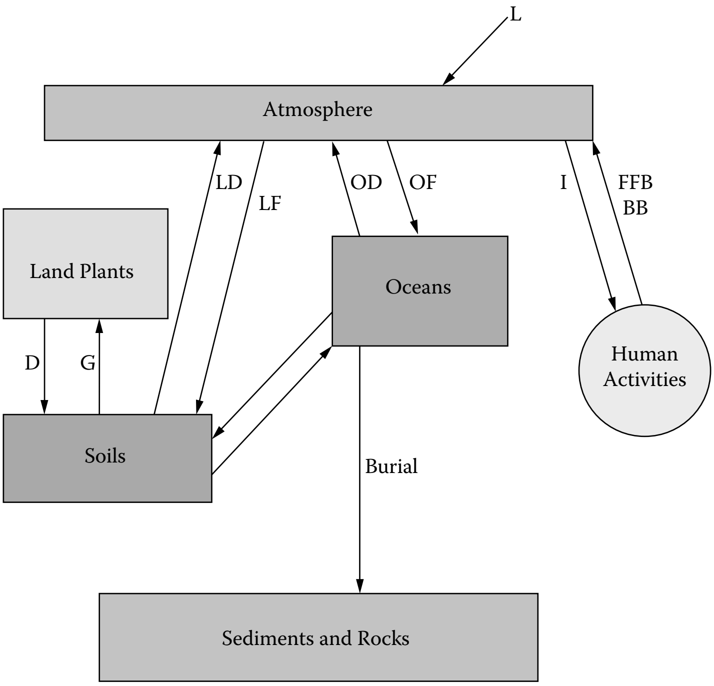
* Much of the information pertaining to atmospheric gases that follows was adapted from *Handbook of Compressed Gases* (Compressed Gas Association, 1990), *Environmental Science and Technology: Concepts and Applications* (Spellman and Whiting, 2006), and *The Science of Air* (Spellman, 2008).



LF = Land Fixation
LD = Land Denitrification
OF = Oceanic Fixation
OD = Oceanic Denitrification
I = Industrial Fixation
FFB = Fossil Fuel Burning
BB = Biomass Burning
L = Lightning
D = Decay
G = Growth

FIGURE 7.1 Nitrogen cycle.

primarily because, over time, it has simply accumulated in the atmosphere and remained in place and in balance. This nitrogen accumulation process has occurred because, chemically, nitrogen is not very reactive. When released by any process, it tends not to recombine with other elements and accumulates in the atmosphere. This is a good thing, because we need nitrogen. No, we don't need it for breathing but we do need it for other life-sustaining processes. Although nitrogen in its gaseous form is of little use to us, after oxygen, carbon, and hydrogen, it is the most common element in living tissues. As a chief constituent of chlorophyll, amino acids and nucleic acids—the "building blocks" of proteins (which are used as structural components in cells)—nitrogen is essential to life. Nitrogen is dissolved in and is carried by the blood. Nitrogen does not appear to enter into any chemical combination as it is carried throughout the body. Each time we breathe, the same amount of nitrogen is exhaled as is inhaled. Animals cannot use nitrogen directly but only when it is obtained by eating plant or animal tissues; plants obtain the nitrogen they need when it is in the form of inorganic compounds, principally nitrate and ammonium.

Gaseous nitrogen is converted to a form usable by plants (nitrate ions) chiefly through the process of nitrogen fixation via the *nitrogen cycle* (see Figure 7.1), when aerial nitrogen is converted into nitrates mainly by microorganisms, bacteria, and blue–green algae. Lightning also converts some aerial nitrogen gas into forms that return to the Earth as nitrate ions in rainfall and other types of precipitation. Ammonia plays a major role in the nitrogen cycle. Excretion by animals and anaerobic decomposition of dead organic matter by bacteria produce ammonia. Ammonia, in

TABLE 7.3
Physical Properties of Nitrogen

Chemical formula	N_2
Molecular weight	28.01
Density of gas at 70°F	0.072 lb/ft^3
Specific gravity of gas at 70°F and 1 atm (air = 1)	0.967
Specific volume of gas at 70°F and 1 atm	13.89 ft^3
Boiling point at 1 atm	–320.4°F
Melting point at 1 atm	–345.8°F
Critical temperature	–232.4°F
Critical pressure	493 psia
Critical density	19.60 lb/ft^3
Latent heat of vaporization at boiling point	85.6 Btu/lb
Latent heat of fusion at melting point	11.1 Btu/lb

turn, is converted by nitrification bacteria into nitrites and then into nitrates. This process is known as *nitrification*. Nitrification bacteria are aerobic. Bacteria that convert ammonia into nitrites are known as nitrite bacteria (*Nitrosococcus* and *Nitrosomonas*). Although nitrite is toxic to many plants, it usually does not accumulate in the soil. Instead, other bacteria (such as *Nitrobacter*) oxidize the nitrite to form nitrate (NO_3^-), the most common biologically usable form of nitrogen.

Nitrogen reenters the atmosphere through the action of denitrifying bacteria, which are found in nutrient-rich habitats such as marshes and swamps. These bacteria break down nitrates into nitrogen gas and nitrous oxide (N_2O), which then reenter the atmosphere. Nitrogen also reenters the atmosphere from exposed nitrate deposits and emissions from electric power plants, automobiles, and volcanoes.

Physical Properties of Nitrogen

The physical properties of nitrogen are provided in Table 7.3.

Uses for Nitrogen

In addition to being the preeminent (with regard to volume) component of Earth's atmosphere and an essential ingredient in sustaining life, nitrogen gas has many commercial and technical applications. As a gas, it is used to heat-treat primary metals, in the production of semiconductor electronic components, as a blanketing atmosphere (e.g., blanketing of oxygen-sensitive liquids and volatile liquid chemicals), to inhibit aerobic bacteria growth, and in the propulsion of liquids through canisters, cylinders, and pipelines.

Nitrogen Oxides

The six oxides of nitrogen are nitrous oxide (N_2O), nitric oxide (NO), dinitrogen trioxide (N_2O_3), nitrogen dioxide (NO_2), dinitrogen tetroxide (N_2O_4), and dinitrogen pentoxide (N_2O_5). Nitric oxide, nitrogen dioxide, and nitrogen tetroxide are fire gases. One or more of them is generated when certain nitrogenous organic compounds (polyurethane) burn. Nitric oxide is the product of incomplete combustion, whereas a mixture of nitrogen dioxide and nitrogen tetroxide is the product of complete combustion. The nitrogen oxides are usually collectively symbolized by the formula NO_x. The U.S. Environmental Protection Agency (USEPA), under the Clean Air Act (CAA), regulates the amount of nitrogen oxides that commercial and industrial facilities may emit to the atmosphere. The primary and secondary standards are the same: The annual concentration of nitrogen dioxide may not exceed 100 mg/m^3 (0.05 ppm).

TABLE 7.4
Physical Properties of Oxygen

Chemical formula	O_2
Molecular weight	31.9988
Freezing point	–361.12°F
Boiling point	–297.33°F
Heat of fusion	5.95 Btu/lb
Heat of vaporization	91.70 Btu/lb
Density of gas at boiling point	0.268 lb/ft^3
Density of gas at room temperature	0.081 lb/ft^3
Vapor density (air = 1)	1.105
Liquid-to-gas expansion ratio	875

ATMOSPHERIC OXYGEN

Oxygen (O_2; from Greek *oxys* for "acid" and *genes* for "forming") constitutes approximately a fifth (21% by volume and 23.2% by weight) of the air in Earth's atmosphere. Gaseous oxygen (O_2) is vital to life as we know it. On Earth, oxygen is the most abundant element. Most oxygen on Earth is not found in the free state but in combination with other elements as chemical compounds. Water and carbon dioxide are common examples of compounds that contain oxygen, but there are countless others. At ordinary temperatures, oxygen is a colorless, odorless, tasteless gas that supports not only life but also combustion. All elements except the inert gases combine directly with oxygen to form oxides; however, oxidation of different elements occurs over a wide range of temperatures. Oxygen is nonflammable but readily supports combustion. All materials that are flammable in air burn much more vigorously in oxygen. Some combustibles, such as oil and grease, burn with nearly explosive violence in oxygen if ignited.

Physical Properties of Oxygen

The physical properties of oxygen are provided in Table 7.4.

Uses for Oxygen

The major uses of oxygen stem from its life-sustaining and combustion-supporting properties. It also has many industrial applications (when used with other fuel gases such as acetylene), including metal cutting, welding, hardening, and scarfing.

Ozone: Just Another Form of Oxygen

Ozone (O_3) is a highly reactive pale-blue gas with a penetrating odor. Ozone is an allotropic modification of oxygen. An allotrope is a variation of an element that possesses a set of physical and chemical properties significantly different from the "normal" form of the element. Only a few elements have allotropic forms; oxygen, phosphorus, and sulfur are some of them. Ozone is just another form of oxygen. It is formed when the molecule of the stable form of oxygen (O_2) is split by ultraviolet (UV) radiation or electrical discharge. It has three instead of two atoms of oxygen per molecule; thus, its chemical formula is represented by O_3. Ozone forms a thin layer in the upper atmosphere, which protects life on Earth from ultraviolet rays, a cause of skin cancer. At lower atmospheric levels it is an air pollutant that contributes to the greenhouse effect. At ground level, ozone, when inhaled, can cause asthma attacks, stunted growth in plants, and corrosion of certain materials. It is produced by the action of sunlight on air pollutants, including car exhaust fumes, and is a major air pollutant in hot summers. More will be said about ozone and the greenhouse effect later in the text.

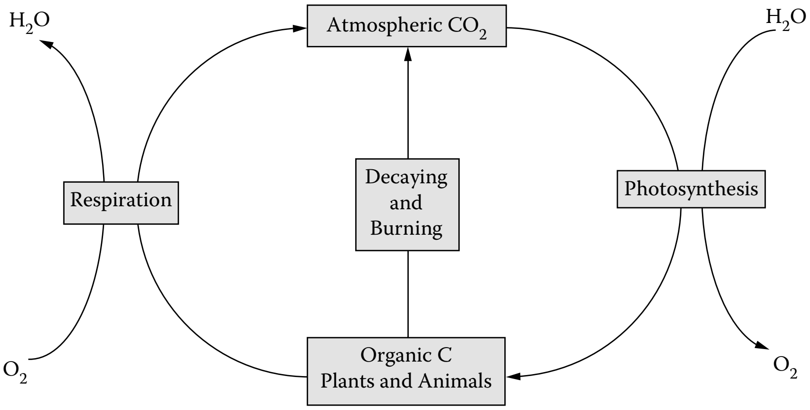


FIGURE 7.2 Carbon cycle.

ATMOSPHERIC CARBON DIOXIDE

Carbon dioxide (CO_2) is a colorless, odorless gas (although it is felt by some persons to have a slight pungent odor and biting taste) that is slightly soluble in water and denser than air (one and half times heavier than air); it is a slightly acid gas. Carbon dioxide gas is relatively nonreactive and nontoxic. It will not burn, and it will not support combustion or life. CO_2 is normally present in atmospheric air at about 0.035% by volume and cycles through the biosphere via the carbon cycle (see Figure 7.2). Carbon dioxide, along with water vapor, is primarily responsible for the absorption of infrared energy re-emitted by the Earth, and, in turn, some of this energy is reradiated back to the Earth's surface. It is also a normal endproduct of human and animal metabolism. Exhaled breath contains up to 5.6% carbon dioxide. In addition, the burning of carbon-laden fossil fuels releases carbon dioxide into the atmosphere. Much of this carbon dioxide is absorbed by ocean water, some of it is taken up by vegetation through photosynthesis in the carbon cycle (see Figure 7.2), and some remains in the atmosphere. Today, it is estimated that the concentration of carbon dioxide in the atmosphere is approximately 350 parts per million (ppm) and is rising at a rate of approximately 20 ppm every decade. The increasing rate of combustion of coal and oil has been primarily responsible for this occurrence, which (as we will see later in this text) may eventually have an impact on global climate.

Physical Properties of Carbon Dioxide

The physical properties of carbon dioxide are provided in Table 7.5.

TABLE 7.5
Physical Properties of Carbon Dioxide

Chemical formula	CO_2
Molecular weight	44.01
Vapor pressure at 70°F	838 psig
Density of the gas at 70°F and 1 atm	0.1144 lb/ft^3
Specific gravity of the gas at 70°F and 1 atm (air = 1)	1.522
Specific volume of the gas at 70°F and 1 atm	8.741 ft^3/lb
Critical temperature	–109.3°F
Critical pressure	1070.6 psia
Critical density	29.2 lb/ft^3
Latent heat of vaporization at 32°F	100.8 Btu/lb
Latent heat of fusion at triple point	85.6 Btu/lb

Uses for Carbon Dioxide

Solid carbon dioxide is used quite extensively to refrigerate perishable foods while in transit. It is also used as a cooling agent in many industrial processes, such as grinding, rubber work, cold-treating metals, vacuum cold traps, and so on. Gaseous carbon dioxide is used to carbonate soft drinks, for pH control in water treatment, in chemical processing, as a food preservative, and in pneumatic devices.

ATMOSPHERIC ARGON

Argon (Ar; from Greek *argos* for "idle") is a colorless, odorless, tasteless, nontoxic, nonflammable gaseous element (noble gas). It constitutes almost 1% of the Earth's atmosphere and is plentiful compared to the other rare atmospheric gases. It is extremely inert and forms no known chemical compounds. It is slightly soluble in water.

Physical Properties of Argon

The physical properties of argon are provided in Table 7.6.

Uses for Argon

Argon is used extensively in filling incandescent and fluorescent lamps and electronic tubes, to provide a protective shield for growing silicon and germanium crystals, and as a blanket in the production of titanium, zirconium, and other reactive metals.

ATMOSPHERIC NEON

Neon (Ne; from Greek *neon* for "new") is a colorless, odorless, gaseous, nontoxic, chemically inert element. Air is about 2 parts per 1000 neon by volume.

Physical Properties of Neon

The physical properties of neon are provided in Table 7.7.

Uses for Neon

Neon is used principally to fill lamp bulbs and tubes. The electronics industry uses neon singly or in mixtures with other gases in many types of gas-filled electron tubes.

TABLE 7.6
Physical Properties of Argon

Chemical formula	Ar
Molecular weight	39.95
Density of the gas at 70°F and 1 atm	0.103 lb/ft^3
Specific gravity of the gas at 70°F and 1 atm	1.38
Specific volume of the gas at 70°F and 1 atm	9.71 ft^3/lb
Boiling point at 1 atm	–302.6°F
Melting point at 1 atm	–308.6°F
Critical temperature at 1 atm	–188.1°F
Critical pressure	711.5 psia
Critical density	33.444 lb/ft^3
Latent heat of vaporization at boiling point and 1 atm	69.8 Btu/lb
Latent heat of fusion at triple point	12.8 Btu/lb

TABLE 7.7
Physical Properties of Neon

Chemical formula	Ne
Molecular weight	20.183
Density of the gas at 70°F and 1 atm	0.05215 lb/ft^3
Specific gravity of the gas at 70°F and 1 atm	0.696
Specific volume of the gas at 70°F and 1 atm	19.18 ft^3/lb
Boiling point at 1 atm	–410.9°F
Melting point at 1 atm	–415.6°F
Critical temperature at 1 atm	–379.8°F
Critical pressure	384.9 psia
Critical density	30.15 lb/ft^3
Latent heat of vaporization at boiling point	37.08 Btu/lb
Latent heat of fusion at triple point	7.14 Btu/lb

TABLE 7.8
Physical Properties of Helium

Chemical formula	He
Molecular weight	4.00
Density of the gas at 70°F and 1 atm	0.0103 lb/ft^3
Specific gravity of the gas at 70°F and 1 atm	0.138
Specific volume of the gas at 70°F and 1 atm	97.09 ft^3/lb
Boiling point at 1 atm	–452.1°F
Critical temperature at 1 atm	–450.3°F
Critical pressure	33.0 psia
Critical density	4.347 lb/ft^3
Latent heat of vaporization at boiling point and 1 atm	8.72 Btu/lb

ATMOSPHERIC HELIUM

Helium (He; from Greek *helios* for "sun") is inert (and, as a result, does not appear to have any major effect on, or role in, the atmosphere), nontoxic, odorless, tasteless, nonreactive, and colorless; it forms no compounds and occurs at about 0.00005% (5 ppm) by volume of air in the Earth's atmosphere. Helium, as with neon, krypton, hydrogen, and xenon, is a noble gas. Helium is the second lightest element; only hydrogen is lighter. It is one-seventh as heavy as air. Helium is nonflammable and is only slightly soluble in water.

Physical Properties of Helium

The physical properties of helium are provided in Table 7.8.

ATMOSPHERIC KRYPTON

Krypton (Kr; from Greek *kryptos* for "hidden") is a colorless, odorless, inert gaseous component of Earth's atmosphere. It is present in very small quantities in the air (about 114 ppm).

Physical Properties of Krypton

The physical properties of krypton are provided in Table 7.9.

TABLE 7.9
Physical Properties of Krypton

Chemical formula	Kr
Molecular weight	83.80
Density of the gas at 70°F and 1 atm	0.2172 lb/ft^3
Specific gravity of the gas at 70°F and 1 atm	2.899
Specific volume of the gas at 70°F and 1 atm	4.604 ft^3/lb
Boiling point at 1 atm	–244.0°F
Melting point at 1 atm	–251°F
Critical temperature at 1 atm	–82.8°F
Critical pressure	798.0 psia
Critical density	56.7 lb/ft^3
Latent heat of vaporization at boiling point	46.2 Btu/lb
Latent heat of fusion at triple point	8.41 Btu/lb

Uses for Krypton

Krypton is used principally to fill lamp bulbs and tubes. The electronics industry uses it singly or in mixture in many types of gas-filled electron tubes.

ATMOSPHERIC XENON

Xenon (Xe; from Greek *xenon* for "stranger") is a colorless, odorless, nontoxic, inert, heavy gas that is present in very small quantities in the air (about 1 part in 20 million).

Physical Properties of Xenon

The physical properties of xenon are provided in Table 7.10.

Uses for Xenon

Xenon is used principally to fill lamp bulbs and tubes. The electronics industry uses it singly or in mixtures in many types of gas-filled electron tubes.

TABLE 7.10
Physical Properties of Xenon

Chemical formula	Xe
Molecular weight	131.3
Density of the gas at 70°F and 1 atm	0.3416 lb/ft^3
Specific gravity of the gas at 70°F and 1 atm	4.560
Specific volume of the gas at 70°F and 1 atm	2.927 ft^3/lb
Boiling point at 1 atm	–162.6°F
Melting point at 1 atm	–168°F
Critical temperature at 1 atm	61.9°F
Critical pressure	847.0 psia
Critical density	68.67 lb/ft^3
Latent heat of vaporization at boiling point	41.4 Btu/lb
Latent heat of fusion at triple point	7.57 Btu/lb

TABLE 7.11
Physical Properties of Hydrogen

Chemical formula	H_2
Molecular weight	2.016
Density of the gas at 70°F and 1 atm	0.00521 lb/ft^3
Specific gravity of the gas at 70° and 1 atm	0.06960
Specific volume of the gas at 70°F and 1 atm	192.0 ft^3/lb
Boiling point at 1 atm	–423.0°F
Melting point at 1 atm	–434.55°F
Critical temperature at 1 atm	–399.93°F
Critical pressure	190.8 psia
Critical density	1.88 lb/ft^3
Latent heat of vaporization at boiling point	191.7 Btu/lb
Latent heat of fusion at triple point	24.97 Btu/lb

ATMOSPHERIC HYDROGEN

Hydrogen (H_2; from Greek *hydros* for "water" and *gen* for "generator") is a colorless, odorless, tasteless, nontoxic, flammable gas. It is the lightest of all the elements and occurs on Earth chiefly in combination with oxygen as water. Hydrogen is the most abundant element in the universe, where it accounts for 93% of the total number of atoms and 76% of the total mass. It is the lightest gas known, with a density approximately 0.07 that of air. Hydrogen is present in the atmosphere in concentrations of only about 0.5 ppm by volume at lower altitudes.

Physical Properties of Hydrogen

The physical properties of hydrogen are provided in Table 7.11.

Uses for Hydrogen

Hydrogen is used by refineries, petrochemical, and bulk chemical facilities for hydrotreating, catalytic reforming, and hydrocracking. Hydrogen is used in the production of a wide variety of chemicals. Metallurgical companies use hydrogen in the production of their products. Glass manufacturers use hydrogen as a protective atmosphere in a process whereby molten glass is floated on a surface of molten tin. Food companies hydrogenate fats, oils, and fatty acids to control various physical and chemical properties. Electronic manufacturers use hydrogen at several steps in the complex processes for manufacturing semiconductors.

ATMOSPHERIC WATER

Leonardo da Vinci understood the importance of water when he said: "Water is the driver of nature." He was actually acknowledging what most scientists and many of the rest of us have come to realize: Water, propelled by the varying temperatures and pressures in Earth's atmosphere, allows life as we know it to exist on our planet (Graedel and Crutzen, 1995). The water vapor content of the lower atmosphere (troposphere) is normally within a range of 1 to 3% by volume with a global average of about 1%. The percentage of water in the atmosphere can vary from as little as 0.1% to as much as 5% water, depending on altitude; the water content of the atmosphere decreases with increasing altitude. Water circulates in the atmosphere in the hydrological cycle, as shown in Figure 7.3. Water vapor contained in Earth's atmosphere plays several important roles: (1) it absorbs infrared radiation; (2) it acts as a blanket at night, retaining heat from the Earth's surface; and (3) it affects the formation of clouds in the atmosphere.

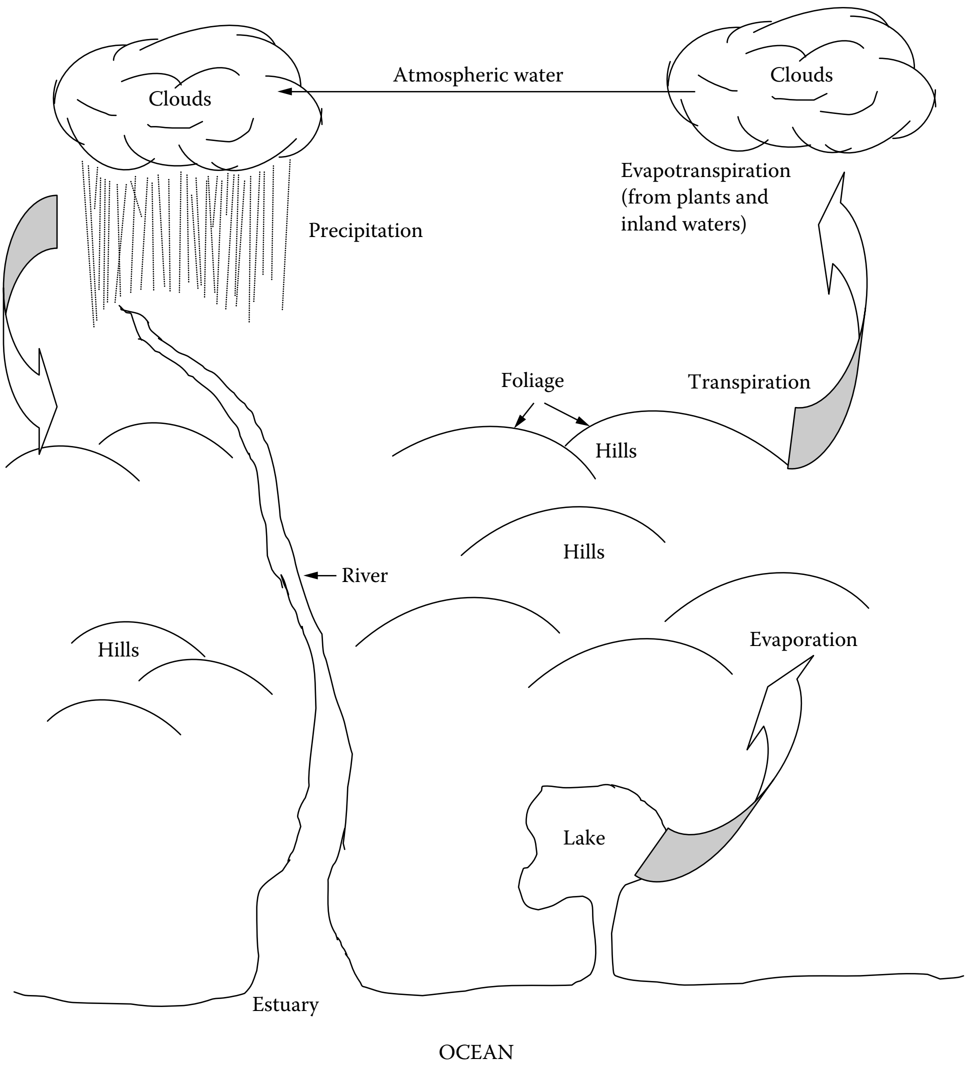


FIGURE 7.3 Water cycle.

Atmospheric Particulate Matter

Significant numbers of particles (particulate matter) are suspended in the atmosphere, particularly the troposphere. These particles originate in nature from smokes, sea sprays, dusts, and the evaporation of organic materials from vegetation. There is also a wide variety of Nature's living or semi-living particles—spores and pollen grains, mites and other tiny insects, spider webs, and diatoms. The atmosphere also contains a bewildering variety of anthropogenic (manmade) particles produced by automobiles, refineries, production mills, and many other human activities.

Atmospheric particulate matter varies greatly in size (colloidal-sized particles in the atmosphere are called *aerosols*—usually less than 0.1 μm in diameter). The smallest are gaseous clusters and ions and submicroscopic liquids and solids. Somewhat larger ones produce the beautiful blue haze in distant vistas, those 2 to 3 times larger are highly effective in scattering light, and the largest consist of such things as rock fragments, salt crystals, and ashy residues from volcanoes, forest fires, or incinerators.

The concentrations of particulates in the atmosphere vary greatly, ranging from more than 10,000,000/cm^3 to less than 1/L (0.001/cm^3). Excluding the particles in gases as well as vegetative material, sizes range from 0.005 to 500 µm, a variation in diameter of 100,000 times. The largest numbers of airborne particulates are always in the invisible range. These numbers vary from less than 1 liter to more than a half a million per cubic centimeter in heavily polluted air to at least 10 times more than that when a gas-to-particle reaction is occurring (Schaefer and Day, 1981).

Based on particulate level, there are two distinct regions in the atmosphere: very clean and dirty. The clean parts have so few particulates that they are almost invisible, making them difficult to collect or measure. In the dirty parts of the atmosphere—the air of a large metropolitan area—the concentration of particles includes an incredible variety of particulates from a wide variety of sources.

Atmospheric particulate matter performs a number of functions, undergoes several processes, and is involved in many chemical reactions in the atmosphere. Probably the most important function of particulate matter in the atmosphere is that it serves as nuclei for the formation of water droplets and ice crystals. Vincent J. Schaefer, who invented cloud seeding, used dry ice in his early attempts, but the process later evolved to adding condensing particles to atmospheres supersaturated with water vapor and the use of silver iodide, which forms huge numbers of very small particles. Another important function of atmospheric particulate matter is that it helps determine the heat balance of the Earth's atmosphere by reflecting light. Particulate matter is also involved in many chemical reactions in the atmosphere such as neutralization, catalytic effects, and oxidation reactions. These chemical reactions will be discussed in greater detail later.

AIR FOR COMBUSTION

It is difficult to imagine where humans would be today or how far we would have progressed from our beginnings to the present day if we had not discovered and developed the use of fire. Today, of course, we are quite familiar with fire. We use the terms *fire*, *combustion*, *oxidation*, and *burning* pretty much to mean the same thing; however, there is a subtle difference between combustion and oxidation. During combustion, two or more substances chemically unite. In practice, one of them is almost always atmospheric oxygen, but combustion reactions are known in which oxygen is not one of the reactants. Thus, it is more correct to describe combustion as a rapid oxidation—or fire. To state that atmospheric air plays an important role in combustion is to understate its significance; that is, we are stating the obvious, something that is readily apparent to most of us. Though air is important in combustion, most of us give little thought to the actual chemical reaction involved in combustion. Combustion is a chemical reaction—one in which a fuel combines with air (oxygen) to produce heat (burning). The combustion of fuels containing carbon and hydrogen is said to be complete when these two elements are oxidized to carbon dioxide and water (e.g., the combustion of carbon $C + O_2 = CO_2$). In air pollution control, it is incomplete combustion that concerns us. Incomplete combustion may lead to (1) appreciable amounts of carbon remaining in the ash, (2) emission of some of the carbon as carbon monoxide, and (3) reaction of the fuel molecules to give a range of products emitted as smoke.

AIR FOR POWER

Along with performing its important function in Earth's atmosphere and its vital role in combustion, most industrial processes use gases to power systems of one type or another. The work is actually performed by a gas under pressure in the system. A gas power system may function as part of a process, such as heating and cooling, or it may be used as a secondary service system, such as compressed air. Compressed air is the gas most often found in industrial applications, but nitrogen and carbon dioxide are also commonly used. A system that uses a gas for transmitting force is referred to as a *pneumatic system*. The word *pneumatic* is derived from the Greek word for an unseen gas. Originally, pneumatic referred only to the flow of air, but today it is used to refer to the flow of any gas in a system under pressure. Pneumatic systems perform work in many ways, including operating pneumatic tools, door openers, linear motion devices, and rotary motion devices. Have you ever watched (or heard) an automobile mechanic remove and replace a tire on your car? The device used to take off and put on tire lug nuts is a pneumatic (air operated) wrench. Pneumatic hoisting equipment may be found in heavy fabricating environments, and pneumatic conveyors are used in the processing of raw materials. Pneumatic systems are also used to control flow valves in chemical process equipment and in large air-conditioning systems. The pneumatic system in an industrial plant usually handles compressed air, which is used for operating portable air tools, such as drills, wrenches, and chipping tools; for vises, chucks, and other clamping devices; for movable locating stops; for operating plastic molding machines; and for supplying air used in various manufacturing processes. Although the pieces of pneumatic equipment just described are different from each other, they all convert compressed air into work. Later we will review some of the laws of force and motion and their relation to pneumatic principles.

GAS PHYSICS

Material Balance

Material balance is one of the most basic and useful tools in the air pollution engineering field. Stated simply, material balance means "what goes in must come out." Matter is neither created nor destroyed in (nonradioactive) industrial processes:

$$\text{Mass}_{(\text{out})} = \text{Mass}_{(\text{in})} \tag{7.1}$$

Material balance is used in a wide variety of air pollution control calculations; for example, it is used to evaluate the following:

- Formation of combustion products in boilers
- Rates of air infiltration into air pollution control systems
- Material requirements for process operations
- Rate of ash collection in air pollution control systems
- Humidities of exhaust gas streams
- Exhaust gas flow rates from multiple sources controlled by a single air pollution control system
- Gas flow rates from combustion processes

This principle, otherwise known as the conservation of matter, can be applied to solving problems involving the quantities of matter moving through various parts of a process.

Compressibility

Air unlike water, is readily compressed, and large quantities can be stored in relatively small containers. The more the air is compressed, the greater its pressure becomes. The higher the pressure in a container, the stronger the container must be. Gases are important compressible fluids, not only from the standpoint that a gas can be a pollutant but also because gases convey particulate matter and gaseous pollutants (Hesketh, 1991).

Gas Laws

Gases can be pollutants as well as the conveyors of pollutants. Air (which is mainly nitrogen) is usually the main gas stream. Gas conditions are usually described in two ways: *standard temperature and pressure* (STP) and *standard conditions* (SC). STP represents 0°C (32°F) and 1 atm. SC is more commonly used and represents typical room conditions of 20°C (70°F) and 1 atm; SC is usually measured in cubic meters (m^3), Nm^3, or standard cubic feet (scf). To understand the physics of air it is imperative to have an understanding of various physical laws that govern the behavior of pressurized gases. One of the more well-known physical laws is Pascal's law, which states: "A confined gas (fluid) transmits externally applied pressure uniformly in all directions, without change in magnitude." This is easily demonstrated by a container that is flexible and assumes a spherical shape (think of a balloon). You probably have noticed that most compressed-gas tanks are cylindrical in shape (which allows the use of thinner sheets of steel without sacrificing safety) with spherical ends to contain the pressure more effectively.

Boyle's Law

Though gases are compressible, note that, for a given mass flow rate, the actual volume of gas passing through the system is not constant within the system due to changes in pressure. This physical property (the basic relationship between the pressure of a gas and its volume) is described by Boyle's law, named for the Irish physicist and chemist Robert Boyle, who discovered this property in 1662. It states: "The absolute pressure of a confined quantity of gas varies inversely with its volume, if its temperature does not change." For example, if the pressure of a gas doubles, its volume will be reduced by a half, and *vice versa*; that is, as pressure goes up, volume goes down, and the reverse is true. This means, for example, that if 12 ft^3 of air at 14.7 psia (pounds per square inch absolute) is compressed to 1 ft^3, air pressure will rise to 176.4 psia, as long as air temperature remains the same. This relationship can be calculated as follows:

$$P_1 \times V_1 = P_2 \times V_2 \tag{7.2}$$

where

P_1 = Original pressure (units for pressure must be absolute).
P_2 = New pressure (units for pressure must be absolute).
V_1 = Original gas volume at pressure P_1.
V_2 = New gas volume at pressure P_2.

This equation can also be written as:

$$\frac{P_2}{P_1} = \frac{V_1}{V_2} \text{ or } \frac{P_1}{P_2} = \frac{V_2}{V_1}$$

To allow for the effects of atmospheric pressure, always remember to convert from gauge pressure (psig, or pounds per square inch gauge) *before* solving the problem, then convert back to gauge pressure *after* solving it:

$$\text{psia} = \text{psig} + 14.7 \text{ psi}$$

and

$$\text{psig} = \text{psia} - 14.7 \text{ psi}$$

Note that in a pressurized gas system where gas is caused to move through the system by the fact that gases will flow from a area of high pressure to that of low pressure, we will always have a greater actual volume of gas at the end of the system than at the beginning (assuming the temperature remains constant). Let's take a look at a typical gas problem using Boyle's law.

■ EXAMPLE 7.1

Problem: What is the gauge pressure of 12 ft^3 of air at 25 psig when compressed to 8 ft^3?

Solution:

$$25 \text{ psig} + 14.7 \text{ psi} = 39.7 \text{ psia}$$

$$P_2 = P_1 \times \frac{V_1}{V_2} = 39.7 \times \frac{12}{8} = 59.6 \text{ psia}$$

$$\text{psig} = \text{psia} - 14.7 \text{ psi} = 59.6 \text{ psia} - 14.7 \text{ psi} = 44.9 \text{ psig}$$

The gauge pressure is 44.9 psig (remember that the pressures should always be calculated on the basis of absolute pressures instead of gauge pressures).

Charles's Law

Another physical law dealing with temperature is Charles's law, discovered by French physicist Jacques Charles in 1787. It states: "The volume of a given mass of gas at constant pressure is directly proportional to its absolute temperature." The absolute temperature is the temperature in Kelvin (273 + °C); absolute zero = –460°F, or 0°R on the Rankine scale. This is calculated as follows:

$$P_2 = P_1 \times \frac{T_2}{T_1} \tag{7.3}$$

Charles's law also states: "If the pressure of a confined quantity of gas remains the same, the change in the volume (V) of the gas varies directly with a change in the temperature of the gas," as given below:

$$V_2 = V_1 \times \frac{T_2}{T_1} \tag{7.4}$$

Ideal Gas Law

The ideal gas law combines Boyle's and Charles's laws because air cannot be compressed without its temperature changing. The ideal gas law can be expressed as

$$\frac{P_1 \times V_1}{T_1} = \frac{P_2 \times V_2}{T_2} \tag{7.5}$$

Note that the ideal gas law is still used as a design equation even though the equation shows that the pressure, volume, and temperature of the second state of a gas are equal to the pressure, volume, and temperature of the first state. In actual practice, however, other factors such as humidity, heat of friction, and efficiency losses all affect the gas. Also, this equation uses absolute pressure (psia) and absolute temperatures (°R) in its calculations.

In air science practice, the importance of the ideal gas law cannot be overstated. It is one of the fundamental principles used in calculations involving gas flow in air-pollution-related work. This law is used to calculate actual gas flow rates based on the quantity of gas present at standard pressures and temperatures. It is also used to determine the total quantity of that contaminant in a gas that can participate in a chemical reaction. The ideal gas law has three important variables:

- Number of moles of gas
- Absolute temperature
- Absolute pressure

In practical applications, practitioners generally use the following standard ideal gas law equation:

$$V = \frac{nRT}{P} \text{ or } PV = nRT$$

where
V = Volume.
n = Number of moles.
R = Universal gas constant.
T = Absolute temperature.
P = Absolute pressure.

■ EXAMPLE 7.2

Problem: What is the volume of 1 pound mole (lb mole) of combustion gas at an absolute pressure of 14.7 psia and a temperature of 68°F? (These are USEPA-defined standard conditions.)

Solution:

$$V = \frac{nRT}{P}$$

Convert the temperature from relative to absolute scale (from °F to °R):

$$\mathrm{T_{Absolute}} = 68°\mathrm{F} + 460 = 528°\mathrm{R}$$

Calculate the gas volume:

$$V = \frac{1 \text{ lb mole} \times \dfrac{10.73 \text{ (psia)(ft}^3)}{\text{(lb mole)(°R)}} \times 528°\text{R}}{14.7 \text{ psia}} = 385.4 \text{ ft}^3$$

FLOW RATE

Gas flow rate is a measure of the volume of gas that passes a point in an industrial system during a given period of time. The ideal gas law tells us that this gas flow rate varies depending on the temperature and pressure of the gas stream and the number of moles of gas moving per unit of time. When gas flow rates are expressed at actual conditions of temperature and pressure, the actual gas flow rate is being used. As you will learn later, gas flow rates can also be expressed at standard conditions of temperature and pressure; this is referred to as the *standard gas flow rate.*

GAS CONVERSIONS

Gases of interest in air pollution control are usually mixtures of several different compounds; for example, air is composed of three major constituents: nitrogen (N_2) at approximately 78.1%, oxygen (O_2) at approximately 20.9%, and argon at 0.9%. Many flue gas streams generated by industrial processes consist of the following major constituents: (1) nitrogen, (2) oxygen, (3) argon, (4) carbon dioxide (CO_2), and (5) water vapor (H_2O). Both air and industrial gas streams also contain minor constituents, including air pollutants, present at concentrations that are relatively low compared to these major constituents. We need ways to express both the concentrations of the major constituents of the gas stream and the concentrations of the pollutants present as minor constituents at relatively low concentrations. The following text presents a variety of ways to express gas phase concentrations, which can easily be converted from on type of units to another.

Major Constituents

Volume percent is one of the most common formats used to express the concentrations of major gas stream constituents such as oxygen, nitrogen, carbon dioxide, and water vapor. The format is very common partially because the gas stream analysis techniques used in USEPA emission testing methods provide data directly in a volume percent format. *Partial pressure* is also used to express concentrations. This expression refers to the portion of the total pressure exerted by one of the constituent gases. Gases composed of different chemical compounds such as molecular nitrogen and oxygen behave physically the same as gases composed of a single compound. At any give temperature, one mole of a gas exerts the same pressure as one mole of any other type of gas. All of the molecules move at a rate that is dependent on the absolute temperature, and they exert pressure. The total pressure is the sum of the pressures of each of the components. The equations below are often referred to as Dalton's law of partial pressures:

$$P_{Total} = p_i + p_{ii} + p_{iii} \dots p_n \tag{7.6}$$

$$P_{Total} = \sum_{i=1}^{n} p_i \tag{7.7}$$

$$\text{Partial pressure (gas)} = \left[\frac{\text{Volume\% (gas)}}{100\%}\right] \times P_{Total} \tag{7.8}$$

Because the partial pressure value is related to the total pressure, concentration data expressed as partial pressure are not the same at actual and standard conditions. The partial pressure values are also different in American engineering units and centimeter–gram–second (CGS) units.

Both Major and Minor Constituents

Mole fraction is simply an expression of the number of moles of a compound divided by the total number of moles of all the compounds present in the gas.

Minor Constituents

All of the concentration units below can be expressed in a dry format as well as corrected to a standard oxygen concentration. These corrections are necessary because moisture and oxygen concentrations can vary greatly in gas streams, causing variations in pollutant concentrations:

- Parts per million (ppm)
- Milligrams per cubic meter (mg/m^3)
- Micrograms per cubic meter (µg/m^3)
- Nanograms per cubic meter (ng/m^3)

GAS VELOCITY

Gas velocity is one of the fundamental design variables for ventilation systems and air pollution control equipment. Gas streams containing particulate are usually maintained at velocities of 3000 to 4500 ft/min in ductwork leading to particulate collectors to minimize particle deposition. The velocity of gas streams without particulate matter is often in the range of 1500 to 3000 ft/min. The gas velocities in air pollution control equipment are usually low to allow for sufficient time to remove the contaminants. For example, gas velocities through electrostatic precipitators are usually in the range of 2.5 to 6 ft/sec. The filtration velocities through pulse jet fabric filters are usually in the range of 2 to 10 ft/min. Variations in the gas velocity can have a direct impact on the contaminant removal efficiency.

$$v = \text{Gas velocity} = \frac{\text{Gas flow rate, actual}}{\text{Area}} \tag{7.9}$$

Gas Stream Treatment (Residence) Time

The flow rate of the gas stream through an air pollution control system determines the length of time that the pollutants can be removed from the gas stream. This is termed the *treatment time* or *residence time*. These common equipment sizing parameters are defined mathematically below:

$$\text{Treatment time} = \text{Residence time} = \frac{\text{Volume of control device}}{\text{Gas flow rate, actual}} \tag{7.10}$$

GAS DENSITY

Gas density is important primarily because it affects the flow characteristics of the moving gas streams. Gas density affects the velocities of gas through ductwork and air pollution control equipment. It determines the ability to move the gas stream using a fan. Gas density affects the velocities of gases emitted from the stack and thereby influences the dispersion of the pollutants remaining in the stack gases. It affects the ability of particles to move through gases. It also affects emission testing. Gas density data are needed in many of the calculations involved in air pollution control equipment evaluation, emission testing, and other studies related to air pollution control.

$$P_{(T=I,P=j)} = \frac{m}{V_{(T=I,P=j)}} \tag{7.11}$$

where

$P_{(T=I,\,P=j)}$ = Density at $T = I$, $P = j$.
m = Mass of a substance.
$V_{(T=I,\,P=j)}$ = Volume at $T = I$, $P = j$.
T = Absolute temperature.
P = Absolute pressure.

HEAT CAPACITY AND ENTHALPY

The heat capacity of a gas is the amount of heat required to change the temperature of a unit-mass of gas one temperature degree. Enthalpy represents the total quantity of internal energy, such as heat, measured for a specific quantity of material at a given temperature. Enthalpy data are often represented in units of energy (e.g., Btu, kcal, joule). The enthalpy content change is often expressed in Btu/unit mass (Btu/lb_m or Btu/scf). The change in enthalpy of the total quantity of material present in a system is expressed in units of Btu/unit time (Btu/min). The symbols H and ΔH denote enthalpy and the change in enthalpy, respectively.

HEAT AND ENERGY IN THE ATMOSPHERE

The prime source of the energy that drives Earth's climatic system is the sun, from which energy reflects, scatters, and is absorbed and reradiated within the system but which does not distribute uniformly. More energy enters some areas than is lost; in other areas, more energy is lost than gained. If this situation were to continue, the areas with surplus energy would become too hot and those with a deficit would become too cold. Because the temperature differences produced help to drive the wind and ocean currents of the world, they carry heat with them and help to counteract the radiation imbalance. Normally, warm winds from the tropics carry excess heat with them. Polar winds blow from areas with a heat deficit and so are cold. Acting together, these energy transfer mechanisms help to produce the current climates on Earth.

Adiabatic Lapse Rate

The atmosphere is always moving, either horizontally or vertically, or both. As air rises, pressure decreases and the air expands. This expansion of air expends energy. Because temperature is a measure of internal energy, this energy expenditure makes the temperature of the air drop—an important process in air physics known as the adiabatic lapse rate. *Adiabatic* refers to a process that occurs without the gain or loss of heat, such as the expansion or contraction of a gas in which a change takes place in the pressure or volume although no heat enters or leaves. *Lapse rate* refers to the rate at which air temperature decreases with increasing height. The normal lapse rate in stationary air is on the order of 3.5°F/1000 ft (6.5°C/km). This value varies with latitude and with changing seasonal and atmospheric conditions:

$$T = T_0 - Rh \tag{7.12}$$

where

T = Temperature of the air.

T_0 = Temperature of the air at the level from which the height is measured.

R = Lapse rate.

h = Height of air.

■ EXAMPLE 7.3

Problem: If the air temperature of stationary air (R = 3.5°F/1000 ft) at the Earth's surface is 70°F, then at 5000 ft what would the stationary air temperature be?

Solution:

$$T = T_0 - Rh = 70°\text{F} - (3.5°\text{F}/1000\text{ ft})(5000\text{ ft}) = 70°\text{F} - 17.5°\text{F} = 52.5°\text{F}$$

The formula simply says that for every 1000 ft of altitude, 3.5° is subtracted from the initial air temperature, in this case. Adiabatic lapse rates have an important relationship with atmospheric stability and will be discussed in greater detail later in the text.

VISCOSITY

All fluids (gases included) resist flow. *Absolute viscosity* is a measure of this resistance to flow. The absolute viscosity of a gas for given conditions can be calculated from the following formula:

$$\begin{aligned}\mu &= 51.12 + 0.372(T) + 1.05 \times 10^{-4}(T)^2 \\ &\quad + 53.147\left(\%O_2/100\%\right) - 74.143\left(\%H_2O/100\%\right)\end{aligned} \tag{7.13}$$

where

μ = Absolute viscosity of gas at the prevailing conditions (micropoise, or µP).

T = Gas absolute temperature (°K).

$\%O_2$ = Oxygen concentration (% by volume).

$\%H_2O$ = Water vapor concentration (% by volume).

As this equation indicates, the viscosity of a gas increases as the temperature increases. It is more difficult to push something (e.g., particles) through a hot gas stream than a cooler one due to increased molecular activity as temperature rises, which results in increased momentum transfer between the molecules. For liquids, the opposite relationship between viscosity and temperature holds. The viscosity of a liquid decreases as temperature increases, so it is more difficult to push something through a cold liquid than a hot one because in liquids hydrogen bonding increases with colder temperatures. Gas viscosity actually increases slightly with pressure, but this variation is very small in most air-pollution-related engineering calculations.

The absolute viscosity and density of a gas are occasionally combined into a single parameter because both of these parameters are found in many common equations describing gas flow characteristics. The combined parameter is termed the *kinematic viscosity*:

$$u = \mu/p \tag{7.14}$$

where

u = Kinematic viscosity (m^2/sec).
μ = Absolute viscosity (Pa·sec).
p = Gas density (g/cm^3).

The kinematic viscosity can be used in equations describing particle motion through gas streams. The expression for kinematic viscosity is used to simplify these calculations.

FLOW CHARACTERISTICS

When fluids such as gases are moving slowly, the bulk material moves as distinct layers in parallel paths. The only movement across these layers is the molecular motion, which creates viscosity. This is termed *laminar flow*. As the velocity of the gas stream increases, the bulk movement of the gas changes. Eddy currents develop and cause mixing across the flow stream. This is called *turbulent flow* and is essentially the only flow characteristic that occurs in air pollution control equipment and emission testing situations.

A dimensionless parameter called the *Reynolds number* is used to characterize fluid flow. It is the ratio of the inertial force that is causing gas movement to the viscous force that is restricting movement. The Reynolds number is calculated as below; consistent units must be used to ensure that the Reynolds number is dimensionless:

$$N_{\mathrm{Re}(g)} = Lvp/\mu \tag{7.15}$$

where

L = Linear dimensions (usually duct diameter).
v = Fluid velocity.
p = Fluid density.
μ = Fluid viscosity.

Reynolds numbers less than 2000 are associated with laminar flow conditions. Due to the relatively low velocities associated with this type of flow, they are rarely encountered in air pollution field situations. Reynolds numbers above 10,000 are associated with turbulent flow. In many field situations, the Reynolds numbers exceed 100,000.

Essentially, all gas flow situations are turbulent in air pollution control systems, emission testing and monitoring equipment, and dispersion modeling studies; however, this does not mean that the gas stream is entirely well mixed. In reality, the side-to-side mixing (and even mixing in the direction of flow) can be limited. For this reason, it is possible to have different concentrations of pollutants at different positions in the duct. This condition is called *pollutant stratification* and can be caused by a variety of factors: combining of two separate gas streams into a single duct, temperature differences in the gas stream, and in-leakage of cold ambient air into the duct.

Stratification does not exist in most industrial gas handling systems; however, it is important to check for this condition prior to installation of continuous emission monitors or other instruments, which are located at a single sampling or measurement point in the gas stream. These measurements can be in error if stratification is severe.

PARTICLE PHYSICS

Particulates constitute a major class of air pollution that includes dusts, fumes, mists, and smoke. They come in a variety of shapes and their physical and chemical properties vary widely. Important particulate matter characteristics include size, size distribution, shape, density, stickiness, corrosivity, reactivity, and toxicity. With such a wide range of characteristics it is apparent that particular types of collection devices might be better suited for some particles than others. For example, particulate matter typically ranges in size from 0.005 to 100 μm in diameter. This wide range in size distribution must certainly be taken into account. Understanding the characteristics of particles is important in air pollution control technology for the following reasons: The efficiency of the particle collection mechanisms depends strongly on particle size, the particle size distribution of the flue gas dictates the manner in which air testing is performed, the particle size distribution of the flue gas determines the operating conditions necessary to collect the particles, and particle characteristics are important in determining the behavior of particles in the respiratory tract.

SURFACE AREA AND VOLUME

The size range of particles of concern in air pollution studies is remarkably broad. Some of the droplets collected in the mist eliminators of wet scrubbers and the solid particles collected in large-diameter cyclones are as large as raindrops. Some of the small particles created in high-temperature incinerators and metallurgical processes can consist of less than 50 molecules clustered together. It is important to recognize the categories because particles behave differently depending on their size. Most particles of primary interest in air pollution emission testing and control have diameters that range from 0.1 to 1000 μm. Following are some useful conversions for particle sizes:

$$\text{Micrometer} = (1/1{,}000{,}000)\ \text{meter} \tag{7.16}$$

$$\text{Micrometer} = (1/10{,}000)\ \text{centimeter} \tag{7.17}$$

$$1000\ \mu\text{m} = 1\ \text{mm} = 0.1\ \text{cm} \tag{7.18}$$

To appreciate the difference in particle sizes commonly found in emission testing and air pollution control, compare the diameters, volumes, and surfaces areas of particles as shown in Table 7.12. The data in Table 7.12 indicate that 1000-μm particles are 1,000,000,000,000 (1 trillion) times larger in volume than 0.1-μm particles. As an analogy, assume that the 1000-μm particle is a large domed sports stadium. A basketball in this stadium would be equivalent to a 5-μm particle. Approximately 100,000 spherical particles of 0.1-μm diameter would fit into this 5-μm basketball. Now consider that the entire 1000-μm stadium is the size of a small raindrop. As previously stated, particles over this entire size range of 0.1 to 1000 μm are of interest in air pollution control (USEPA, 2006). Equations for calculating the volume and surface area of spheres are provided below:

$$\text{Surface area of a sphere} = 4\pi r^2 = \pi D^2 \tag{7.19}$$

TABLE 7.12
Spherical Particle Diameter, Volume, and Area

Particle Diameter (μm)	Particle Volume (cm^3)	Particle Area (cm^2)
0.1	5.23×10^{-16}	3.14×10^{-10}
1	5.23×10^{-13}	3.14×10^{-8}
10	5.23×10^{-10}	3.14×10^{-6}
100	5.23×10^{-7}	3.14×10^{-4}
1000	5.23×10^{-4}	3.14×10^{2}

Source: Adapted from USEPA, *Basic Concepts in Environmental Sciences*, U.S. Environmental Protection Agency, Washington, DC, 2007 (http://www.epa.gov/air/oaqps/eog/bces/module1/).

$$\text{Volume of a sphere} = \frac{4}{3}\pi r^3 = \pi D^3/6 \tag{7.20}$$

where

r = Radius of sphere.
D = Diameter of sphere.

■ EXAMPLE 7.4

Problem: Calculate the volumes of three spherical particles (in cm^3) given that their diameters are 0.6, 6.0, and 60 μm.

Solution:

$$V = (4/3) \times \pi \times r^3 = 4.19 \times r^3$$

For a 0.6-μm particle, $r = 0.3$ μm = 0.00003 cm:

$$V = 4.19 \times (0.00003\text{ cm})^3 = 1.13 \times 10^{-13}\text{ cm}^3$$

For a 6.0-μm particle, $r = 3.0$ μm = 0.0003 cm:

$$V = 4.19 \times (0.0003\text{ cm})^3 = 1.13 \times 10^{-10}\text{ cm}^3$$

For a 60-μm particle, $r = 30$ μm = 0.003 cm:

$$V = 4.19 \times (0.003\text{ cm})^3 = 1.13 \times 10^{-7}\text{ cm}^3$$

AERODYNAMIC DIAMETER

Particles emitted from air pollution sources and formed by natural processes have a number of different shapes and densities. Defining particle size for a spherical particle is easy; it is simply the diameter of the particle. For nonspherical particles, the term "diameter" is not strictly applicable. In air pollution control, particle size is based on particle behavior in the Earth's gravitational field. The *aerodynamic equivalent diameter* refers to a spherical particle of unit density that falls at a standard velocity. As noted earlier, particle size is important because it determines atmospheric lifetime, effects on light scattering, and deposition in the lungs. It is important to keep in mind that, when we speak of particulate size, we are not referring to particulate shape. This is an obvious point, but also a very important one. For the sake of simplicity, it is common practice to assume that particles are spherical, even though particles are not spherical and are usually quite irregularly shaped. In pollution control technology design applications, size of the particle is taken into consideration, but it is the behavior of the particle in a gaseous waste stream that we are most concerned with.

To better understand this important point, drop a flat piece of regular typing paper from the top of a 6-foot ladder. The paper will fall irregularly to the floor. Now, crumple the same sheet of paper and drop it from the ladder and see what happens. The crumpled paper will fall rapidly. Thus, size is important but other factors such as particle shape are also important. The aerodynamic diameter for all particles greater than 0.5 μm can be approximated using the following equation (for particles less than 0.5 μm, refer to aerosol textbooks to determine the aerodynamic diameter):

$$d_{pa} = d_{ps}\sqrt{P_p} \tag{7.21}$$

where

d_{pa} = Particle aerodynamic diameter (μm).
d_{ps} = Stokes diameter (μm).
P_p = Particle density (g/cm^3).

Along with particle size and shape, particle density must be taken into consideration; for example, a baseball and a whiffle ball have approximately the same diameter but behave quite differently when tossed into the air. Particle density affects the motion of a particle through a fluid and is taken into account in Equation 7.21. The Stokes diameter for a particle is the diameter of the sphere that has the same density and settling velocity of the particle. It is based on the aerodynamic drag force caused by the difference in velocity of the particle and the surrounding fluid. For smooth, spherical particles, the Stokes diameter is identical to the physical or actual diameter.

Inertial sampling devices such as cascade impactors are used for particle sizing to determine the aerodynamic diameter. The aerodynamic diameter is a useful measure for all particles including fibers and particle clusters, but it is not a true size because nonspherical particles require more than one dimension to characterize their size.

> ***Note:*** In this text, particle diameter and particle size refer to the aerodynamic diameter, unless otherwise stated.

PARTICLE SIZE CATEGORIES

Because the range of particle sizes of concern for air emission evaluation is quite broad, it is beneficial to divide this range into smaller categories. Defining different size categories is useful because particles of different sizes behave differently in the atmosphere and the respiratory system. The USEPA has defined terms for categorizing particles of different sizes; Table 7.13 displays this terminology along with the corresponding particle sizes.

Regulated Particulate Matter Categories

In addition to the terminology provided in Table 7.13, the USEPA also categorizes particles as indicated in the following text. These particle categories are important because particulate matter is regulated and tested for under these categories.

Total Suspended Particulate Matter

Particles ranging in size from 0.1 to about 30 μm in diameter are referred to as total suspended particulate matter (TSP). TSP covers a broad range of particle sizes, including fine, coarse, and supercoarse particles.

TABLE 7.13
EPA Terminology for Particle Sizes

EPA Description	Particle Size
Supercoarse	$d_{pa} > 10\ \mu m$
Coarse	$2.5\ \mu m < d_{pa} \le 10\ \mu m$
Fine	$0.1\ \mu m < d_{pa} \le 2.5\ \mu m$
Ultrafine	$d_{pa} \le 0.1\ \mu m$

Note: d_{pa} = particle aerodynamic diameter.

PM_{10}

PM_{10} is defined as particulate matter with a diameter of 10 μm collected with 50% efficiency by a PM_{10} sampling collection device. For convenience in this text, the term PM_{10} will be used to include all particles having an aerodynamic diameter of less than or equal to 10 μm. PM_{10} is regulated as a specific type of pollutant because particles this size are considered respirable. In other words, particles less than approximately 10 μm can penetrate into the lower respiratory tract. The particle size range between 0.1 and 10 μm is especially important in air pollution studies. A major fraction of the particulate matter generated in some industrial sources is in this size range.

$PM_{2.5}$

$PM_{2.5}$ is defined as particulate matter with a diameter of 2.5 μm collected with 50% efficiency by a $PM_{2.5}$ sampling collection device. For convenience in this text, the term $PM_{2.5}$ will be used to include all particles having an aerodynamic diameter of less than or equal to 2.5 μm. USEPA chose 2.5 μm as the partition between fine and coarse particulate matter. Particles less than approximately 2.5 μm are regulated as $PM_{2.5}$. Air emission testing and air pollution control methods for $PM_{2.5}$ particles are different than those for coarse and supercoarse particles. $PM_{2.5}$ particles settle quite slowly in the atmosphere relative to coarse and supercoarse particles. Normal weather patterns can keep $PM_{2.5}$ particles airborne for several hours to several days and allow these particles to cover hundreds of miles. $PM_{2.5}$ particles can cause health problems due to their potentially long airborne retention time and the inability of the human respiratory system to defend itself against particles of this size. In addition, the chemical makeup of $PM_{2.5}$ particles is quite different than for coarse and supercoarse particles. USEPA data indicate that $PM_{2.5}$ particles are composed primarily of sulfates, nitrates, organic compounds, and ammonium compounds. USEPA has also determined that $PM_{2.5}$ particles often contain acidic materials, metals, and other contaminants believed to be associated with adverse health effects. Particles less than 1 μm in diameter are termed *submicrometer particles* and can be the most difficult size to collect. Particles in the range of 0.2 to 0.5 μm are common in many types of combustion, waste incineration, and metallurgical sources. Particles in the range of 0.1 to 1.0 μm are important because they can represent a significant fraction of the particulate emissions from some types of industrial sources and because they are relatively difficult to collect.

Particles Less Than 0.1 μm

Particles can be much smaller than 0.1 μm. In fact, particles composed of as few as 20 to 50 molecules clustered together can exist in a stable form. Some industrial processes such as combustion and metallurgical sources generate particles in the range of 0.01 to 0.1 μm. These sizes are approaching the size of individual gas molecules, which are in the range of 0.0002 to 0.001 μm. However, particles in the size range of 0.01 to 0.1 μm tend to agglomerate rapidly to yield particles in the greater than 0.1-μm range. Accordingly, very little of the particulate matter entering an air pollution control device or leaving the stack remains in the very small size range of 0.01 to 0.1 μm.

Condensable Particulate Matter

Particulate matter that forms from condensing gases or vapors is referred to as *condensable particulate matter*. Condensable particulate matter forms by chemical reactions as well as by physical phenomena. Condensable particulate matter is usually formed from material that is not particulate matter at stack conditions but which condenses or reacts upon cooling and dilution in the ambient air to form particulate matter. The formation of condensable particulate matter occurs within a few seconds after discharge from the stack. From a health standpoint, condensable particulate matter is important because it is almost entirely contained in the $PM_{2.5}$ classification.

SIZE DISTRIBUTION

Particulate emissions from both manmade and natural sources do not consist of particles of any one size. Instead, they are composed of particles over a relatively wide size range. It is often necessary to describe this size range. Particulate matter for size distribution evaluation is measured in a variety of ways. The data must be measured in a manner whereby they can be classified into successive particle diameter size categories.

PARTICLE FORMATION

The range of particle sizes formed in a process is largely dependent on the types of particle formation mechanisms present. The general size range of particles can be estimated by simply recognizing which particle formation mechanisms are most important in the process being evaluated. The most important particle formation mechanisms in air pollution sources include physical attrition/mechanical dispersion, combustion particle burnout, homogeneous and heterogeneous nucleation, and droplet evaporation. Several particle formation mechanisms can be present in an air pollution source. As a result, the particles created can have a wide range of sizes and chemical composition. Particle formation mechanisms are described in detail below.

Physical Attrition

Physical attrition generates primarily moderate-to-large sized particles and occurs when two surfaces rub together; for example, the grinding of a metal rod on a grinding wheel yields small particles that break off from both surfaces. The compositions and densities of these particles are identical to the parent materials. In order for fuel to burn, it must be pulverized or atomized so there is sufficient surface area exposed to oxygen and high temperature. As indicated in Table 7.14, the surface area of particles increases substantially as more and more of the material is reduced in size. Accordingly, most industrial-scale combustion processes use one or more types of physical attrition to prepare their fuel or introduce it into the furnace. For example, oil-fired boilers use pulverizers to reduce the chunks of coal to sizes that can be burned quickly. Oil-fired boilers use atomizers to disperse the oil as fine droplets. In both cases, the fuel particle size is generally reduced to the range of 10 to 1000 μm by physical attrition.

Combustion Particle Burnout

When fuel particles are injected into the hot furnace area of the combustion process, such as in fossil-fuel-fired boilers, most of the organic compounds in the fuel are vaporized and oxidized in the gas stream. Fuel particles become smaller as the volatile matter leaves, and they are quickly reduced to only the incombustible matter (ash) and the slow-burning char composed of organics compounds. Eventually, most of the char will also burn, leaving primarily the incombustible material. As combustion progresses, the fuel particles, which started as 10- to 1000-μm particles, are reduced to ash and char particles that are primarily in the range of 1 to 100 μm. This mechanism for particle formation is combustion particle burnout.

TABLE 7.14
Surface Area Comparison for Spherical Particles of Different Diameters[a]

Total Mass	Diameter of Particles (µm)	Number of Particles (Approximate, in millions)	Total Surface Area (cm^2)	Total Surface Area (m^2)
	1000	0.002	60	0.006
	100	2	600	0.06
1.0 g	10	2000	6000	0.6
	1	2,000,000	60,000	6
	0.1	2,000,000,000	600,000	60

Source: Adapted from USEPA, *Basic Concepts in Environmental Sciences*, U.S. Environmental Protection Agency, Washington, DC, 2007 (http://www.epa.gov/air/oaqps/eog/bces/module1/).

[a] Based on density of 1.0 g/cm^3.

Homogeneous and Heterogeneous Nucleation

Homogeneous and heterogeneous nucleation involves the conversion of vapor-phase materials to a particulate form. In both cases, the vapor-containing gas streams must cool to the temperature at which nucleation can occur, which is the dew point. Each vapor-phase element and compound has a different dew point; therefore, some materials nucleate in relatively hot gas zones while others remain as vapor until the gas stream is cold.

- *Homogeneous nucleation* is the formation of new particles composed almost entirely of the vapor-phase material. The formation of particles by homogeneous nucleation involves only one compound.
- *Heterogeneous nucleation* is the accumulation of material on the surfaces of existing particles. In the case of heterogeneous nucleation, the resulting particle consists of more than one compound.

There are two main categories of vapor-phase material that can nucleate air pollution source gas streams: (1) organic compounds, and (2) inorganic metals and metal compounds. In a waste incinerator, waste that volatizes to organic vapor is generally oxidized completely to carbon dioxide and water. However, if there is an upset in the combustion process, a portion of the organic compounds or their partial oxidation products remain in the gas stream as it leaves the incinerator. Volatile metals and metal compounds such as mercury, lead, lead oxide, cadmium, cadmium oxide, and arsenic trioxide can also volatilize in the hot incinerator. Once the gas stream passes through the heat-exchange equipment (i.e., waste heat boiler) used to produce steam, the organic vapors and metal vapors can condense homogeneously or heterogeneously. Generally, the metals and metal compounds search their dew point first and begin to nucleate in relatively hot zones of the unit.

The organic vapors begin to condense in areas downstream from the process where the gas temperatures are cooler. These particles must then be collected in the downstream air pollution control systems. Homogeneous and heterogeneous nucleation generally creates particles that are very small, often between 0.1 and 1.0 µm.

Heterogeneous nucleation facilitates a phenomenon known as enrichment of particles in the submicrometer size range. The elemental metals and metal compounds volatized during high-temperature operations (e.g., fossil-fuel combustion, incineration, industrial furnaces, metallurgical processes) nucleate preferentially as small particles or on the very small particles produced by these processes. Consequently, very small particles have more potentially toxic materials than the very large particles leaving the processes. Heterogeneous nucleation contributes to the formation of article distributions that have quite different chemical compositions in different size ranges.

Another consequence of particle formation by heterogeneous nucleation is that a greater variety of chemical reactions may occur in the gas stream than would otherwise happen. During heterogeneous nucleation, small quantities of metals are deposited on the surfaces of many small particles. In this form, the metals are available to participate in catalytic reactions with gases or other vapor-phase materials that are continuing to nucleate. Accordingly, heterogeneous nucleation increases the types of chemical reactions that can occur as the particles travel in the gas stream from the process source and through the air pollution control device.

Droplet Evaporation

Some air pollution control system use solids-containing water recycled from wet scrubbers to cool the gas streams. This practice inadvertently creates another particle formation mechanism that is very similar to fuel burnout. The water streams are atomized during injection into the hot gas streams. As these small droplets evaporate to dryness, the suspended and dissolved solids are released as small particles. The particle size range created by this mechanism has not been extensively studied; however, it probably creates particles that range in size from 0.1 to 20 μm. All of these particles must then be collected in the downstream air pollution control systems.

COLLECTION MECHANISMS

When sunlight streams into a quiet room, particles of many different shapes and sizes can be seen; some appear to float while others slowly settle to the floor. All of these small particles are denser than the room air, but they do not settle very quickly. The solid, liquid, and fibrous particles formed in air pollution sources behave in a manner that is very similar to standard household dusts and other familiar particles. What we instinctively understand about these everyday particles can be applied in many respects to the particles from air pollution sources. There are, however, two major differences between industrially generated particles and those in more familiar settings. The industrial particles are much smaller than most household particles. Also, some industrial particles have complex chemical compositions and include compounds and elements that are known to be toxic. Emission testing devices and air pollution control systems apply forces to the particles in order to remove them from the gas stream. These forces include inertial impaction and interception, Brownian diffusion, gravitational settling, electrostatic attraction, thermophoresis, and diffusiophoresis. These forces are basically the "tools" that can be used for separating particles from the gas stream. All of these collection mechanism forces are strongly dependent on particle size.

INERTIAL IMPACTION AND INTERCEPTION

Due to inertia, a particle moving in a gas stream can strike slowly moving or stationary obstacles (targets) in its path. As the gas stream deflects around the obstacle, the particle continues toward the object and impacts it. The obstacle may be a solid particle, stationary object or a water droplet. Two primary factors affect the probability of an impaction occurring: (1) aerodynamic article size, and (2) the difference in velocity between the particle and the obstacle. Larger particles are collected more easily than smaller particles due to their greater inertia. Also, collection efficiency increases as the difference in velocity between the particle in the gas stream and the obstacle (or target) increases.

Inertial impaction is analogous to a small car riding down an interstate highway at 65 mph and approaching a merge lane where a slow-moving truck is entering the highway. If the car is unable to get into the passing lane to go around the merging truck, there could be an impaction incident.

Larger cars will have more difficulty going around the truck than smaller cars. Also, the faster the car is going relative to the truck, the more probable is an impaction.

The efficiency of impaction is directly proportion to the impaction parameter shown in Equation 7.22. As the value of this parameter increases, the efficiency of inertial impaction increases. This parameter is related to the square of the Stokes particle diameter and the difference in velocity between the particle and the target droplet:

$$K_I = \frac{C_c \left(d_{ps}\right)^2 vP_p}{18\mu D_c} \tag{7.22}$$

where

K_I = Impaction parameter (dimensionless).
C_c = Cunningham slip correction factor (dimensionless).
d_{ps} = Stokes particle diameter (μm).
v = Difference in velocity (cm/sec).
P_p = Particle density (g/cm^3).
μ = Gas viscosity (g/cm-sec).
D_c = Diameter of a droplet (cm).

The Cunningham slip correction factor (also called Cunningham's correction factor) accounts for molecular slip. Molecular slip occurs when the size of the particle is the same magnitude as the distance between gas molecules. The particle no longer moves as a continuum in the gas but as a particle among discrete gas molecules, thereby reducing the drag force. For particles in air with actual diameter of 1.0 μm and less, the Cunningham correction factor is significant.

Inertial impaction occurs when obstacles (e.g., water droplets) are directly in the path of the particle moving in the gas stream. Sometimes the obstacle or target is offset slightly from the direct path of the moving particle. In this instance, as the particle approaches the edge of the obstacle, the obstacle may collect the particle through a process called *interception*.

BROWNIAN DIFFUSION

Brownian diffusion becomes the dominant collection mechanism for particles less than 0.3 μm and is especially significant for particles ranging in size from 0.01 to 0.1 μm. Very small particles in a gas stream deflect slightly when gas molecules strike them. Transfer of kinetic energy from the rapidly moving gas molecule to the small particle causes this deflection, called *Brownian diffusion*. These small particles are captured when they impact a target (e.g., liquid droplet) as a result of this random movement. *Diffusivity* is a measure of the extent to which molecular collisions influence very small particles, causing them to move in a random manner across the direction of gas flow. The diffusion coefficient in the equation below represents the diffusivity of a particle at certain gas stream conditions.

$$D_p = \frac{C_c KT}{3\pi d_{pa}\mu} \tag{7.23}$$

where

D_p = Diffusion coefficient (cm^2/sec).
C_c = Cunningham slip correction factor (dimensionless).
K = Boltzmann constant (g-cm^2/sec^2 K).
T = Absolute temperature (degrees K).
d_{pa} = Particle aerodynamic diameter (μm).
μ = Gas viscosity (kg/m-sec).

GRAVITATIONAL SETTLING

Particles in still air have two forces acting on them: (1) a gravitational force downward, and (2) the air resistance (or drag) force upward. When particles begin to fall, they quickly reach a terminal settling velocity, which represents the constant velocity of a falling particle when the gravitational force downward is balanced by the air resistance (or drag) force upward. The terminal settling velocity can usually be expressed using Equation 7.24. (*Note:* Equation 7.24 is applicable for particles less than 80 μm in size [aerodynamic diameter] with a Reynolds number less than 2.0 and a low velocity.)

$$v_t = \frac{GP_p\left(d_{ps}\right)^2 C_c}{18\mu} \tag{7.24}$$

where

v_t = Terminal settling velocity (cm/sec).
G = Gravitational acceleration (cm/sec^2).
P_p = Density of particle (g/cm^3).
d_{ps} = Stokes particle diameter (cm).
C_c = Cunningham slip correction factor (dimensionless).
μ = Viscosity of air (g/cm-sec).

ELECTROSTATIC ATTRACTION

In air pollution control, electrostatic precipitators (ESPs) utilize electrostatic attraction for particulate collection. Electrostatic attraction of particles is accomplished by establishing a strong electrical field and creating unipolar ions. The particles passing through the electrical field are charged by the ions being driven along the electrical field lines. Several parameters dictate the effectiveness of electrostatic attraction, including the particle size, gas flow rate, and resistivity. The particles will eventually reach a maximum or saturation charge, which is a function of the particle area. The saturation charge occurs when the localized field created by the already captured ions is sufficiently strong to deflect the electrical field lines. Particles can also be charged by diffusion of ions in the gas stream. The strength of the electrical charges imposed on the particles by both mechanisms is particle size dependent.

Resistivity is a measure of the ability of the particle to conduct electricity and is expressed in units of ohm-cm. Particles with low resistivity have a greater ability to conduct electricity (and higher electrostatic attraction) than particles with high resistivity. The following factors influence resistivity:

- Chemical composition of the gas stream
- Chemical composition of the particle
- Gas stream temperature

Thermophoresis

Thermophoresis is particle movement caused by thermal differences on two sides of the particle. Gas molecules at higher temperatures have greater kinetic energy than those at lower temperatures. Therefore, when the particle collides with a gas molecule from the hotter side, the particle receives more kinetic energy than when it collides with a gas molecule from the cooler side. Accordingly, particles tend to be deflected toward the colder area.

Diffusiophoresis

Diffusiophoresis is particle movement caused by concentration differences on two sides of the particle. When there is a strong difference in the concentration of gas molecules on two sides of the particle, there is a difference in the number of molecular collisions, which causes an imbalance in the total kinetic energies of the gas molecules. Gas molecules in the high-concentration area that strike a particle transmit more kinetic energy to the particle than do molecules in the area with a lower concentration; therefore, particles tend to move toward the area of lower concentration.

ATMOSPHERIC CHEMISTRY AND RELATED PHENOMENA*

A full range of chemistry (e.g., slow and fast reactions, dissolving crystals, precipitation of solids) occurs in the atmosphere, and the atmosphere has been described as a "flask without walls" (Graedel and Crutzen, 1995). Excluding highly variable amounts of water vapor, more than 99% of the molecules comprising the Earth's atmosphere are nitrogen, oxygen, and chemically inert gases (noble gases such as argon, etc.). The chemistry and thus the reactivity of these natural gases (nitrogen, oxygen, carbon dioxide, argon, and others) are well known. Chemically reactive, anthropogenically produced chemicals are also known to be part of Earth's atmosphere, but opinions differ as to their actual effect on our environment. For example, methane is by far the most abundant reactive compound in the atmosphere and currently is at a ground-level concentration (in the Northern Hemisphere) of about 1.7 ppmv. We know a great deal about methane, such as its generation and fate when discharged and its influence on the atmosphere; however, we are still conducting research to find out more, as we should.

Many different reactive molecules exist in the atmosphere. We may not be familiar with each of these reactants, but many of us certainly are familiar with their consequences: the ozone hole, greenhouse effect, global warming, smog, acid rain, rising tides, and so on. It may surprise you to learn, however, that the total amount of all these reactants in the atmosphere is seldom more than 10 ppmv volume anywhere in the world at any given time. The significance should be obvious: The atmospheric problems currently occurring on Earth at this time are being caused by fewer than 1/1000 of 1% of all of the molecules in the atmosphere. This indicates that environmental damage leading to global atmospheric problems can result from far lower levels than the tremendous amounts of reactive substances we imagine are dangerous.

The quality of the air we breathe, the visibility and atmospheric esthetics, and our climate, all of which are dependent on chemical phenomena that occur in the atmosphere, are important to our health and to our quality of life. Global atmospheric problems, such as the nature and level of air pollutants, concern the air science practitioner the most because they affect our health and our quality of life. Let's take a look at some of the important chemical species and their reactions primarily within the stratosphere of our atmosphere.

PHOTOCHEMICAL REACTION—SMOG PRODUCTION

A *photochemical reaction*, generally, is any chemical reaction in which light is produced or light initiates the reaction. Light can initiate reactions by exciting atoms or molecules and making them more reactive. The light energy becomes converted to chemical energy. The photochemical reaction we are concerned with here is the action or absorption electromagnetic solar radiation (light) by chemical species, which causes the reactions. The ability of electromagnetic radiation to cause photochemical reactions to occur is a function is shown in the relationship

$$E = h \times v \tag{7.25}$$

where

E = Energy of a photon.
h = Planck's constant (6.62×10^{-27}).
v = Frequency.

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* In the brief discussion that follows describing the chemistry of Earth's atmosphere, keep in mind that the atmosphere as it is at present is what is referred to. The atmosphere previous to this period was chemically quite different. Note also that atmospheric chemistry is a scientific discipline that can stand on its own. The nuts and bolts of atmospheric chemistry are beyond the scope of this text, but certain important atmospheric chemistry phenomena are highlighted here.

The major photochemical reaction we are concerned with here is the one that produces *photochemical smog*. The formation of photochemical smog, the characteristic haze of minute droplets, is initiated by nitrogen dioxide, which absorbs the visible or ultraviolet energy of sunlight, forming nitric oxide to free atoms of oxygen (O), which then combine with molecular oxygen (O_2) to form *ozone* (O_3). In the presence of hydrocarbons (other than methane) and certain other organic compounds, a variety of chemical reactions takes place. Some 80 separate reactions have been identified or postulated. The photochemical reaction that produces the smog we are familiar with depends on two factors:

1. Smog concentration is linked to both the amount of sunlight and hydrocarbons present.
2. The amount is dependent on the initial concentration of nitrogen oxides.

During the production of photochemical smog, many different substances are formed in sequence, including acrolein, formaldehyde, and peroxyacetylnitrate (PAN). Photochemical smog is a result of condensed, low-volatility organic compounds. The organics irritate the eye and, together with ozone, can cause severe damage to leafy plants. Photochemical smog tends to be most intense in the early afternoon when sunlight intensity is greatest. It differs from traditional smog (Los Angeles-type smog), which is most intense in the early morning and is dispersed by solar radiation.

In addition to the photochemical reactions that produce smog, many other chemical reactions take place in the Earth's atmosphere, including ozone production, production of free radicals, chain reactions, oxidation processes, acid–base reactions, the presence of electrons and positive ions, among others.

AIR QUALITY

When undertaking a comprehensive discussion of air, the discussion begins and ends with the Earth's atmosphere. This chapter addresses concepts that will enable us to better understand the anthropogenic impact of pollution on the atmosphere, which in turn will help us to better understand the key parameters used to measure air quality. Obviously, having a full understanding of air quality is essential, so it is necessary to review a few basic concepts here.

EARTH'S HEAT BALANCE

The energy expended in virtually all atmospheric processes is originally derived from the sun. This energy is transferred by the radiation of heat in the form of electromagnetic waves. Radiation from the sun has its peak energy transmission in the visible wavelength range (038 to 0.78 μm) of the electromagnetic spectrum. However, the sun also releases considerable energy in the ultraviolet and infrared regions; 99% of the sun's energy is emitted in wavelengths between 0.15 and 40 μm. Furthermore, wavelengths longer than 2.5 μm are strongly absorbed by water vapor and carbon dioxide in the atmosphere. Radiation at wavelengths less than 0.29 μm is absorbed high in the atmosphere by nitrogen and oxygen. Therefore, solar radiation striking the Earth generally has a wavelength between 0.29 and 2.5 μm (USEPA, 2005).

Because energy from the sun is always entering the atmosphere, the Earth would overheat if all this energy were stored in the Earth–atmosphere system, so energy must eventually be released back into space. On the whole, this is what happens—approximately 50% of the solar radiation entering the atmosphere reaches Earth's surface, either directly or after being scattered by clouds, particulate matter, or atmospheric gases. The other 50% is either reflected directly back or absorbed in the atmosphere and its energy reradiated back into space at a later time as infrared radiation. Most of the solar energy reaching the surface is absorbed, and must be returned to space to maintain the *heat balance* (or *radiational balance*). The energy produced within the Earth's interior from the hot mantle area via convection and conduction that reaches the Earth's surface (about 1% of that received from the sun) must also be lost.

Reradiation of energy from the earth is accomplished by three energy transport mechanisms: radiation, conduction, and convection. *Radiation* of energy occurs through electromagnetic radiation in the infrared region of the spectrum. The crucial importance of the radiation mechanism is that it carries energy away from Earth on a much longer wavelength than the solar energy (sunlight) that brings energy to the Earth and, in turn, works to maintain the Earth's heat balance. The Earth's heat balance is of particular interest to us in this text because it is susceptible to upset by human activities.

A comparatively smaller but significant amount of heat energy is transferred to the atmosphere by conduction from the Earth's surface. *Conduction* of energy occurs through the interaction of adjacent molecules with no visible motion accompanying the transfer of heat; for example, the whole length of a metal rod will become hot when one end is held in a fire. Because air is a poor heat conductor, conduction is restricted to the layer of air in direct contact with the Earth's surface. The heated air is then transferred aloft by *convection*, the movement of whole masses of air, which may be either relatively warm or cold. Convection is the mechanism by which abrupt temperature variations occur when large masses of air move across an area. Air temperature tends to be greater near the surface of the Earth and decreases gradually with altitude. A large amount of the Earth's surface heat is transported to clouds in the atmosphere by conduction and convection before ultimately being lost by radiation, and this redistribution of heat energy plays an important role in weather and climate conditions.

The average surface temperature of the Earth is maintained at about 15°C because of an atmospheric greenhouse effect. This greenhouse effect occurs when the gases of the lower atmosphere transmit most of the visible portion of incident sunlight in the same way as the glass of a garden greenhouse. The warmed Earth emits radiation in the infrared region, which is selectively absorbed by the atmospheric gases whose absorption spectrum is similar to that of glass. This absorbed energy heats the atmosphere and helps maintain the temperature of the Earth. Without this greenhouse effect, the surface temperature would average around –18°C. Most of the absorption of infrared energy is performed by water molecules in the atmosphere. In addition to the key role played by water molecules, carbon dioxide, although to a lesser extent, is also essential in maintaining the heat balance. Environmentalists and others involved in environmental issues are concerned that an increase in the carbon dioxide level in the atmosphere could prevent sufficient energy loss, resulting in damaging increases in the temperature of the planet. This phenomenon, commonly known as the *anthropogenic greenhouse effect*, may occur due to elevated levels of carbon dioxide levels caused by increased use of fossil fuels and the reduction in carbon dioxide absorption because of destruction of the rainforest and other forest areas.

INSOLATION*

Insolation is the amount of incoming solar radiation received at a particular time and location in the Earth–atmosphere system. Insolation is governed by four factors:

1. Solar constant
2. Transparency of the atmosphere
3. Daily sunlight duration
4. Angle at which the sun's rays strike the Earth

Solar Constant

The solar constant is the average amount of radiation received at a point perpendicular to the sun's rays that is located outside the Earth's atmosphere at the mean distance of the Earth from the sun. The average amount of solar radiation received at the outer edge of the atmosphere varies slightly

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* This section is adapted from USEPA, *Basic Air Pollution Meteorology*, U.S. Environmental Protection Agency, Washington, DC, 2005 (www.epa.gov/apti).

depending on the energy output of the sun and the distance of the Earth relative to the sun. Due to the eccentricity of the Earth's orbit around the sun, the earth is closer to the sun in January than in July. Also, the radiation emitted from the sun varies slightly, probably less than a few percent. These slight variations that affect the solar constant are trivial considering the atmospheric properties that deplete the overall amount of solar radiation reaching the Earth's surface. Transparency of the atmosphere, duration of daylight, and the angle at which the sun's rays strike the Earth are much more important in influencing the amount of radiation actually received, which in turn includes the weather.

Transparency

Transparency of the atmosphere has an important bearing on the amount of insolation that reaches the Earth's surface. The emitted radiation is depleted as it passes through the atmosphere. Different atmospheric constituents absorb or reflect energy in different ways and in varying amounts. Transparency of the atmosphere refers to how much radiation penetrates the atmosphere and reaches the Earth's surface without being depleted. The general reflectivity of the various surfaces of the Earth is referred to as the *albedo*, which is defined as the fraction (or percentage) of incoming solar energy that is reflected back to space. Different surfaces (e.g., water, snow, sand) have different albedo values. For the Earth and atmosphere as a whole, the average albedo is 30% for average conditions of cloudiness over the Earth. This reflectivity is greatest in the visible range of wavelengths. Some of the gases in the atmosphere (notably water vapor) absorb solar radiation, causing less radiation to reach the Earth's surface. Water vapor, although representing only about 3% of the atmosphere, on the average absorbs about six times as much solar radiation as all other gases combined. The amount of radiation received at the Earth's surface is therefore considerably less than that received outside the atmosphere as represented by the solar constant.

Daylight Duration

The duration of daylight also affects the amount of insolation received: the longer the period of sunlight, the greater the total possible insolation. Daylight duration varies with latitude and the seasons. At the equator, day and night are always equal. In the polar regions, the daylight period reaches a maximum of 24 hours in summer and a minimum of zero hours in winter.

Angle of Sun's Rays

The angle at which the sun's rays strike the Earth varies considerably as the sun "shifts" back and forth across the equator. A relatively flat surface perpendicular to an incoming vertical sun ray receives the largest amount of insolation. Therefore, areas at which the sun's rays are oblique receive less insolation because the oblique rays must pass through a thicker layer of reflecting and absorbing atmosphere and are spread over a greater surface area. This same principle also applies to the daily shift of the sun's rays. At solar noon, the intensity of insolation is greatest. In the morning and evening hours, when the sun is at a low angle, the amount of insolation is small.

HEAT DISTRIBUTION

The Earth, as a whole, experiences great contrasts in heat and cold at any particular time. Warm, tropical breezes blow at the equator while ice caps are forming in the polar regions. In fact, due to the extreme temperature differences at the equator and the poles, the Earth–atmosphere system resembles a giant "heat engine." Heat engines depend on hot–cold contrasts to generate power. As you will see, this global "heat engine" influences the major atmospheric circulation patterns as warm air is transferred to cooler areas. Different parts of the Earth receiving different amounts of insolation account for much of this heat imbalance. As discussed earlier, latitude, the seasons, and daylight duration cause different locations to receive varying amounts of insolation.

Differential Heating

Not only do different amounts of solar radiation reach the Earth's surface, but also different Earth surfaces absorb heat energy at different rates; for example, land masses absorb and store heat differently than water masses. Also, different types of land surfaces vary in their ability to absorb and store heat. The color, shape, surface texture, vegetation, and presence of buildings can all influence the heating and cooling of the ground. Generally, dry surfaces heat and cool faster than moist surfaces. Plowed fields, sandy beaches, and paved roads become hotter than surrounding meadows and wooded areas. During the day, the air over a plowed field is warmer than over a forest or swamp; during the night, the situation is reversed. The property of different surfaces that causes them to heat and cool at different rates is referred to as *differential heating*. Absorption of heat energy from the sun is confined to a shallow layer of land surface; consequently, land surfaces heat rapidly during the day and cool quickly at night. Water surfaces, on the other hand, heat and cool more slowly than land surfaces for the following reasons:

- Water movement distributes heat.
- The sun's rays are able to penetrate the water surface.
- More heat is required to change the temperature of water due to its higher specific heat. (It takes more energy to raise the temperature of water than it does to change the temperature of the same amount of soil.)
- Evaporation of water occurs which is a cooling process.

Transport of Heat

Remember that, in addition to radiation, heat is transferred by conduction, convection, and advection, processes that affect the temperature of the atmosphere near the surface of the Earth. *Conduction* is the process by which heat is transferred through matter without the transfer of matter itself. For example, the handle of an iron skillet becomes hot due to the conduction of heat from the stove burner. Heat is conducted from a warmer object to a cooler one. Heat transfer by *convection* occurs when matter is in motion. Air that is warmed by a heated land surface (by conduction) will rise because it is lighter than the surrounding air. This heated air rises, transferring heat vertically. Likewise, cooler air aloft will sink because it is heavier than the surrounding air. This goes hand in hand with rising air and is part of heat transfer by convection. Meteorologists also use the term *advection* to denote heat transfer that occurs mainly by horizontal motion rather than by vertical movement or air (convection).

Global Distribution of Heat

As mentioned before, the world distribution of insolation is closely related to latitude. Total annual insolation is greatest at the equator and decreases toward the poles. The amount of insolation received annually at the equator is over four times that received at either of the poles. As the rays of the sun shift seasonally from one hemisphere to the other, the zone of maximum possible daily insolation moves with them. For the Earth as a whole, the gains in solar energy equal the losses of energy back into space (heat balance). However, because the equatorial region does gain more heat than it loses and the poles lose more heat than they gain, something must happen to distribute heat more evenly around the Earth. Otherwise, the equatorial regions would continue to heat and the poles would continue to cool. In order to reach equilibrium, a continuous large-scale transfer of heat (from low to high altitudes) is carried out by atmospheric and oceanic circulations.

The atmosphere drives warm air poleward and brings cold air toward the equator. Heat transfer from the tropics poleward takes place throughout the year, but at a much slower rate in summer than in winter. The temperature difference between low and high latitudes is considerably smaller in summer than in winter (only about half as large in the Northern Hemisphere). As would be expected, the winter hemisphere has a net energy loss and the summer hemisphere a net gain. Most of the summertime gain is stored in the surface layers of land and ocean, mainly in the ocean.

The oceans also play a role in heat exchange. Warm water flows poleward along the western side of an ocean basin and cold water flows toward the equator on the eastern side. At higher latitudes, warm water moves poleward in the eastern side of the ocean basin and cold water flows toward the equator on the western side. The oceanic currents are responsible for about 40% of the transport of energy from the equator to the poles. The remaining 60% is attributed to the movement of air.

AIR QUALITY MANAGEMENT

Proper air quality management includes several different areas related to air pollutants and their control. For example, we can apply mathematical modeling to predict where pollutants emitted from a source will be dispersed in the atmosphere and eventually fall to the ground and at what concentration. We have found that pollution control equipment can be added to various sources to reduce the amount of pollutants before they are emitted into the air. We have found that certain phenomena such as acid rain, the greenhouse effect, and global warming are all indicators of adverse effects to the air and other environmental mediums resulting from the excessive amount of pollutants being released into the air. We have found that we must concern ourselves not only with ambient air quality in our local outdoor environment but also with the issue of indoor air quality.

To accomplish effective air quality management, it has been found that managing is one thing—and accomplishing significant improvement is another. We need to add regulatory authority, regulations, and regulatory enforcement authority to the air quality management scheme, as strictly voluntary compliance is ineffective. We cannot maintain a quality air supply without proper management, regulation, and regulatory enforcement. This section presents the regulatory framework governing air quality management. It provides an overview of the environmental air quality laws and regulations used to protect human health and the environment from the potential hazards of air pollution. New legislation, reauthorizations of acts, and new National Ambient Air Quality Standards (NAAQS) have created many changes in the way government and industry manage their business. Fortunately for our environment and for us they are management tools that are effective and are working to manage air quality.

CLEAN AIR ACT

When you look at a historical overview of air quality regulations, you might be surprised to discover that most air quality regulations are recent; for example, in the United States, the first attempt at regulating air quality came about through passage of the Air Pollution Control Act of 1955 (Public Law 84-159). This act was a step forward but that was about all; it did little more than move us toward effective legislation. Revised in 1960 and again in 1962, the act was supplanted by the Clean Air Act (CAA) of 1963 (Public Law 88-206), which has been amended several times, most recently in 1990. The CAA is the primary means by which the USEPA regulates potential emissions that could affect air quality. The CAA encouraged state, local, and regional programs for air pollution control but reserved the right of federal intervention should pollution from one state endanger the health and welfare of citizens residing in another state. In addition, the CAA initiated the development of air quality criteria upon which the air quality and emissions standards of the 1970s were based.

The move toward air pollution control gained momentum in 1970, first by creation of the Environmental Protection Agency and second by passage of amendments to the Clean Air Act (Public Law 91-604), which the USEPA was responsible for implementing. The Act was important because it set primary and secondary ambient air quality standards. Primary standards (based on air quality criteria) allowed for an extra margin of safety to protect public health, whereas the secondary standards (also based on air quality criteria) were established to protect public welfare—animals, property, plants, and materials. The 1977 amendments to the Clean Air Act (Public Law 95-95) further strengthened the existing laws and set the nation's course toward cleaning up our atmosphere. In 1990, further amendments to the Clean Air Act were passed to

- Encourage the use of market-based principles and other innovative approaches, such as performance-based standards and emissions banking and trading.
- Promote the use of clean, low-sulfur coal and natural gas, as well as the use of innovative technologies to clean high-sulfur coal through the acid rain program.
- Reduce enough energy waste and create enough of a market for clean fuels derived from grain and natural gas to cut dependency on oil imports by 1 million bbl/day.
- Promote energy conservation through an acid rain program that gives utilities flexibility to obtain needed emission reductions through programs that encourage customers to conserve energy.

Components of the 1990 amendments to the CAA include the following:

- Title 1, which specifies provisions for attainment and maintenance of National Ambient Air Quality Standards (NAAQS)
- Title 2, which specifies provisions for mobile sources of pollutants
- Title 3, which covers air toxics
- Title 4, which covers specifications for acid rain control
- Title 5, which addresses permits
- Title 6, which specifies stratospheric ozone and global protection measures
- Title 7, which discusses provisions relating to enforcement

TITLE 1: ATTAINMENT AND MAINTENANCE OF NAAQS

The 1977 amendments to the Clean Air Act brought about significant improvements in U.S. air quality, but the urban air pollution problems of smog (ozone), carbon monoxide (CO), and particulate matter (PM_{10}) persisted. In 1990, over 100 million Americans were living in cities that had not attained the public health standards for ozone, and a new strategy for attacking the urban smog problem was needed. The 1990 amendments to the Clean Air Act created such a strategy. Under these new amendments, states were given more time to meet the air quality standards (e.g., up to 20 years for ozone in Los Angeles) but they had to make steady, impressive progress in reducing emissions. Specifically, the 1990 amendments required the federal government to reduce emissions from (1) cars, buses, and trucks; (2) consumer products such as window-washing compounds and hair spray; and (3) ships and barges during loading and unloading of petroleum products. In addition, the federal government was directed to develop the technical guidance required by states to control stationary sources.

With regard to urban air pollution problems involving smog (ozone), carbon monoxide (CO), and particulate matter (PM_{10}), the new amendments clarified how areas are designated and redesignated as achieving attainment. The USEPA is also allowed to define the boundaries of nonattainment areas (geographical areas whose air quality does not meet federal air quality standards designed to protect public health). The 1990 amendments also established provisions defining when and how the federal government can impose sanctions on areas of the country that have not met certain conditions.

For ozone specifically, the amendments established nonattainment area classifications ranked according to the severity of the area's air pollution problem:

- Marginal
- Moderate
- Serious
- Severe
- Extreme

The USEPA assigns each nonattainment area one of these categories, thus prompting varying requirements the areas must comply with in order to meet the ozone standard. Again, nonattainment areas have to implement different control measures, depending on their classifications. Those closest to meeting the standard, for example, are the marginal areas, which are required to conduct an inventory of their ozone-causing emissions and institute a permit program. Various control measures must be implemented by nonattainment areas with more serious air quality problems; that is, the worse the air quality, the more controls areas will have to implement.

For carbon monoxide and particulate matter, the 1990 CAA amendments established similar programs for areas that do not meet the federal health standard. Areas exceeding the standards for these pollutants are divided into the classifications of moderate and serious. Areas that exceed the carbon monoxide standard are required primarily to implement programs introducing oxygenated fuels or enhanced emission inspection programs. Likewise, areas exceeding the particulate matter standard have to (among other requirements) implement either reasonably available control measures (RACMs) or best available control measures (BACMs).

Title 1 attainment and maintenance of NAAQS requirements (see Table 7.15) have gone a long way toward improving air quality in most locations throughout the United States; however, in 1996, in an effort to upgrade NAAQS for ozone and particulate matter, the USEPA put into effect two new NAAQS for ozone (62 FR 38855) and $PM_{2.5}$, particulate matter smaller than 2.5 μm in diameter (62 FR 38651). They were the first update in 20 years for ozone (smog) and the first in 10 years for particulate matter (soot).

TABLE 7.15
National Ambient Air Quality Standards (NAAQs)

Pollutant	**Standard Value**	
Carbon monoxide (CO)		
8-hour average	9 ppm	10 mg/m^3
1-hour average	35 ppm	40 mg/m^3
Nitrogen dioxide (NO_2)		
Annual arithmetic mean	0.053 ppm	100 μg/m^3
Ozone (O_3)		
1-hour average	0.12 ppm	235 μg/m^3
8-hour average	0.08 ppm	157 μg/m^3
Lead (Pb)		
Quarterly average	1.5 μg/m^3	
Particulate matter (PM_{10})[a]		
Annual arithmetic mean	50 μg/m^3	
24-hour average	150 μg/m^3	
Particulate matter ($PM_{2.5}$)[b]		
Annual arithmetic mean	15 μg/m^3	
24-hour average	65 μg/m^3	
Sulfur dioxide (SO_2)		
Annual arithmetic mean	0.03 ppm	80 μg/m^3
24-hour average	0.14 ppm	365 μg/m^3

Source: USEPA, *National Ambient Air Quality Standards (NAAQS)*, U.S. Environmental Protection Agency, Washington, DC, 2007.

[a] Particles with diameters of 10 μm or less.

[b] Particles with diameters of 2.5 μm or less.

Note that the NAAQS are important but are not enforceable by themselves. The standards set ambient concentration limits for the protection of human health and environment-related values; however, it is important to remember that it is a very rare case where any one source of air pollutants is responsible for the concentrations in an entire area.

TITLE 2: MOBILE SOURCES

Even though great strides have been made since the 1960s in reducing vehicle emissions, cars, trucks, and buses account for almost half the emissions of the ozone precursors volatile organic compounds (VOCs) and nitrogen oxides, and up to 90% of CO emissions in urban areas. A large portion of the emission reductions gained from motor vehicle emission controls has been offset by the rapid growth in the number of vehicles on the highways and the total miles driven. Because of the unforeseen growth in automobile emissions in urban areas, compounded with serious air pollution problems in many urban areas, Congress made significant changes to the motor vehicle provisions found in the 1977 amendments to the Clean Air Act. The 1990 amendments established even tighter pollution standards for emissions from motor vehicles. These standards were designed to reduce tailpipe emissions of hydrocarbons, nitrogen oxides, and carbon monoxide on a phased-in basis beginning with model year 1994. Automobile manufacturers are also required to reduce vehicle emissions resulting from the evaporation of gasoline during refueling operations. The latest version of the Clean Air Act (1990, with 1997 amendments for ozone and particulate matter) also requires fuel quality to be controlled. New programs requiring cleaner or reformulated gasoline were initiated in 1995 for the nine cities with the worst ozone problems. Other cities were given the option to "opt in" to the reformulated gasoline program. In addition, a clean fuel car pilot program was established in California, which required the phasing-in of tighter emission limits for several thousand vehicles in model year 1996 and up to 300,000 by model year 1999. The law allows these standards to be met with any combination of vehicle technology and cleaner fuels. The standards became even stricter in 2001.

TITLE 3: AIR TOXICS

Toxic air pollutants that are hazardous to human health or the environment (typically carcinogens, mutagens, and reproductive toxins) were not specifically covered under the 1977 amendments to the Clean Air Act. This situation is quite surprising when we consider that information generated as a result of Title III of the Superfund Amendments and Reauthorization Act (SARA) (Section 313) indicates that in the United States more than 2 billion pounds of toxic air pollutants are emitted annually. The 1990 amendments to the Clean Air Act offered a comprehensive plan for achieving significant reductions in emissions of hazardous air pollutants from major sources. The new law improved the USEPA's ability to address this problem effectively and dramatically accelerated progress in controlling major toxic air pollutants. The 1990 amendments include a list of 189 toxic air pollutants whose emissions must be reduced. The USEPA was required to publish a list of source categories that emit certain levels of these pollutants and was also required to issue maximum achievable control technology (MACT) standards for each listed source category. The law also established a Chemical Safety Board to investigate accidental releases of extremely hazardous chemicals.

TITLE 4: ACID DEPOSITION

The purity of rainfall is a major concern for many people, especially regarding the acidity of the precipitation. Most rainfall is slightly acidic because of decomposing organic matter, the movement of the sea, and volcanic eruptions, but the principal factor is atmospheric carbon dioxide, which causes carbonic acid to form. *Acid rain* ($pH < 5.6$) is produced by the conversion of the primary pollutants sulfur dioxide and nitrogen oxides to sulfuric acid and nitric acid, respectively. These processes are complex, depending on the physical dispersion processes and the rates of the chemical conversions.

Contrary to popular belief, acid rain is not a new phenomenon nor does it result solely from industrial pollution. Natural processes—volcanic eruptions and forest fires, for example—produce and release acid particles into the air, and the burning of forest areas to clear land in Brazil, Africa, and other countries also contributes to acid rain; however, the rise in manufacturing that began with the Industrial Revolution literally dwarfs all other contributions to the problem. The main culprits are emissions of sulfur dioxide from the burning of fossil fuels, such as oil and coal, and nitrogen oxide, formed mostly from internal combustion engine emissions, which is readily transformed into nitrogen dioxide. These mix in the atmosphere to form sulfuric acid and nitric acid.

When dealing with atmospheric acid deposition, the Earth's ecosystems are not completely defenseless; they can deal with a certain amount of acid through natural alkaline substances in soil or rocks that buffer and neutralize acid. Highly alkaline soil (limestone and sandstone) in the American Midwest and southern England provides some natural neutralization; however, areas with thin soil and those laid on granite bedrock have little ability to neutralize acid rain.

Scientists continue to study how living beings are injured or even killed by acid rain. This complex subject has many variables. We know from various episodes of acid rain that pollution can travel over very long distances. Lakes in Canada and New York are feeling the effects of coal burning in the Ohio Valley. For this and other reasons, the lakes of the world are where most of the scientific studies have taken place. In lakes, the smaller organisms often die off first, leaving the larger animals to starve to death. Sometimes the larger animals (e.g., fish) are killed directly; as lake water becomes more acidic, it dissolves heavy metals, leading to toxic and often lethal concentrations. Have you ever wandered up to the local lake shore and observed thousands of fish belly-up? Not a pleasant sight or smell, is it? Loss of life in lakes also disrupts the system of life on the land and the air around them. In some parts of the United States, the pH of rainfall has fallen well below 5.6. In the northeastern United States, for example, the average pH of rainfall is 4.6, and rainfall with a pH of 4.0, a level 1000 times more acidic than distilled water, has occurred.

Despite intensive research into most aspects of acid rain, there are still many areas of uncertainty and disagreement. That is why progressive, forward-thinking countries emphasize the importance of further research into acid rain, and that is why the 1990 amendments to the Clean Air Act initiated a permanent reduction in SO_2 levels. One of the interesting features of the Clean Air Act is that it allowed utilities to trade allowances within their systems or buy and sell allowances to and from other affected sources. Each source must have sufficient allowances to cover its annual emissions. If not, the source is subject to excess emissions fees and a requirement to offset the excess emissions in the following year. The 1990 amendments also include specific requirements for reducing emissions of nitrogen oxides for certain boilers.

TITLE 5: PERMITS

The 1990 CAA amendments also introduced an operating permit system similar to the National Pollutant Discharge Elimination System (NPDES). The permit system has a twofold purpose: (1) to ensure compliance with all applicable requirements of the CAA, and (2) to enhance the USEPA's ability to enforce the Act. Under the Act, air pollution sources must develop and implement the program, and the USEPA must issue permit program regulations, review each state's proposed program, and oversee the state's effort to implement any approved program. The USEPA must also develop and implement a federal permit program when a state fails to adopt and implement its own program.

TITLE 6: OZONE AND GLOBAL CLIMATE PROTECTION

Ozone is formed in the stratosphere by radiation from the sun and helps to shield life on Earth from some of the sun's potentially destructive ultraviolet radiation. In the early 1970s, scientists suspected that the ozone layer was being depleted. By the 1980s, it became clear that the ozone shield is indeed thinning in some places and at times even has a seasonal hole in it, notably over Antarctica. The exact causes and actual extent of the depletion are not yet fully known, but most scientists believe that various chemicals in the air are responsible.

Most scientists identify the family of chlorine-based compounds, most notably chlorofluorocarbons (CFCs) and chlorinated solvents (carbon tetrachloride and methyl chloroform), as the primary culprits involved in ozone depletion. Molina and Rowland (1974) hypothesized that the chlorine-containing CFCs were responsible for ozone depletion. They pointed out that chlorine molecules are highly active and readily and continually break apart three-atom ozone into the two-atom form of oxygen generally found close to Earth, in the lower atmosphere. The Interdepartmental Committee for Atmospheric Sciences (ICAS, 1975) estimated that a 5% reduction in ozone could result in nearly a 10% increase in cancer. This already frightening scenario was made even more frightening by 1987 when evidence showed that CFCs destroy ozone in the stratosphere above Antarctica every spring. The ozone hole had become larger, with more than half of the total ozone column wiped out, and essentially all ozone disappeared from some regions of the stratosphere (Davis and Cornwell, 1991).

In 1988, it was reported that, on a worldwide basis, the ozone layer had shrunk approximately 2.5% in the preceding decade (Zurer, 1988). This obvious thinning of the ozone layer, with its increased chances of skin cancer and cataracts, is also implicated in suppression of the human immune system and damage to other animals and plants, especially aquatic life and soybean crops. The urgency of the problem spurred the 1987 signing of the Montreal Protocol by 24 countries, which required signatory countries to reduce their consumption of CFCs by 20% by 1993 and by 50% by 1998, marking a significant achievement in solving a global environmental problem.

The 1990 amendments to the Clean Air Act borrowed from USEPA requirements already on the books in other regulations and mandated phase-out of the production of substances that deplete the ozone layer. Under these provisions, the USEPA was required to list all regulated substances along with their ozone-depletion potential, atmospheric lifetime, and global warming potentials.

TITLE 7: ENFORCEMENT

A broad array of authorities is contained within the Clean Air Act to make the law more readily enforceable. The 1990 amendments gave the USEPA new authority to issue administrative penalties with fines, and field citations (with fines) for smaller infractions. In addition, sources must certify their compliance, and the USEPA has authority to issue administrative subpoenas for compliance data.

CLEAN AIR ACT AMENDMENT REQUIREMENTS*

The Clean Air Act amendments require that State Implementation Plans (SIPs) be developed, the impact upon the atmosphere be evaluated for new sources, and air quality modeling analyses be performed. These regulatory programs require knowledge of the air quality in the region around a source, air quality modeling procedures, and the fate and transport of pollutants in the atmosphere. Implicit in air pollution programs is knowledge of the climatology of the area in question.

STATE IMPLEMENTATION PLANS

State Implementation Plans (SIPs) are federally approved plans developed by state (or local) air quality management authorities to attain and maintain the National Ambient Air Quality Standards. Generally, these SIPs are a state's (local) air quality rules and regulations that are considered an acceptable control strategy once approved by the USEPA. The purpose of SIPs is to control the

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* This section is adapted from USEPA, *Basic Air Pollution Meteorology*, U.S. Environmental Protection Agency, Washington, DC, 2005 (www.epa.gov/apti).

amount and types of pollution for any given area or region of the United States. In these types of control strategies, emission limits should be based on ambient pollutant concentration estimates for the averaging time that results in the most stringent control requirements. In all cases, these concentration estimates are assumed to be the sum of the pollutant concentrations contributed by the source and an appropriate background concentration. An air quality model is used to determine which averaging time (e.g., annual, 24-hour, 8-hour, 3-hour, 1-hour) results in the highest ambient impact. For example, if the annual average air quality standard is approached by a greater degree (percentage) than standards for other averaging times, the annual average is considered the restrictive standard. In this case, the sum of the highest estimated annual average concentration and the annual average background concentration provides the concentration that should be used to specify emission limits; however, if a short-term standard is approached by a greater degree and is thus identified as the restrictive standard, other considerations are required because the frequency of occurrence must also be taken into account.

New Source Review

New major stationary sources or major modifications to existing sources of air pollution are required by the Clean Air Act to obtain an air quality permit before construction is started. This process is called a New Source Review (NSR), and it is required for any new major stationary source or major modification to an existing source regardless of whether or not the NAAQS are exceeded. Sources located in areas that exceed the NAAQS (nonattainment areas) would undergo a nonattainment NSR. New Source Reviews for major sources in areas where the NAAQS are not violated (attainment areas) would involve the preparation of a Prevention of Significant Deterioration (PSD) permit. Some sources will have the potential to emit pollutants for which their area is in attainment (or unclassifiable) as well as the potential to emit pollutants for which their area is in nonattainment. When this is the case, the source's permit will contain terms and conditions to meet both the PSD and nonattainment area major NSR requirements because these requirements are pollutant specific. In most cases, any new source must obtain a nonattainment NSR permit if it will emit, or has the potential to emit, 100 tons per year or more of any regulated NSR pollutant for which that area is in nonattainment, from marginal to extreme. In areas where air quality problems are more severe, the USEPA has established lower thresholds for three criteria pollutants: ozone (VOCs), particulate matter (PM_{10}), and carbon monoxide. The significance levels are lower for modifications to existing sources.

In general, a new source located in an attainment or unclassifiable area must get a PSD permit if it will emit, or has the potential to emit, 250 tons per year (tpy) or more of any criteria or NSR regulated pollutant. If the source is on the USEPA's list of 28 PSD source categories, a PSD permit is required if it will or may emit 100 tpy or more of any NSR regulated pollutant. The significance levels are lower for modifications to existing sources. In addition, PSD review would be triggered, with respect to a particular pollutant, if a new source or major modification is constructed within 10 kilometers of a Class 1 area (see below) and would have an impact on such area equal to or greater than 1 mg/m^3 (24-hour average) for the pollutant, even though the emissions of such pollutants would not otherwise be considered significant.

Some new sources or modifications to sources that are in attainment areas may be required to perform an air quality modeling analysis. This *air quality impact analysis* should determine if the source will cause a violation of the NAAQS or cause air quality deterioration that is greater than the available PSD increments. PSD requirements provide an area classification system based on land use for areas within the United States. These three areas are Class I, Class II, and Class III, and each class has an established set of increments that cannot be exceeded. Class I areas consist of national parks and wilderness areas that are only allowed a small amount of air quality deterioration. Due to the pristine nature of these areas, the most stringent limits on air pollution are enforced in the Class I areas. Class II areas consist of normal, well-managed industrial development. Moderate levels of air quality deterioration are permitted in these regions. Class III areas allow the largest amount of air quality deterioration to occur. When a PSD analysis is performed, the PSD increments set forth a maximum allowable increase in pollutant concentrations, which limit the allowable amount of air quality deterioration in an area. This in turn limits the amount of pollution that enters the atmosphere for a given region. In order to determine if a source of sulfur dioxide, for example, will cause an air quality violation, the air quality analysis uses the highest estimated concentration for annual averaging periods, and the second highest estimated concentration for averaging periods of 24 hours or less. The new NAAQS for PM and ozone contain specific procedures for determining modeled air quality violations. For reviews of new or modified sources, the air quality impact analysis should generally be limited to the area where the source's impact is significant, as defined by regulations. In addition, due to the uncertainties in making concentration estimates of large downwind distances, the air quality impact analysis should generally be limited to a downwind distance of 50 km, unless adverse impacts in a Class I area may occur at greater distances.

AIR QUALITY MONITORING

Air quality modeling is necessary to ensure that a source is in compliance with the SIP and New Source Review requirements. When air quality modeling is required, the selection of a model is dependent on the source characteristics, pollutants emitted, terrain, and meteorological parameters. The USEPA's *Guideline on Air Quality Modeling* (40 CFR 1, Appendix W) summarizes the available models, techniques, and guidance in conducting air quality modeling analyses used in regulatory programs. This document was written to promote consistency among modelers so that all air quality modeling activities would be based on the same procedures and recommendations.

When air quality modeling is required, the specific model used (from a simple screening tool to a refined analysis) will require meteorological data. The data can vary from a few factors such as average wind speed and Pasquill–Gifford stability categories to a mathematical representation of turbulence. Whatever model is chosen to estimate air quality, the meteorological data must match the quality of the model used; for example, average wind speed used in a simple screening model will not be sufficient for a complex refined model. An air quality modeling analysis incorporates the evaluation of terrain, building dimensions, ambient monitoring data, relevant emissions from nearby sources, and the aforementioned meteorological data. For a dispersion model to provide useful and valid results, the meteorological data used in the model must be representative of the transport and dispersions characteristics in the vicinity of the source that the model is trying to simulate. The representativeness of the meteorological data is dependent on the following:

- The proximity of the meteorological monitoring site to the area under consideration
- The complexity of the terrain in the area
- The exposure of the meteorological monitoring site
- The period of time during which the data are collected

In addition, the representativeness of the data can be adversely affected by large distances between the source and the receptor of interest. Similarly, valley/mountain, land/water, and urban/rural characteristics affect the accuracy of the meteorological data for the source under consideration. For control strategy evaluations and New Source Reviews, the minimum meteorological data required to describe transport and dispersion of air pollutants in the atmosphere are wind direction, wind speed, mixing height, and atmospheric stability (or related indicators of atmospheric turbulence and mixing). Because of the question of representativeness of meteorological data, site-specific data are preferable to data collected offsite. Typically, 1 year of onsite data is required. If an offsite database is used (from a nearby airport for example), 5 years of data are normally required. With 5 years of data, the model can incorporate most of the possible variations in the meteorological conditions at the site.

VISIBILITY

Visibility is the distance an observer can see along the horizon. The scattering and absorption of light by air pollutants in the atmosphere impair visibility. There are generally two types of air pollution that impair visibility. The first type consists of smoke, dust, or gaseous plumes which obscure the sky or horizon and are emitted from a single source or small group of sources. The second type is a widespread area of haze that impairs visibility in every direction over a large area and originates from a multitude of sources. Regardless of the type of air pollution that impairs the visibility at a particular location, any change in the meteorology or source emissions that would increase the pollutant concentration in the atmosphere will result in increased visibility impairment. PSD Class I areas have the most stringent PSD increments and therefore must be protected from not only high pollutant concentrations but also the additional problems pollutants in the atmosphere can cause. Under the Clean Air Act, PSD Class I areas must be evaluated for visibility impairment. This may involve a visibility impairment analysis. According to USEPA regulations, visibility impairment is defined as any humanly perceptible change in visibility (visual range, contrast, or coloration) from natural conditions; therefore, any location is susceptible to visibility impairment due to air pollution sources. Because PSD Class I areas (national parks and wilderness areas) are known for their aesthetic quality any change or alteration in the visibility of the area must be analyzed.

POLLUTANT DISPERSION

Pollutant dispersion is the process of pollutants being removed from the atmosphere and deposited onto the surface of the Earth. Stack plumes contain gases and a small amount of particles that are not removed from the gas stream. When the plume emerges from the stack, these particles are carried with it. Once airborne, the particles begin to settle out and become deposited on the ground and on surface objects. There are basically two ways the particles can be deposited: dry deposition (gravitational settling) or wet deposition (precipitation scavenging). Depending on the meteorological conditions during the time of pollutant emission, these may

1. Settle out quickly due to their weight and the effect of gravity
2. Be transported further downwind of the source due to buoyancy and wind conditions
3. Be washed out of the atmosphere by precipitation or clouds (wet deposition)

In any case, the deposition of these pollution particles is important to understand and quantify because pollutants deposited upon the ground can impact human health, vegetation, and wildlife. Pollutant deposition concentrations must be predicted to minimize the risk to human health. In order to quantify the amount of pollutant deposition that occurs from stack emissions, air quality models can be used. These models determine pollution deposition based on the chemical reactivity and solubility of various gases and by using detailed data on precipitation for the areas in question.

VAPOR-PLUME-INDUCED ICING

Vapor plumes are emitted from cooling towers and stacks and consist mainly of water vapor. Although pollutant concentrations are not a major concern with vapor plumes, other problems arise when vapor plume sources are located close to frequently traveled roads and populated areas. Vapor emitted from a stack is warm and moist. When meteorological conditions are favorable, the moisture in the vapor plume condenses out and settles on cooler objects (e.g., road surfaces). This phenomenon is similar to the moisture that collects on the sides of a glass of water on a warm day. If temperatures are at or below freezing when the moisture condenses, road surfaces can freeze rapidly, creating hazardous driving conditions. In addition, light winds can cause the plume to remain stagnant, creating a form of ground fog that can cause low visibility as well. Water vapor plumes that lower visibility can create hazards for aircraft, especially during critical phases of flight, including landings and takeoffs.

AIR POLLUTION MECHANICS

In the past, the sight of belching smokestacks was a comforting sight to many people: More smoke equaled more business, which indicated that the economy was healthy. But, many of us are now troubled by evidence that indicates that polluted air adversely affects our health. Many toxic gases and fine particles entering the air pose health hazards (e.g., cancer, genetic defects, respiratory disease). Nitrogen and sulfur oxides, ozone, and other air pollutants from fossil fuels are inflicting damage on our forests, crops, soils, lakes, rivers, coastal waters, and buildings. Chlorofluorocarbons (CFCs) and other pollutants entering the atmosphere are depleting the Earth's protective ozone layer, allowing more harmful ultraviolet radiation to reach the surface of the Earth. Fossil fuel combustion is increasing the amount of carbon dioxide in the atmosphere which can have a severe, long-term environmental impact.

It is interesting to note that when ambient air is considered, the composition of "unpolluted" air is unknown to us. Humans have lived on the planet thousands of years, and they influenced the composition of the air through their many activities before it was possible to measure the constituents of the air. In theory, the air has always been polluted to some degree. Natural phenomena such as volcanoes, wind storms, the decomposition of plants and animals, and even the aerosols emitted by the ocean can be considered to pollute the air. The pollutants we usually refer to when we talk about air pollution, though, are those generated as a result of human activity. An *air pollutant* can be considered to be a substance in the air that, in high enough concentrations, produces a detrimental environmental effect. These effects can be either health effects or welfare effects. A pollutant can affect the health of humans, as well as the health of plants and animals. Pollutants can also affect non-living materials such as paints, metals, and fabrics. An *environmental effect* is defined as a measurable or perceivable detrimental change resulting from contact with an air pollutant. Human activities have had a detrimental effect on the makeup of air. Activities such as driving cars and trucks; burning coal, oil, and other fossil fuels; and manufacturing chemicals have changed the composition of air by introducing many pollutants. There are hundreds of pollutants in the ambient air. Ambient air is the air to which the general public has access (i.e., any unconfined portion of the atmosphere). The two basic physical forms of air pollutants are particulate matter and gases. Particulate matter includes small solid and liquid particles such as dust, smoke, sand, pollen, mist, and fly ash. Gases include substances such as carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and volatile organic compounds (VOCs).

It was once thought that air renewed itself, through interactions with vegetation and the oceans, at a sufficient rate to make up for the influx of anthropogenic pollutants. Today, however, this kind of thinking is being challenged by evidence that clearly indicates that increased use of fossil fuels, expanding industrial production, and the growing use of motor vehicles are having a detrimental effect on air and the environment. This section discusses air pollution mechanics (pollutant dispersal, transformation, deposition mechanisms) and examines the types and sources of air pollutants related to these concerns.

ATMOSPHERIC DISPERSION, TRANSPORTATION, AND DEPOSITION*

A source of air pollution is any activity that causes pollutants to be emitted into the air. There have always been natural sources of air pollution, also known as *biogenic sources*; for example, volcanoes have spewed particulate matter and gases into our atmosphere for millions of years. Lightning strikes have caused forest fires, with their resulting contribution of gases and particles, for as long as storms and forests have existed. Organic matter in swamps decays and wind storms whip up dust. Trees and other vegetation contribute large amounts of pollen and spores to our atmosphere. These natural pollutants can be problematic at times but generally are not as much of a problem as

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* This section is adapted from USEPA, *Basic Air Pollution Meteorology*, U.S. Environmental Protection Agency, Washington, DC, 2005 (www.epa.gov/apti).

human-generated pollutants, or anthropogenic sources. The quality of daily life depends on many modern conveniences. People enjoy the freedom to drive cars and travel in airplanes for business and pleasure. They expect their homes to have electricity and their water to be heated for bathing and cooking. They use a variety of products such as clothing, pharmaceuticals, and furniture made of synthetic materials. At times, they rely on services that use chemical solvents, such as the local dry cleaner and print shop. Yet, the availability of these everyday conveniences comes at a price, because they all contribute to air pollution. Air pollutants are released from both stationary and mobile sources. Scientists have gathered much information on the sources, quantity, and toxicity levels of these pollutants. The measurement of air pollution is an important scientific skill, and such practitioners are usually well grounded in the relevant sciences, particularly with respect to modeling and analyses of air pollutants in the ambient atmosphere. To get at the very heart of air pollution, however, the practitioner must also be well versed in how to determine the origin of the pollutants and must understand the mechanics of pollutant dispersal, transport, and deposition. Air pollution practitioners must constantly deal with one basic fact: Air pollutants rarely stay at their release location; instead, wind flow conditions and turbulence, local topographic features, and other physical conditions work to disperse these pollutants. So, along with having a thorough knowledge and understanding of the pollutants in question, the air pollution practitioner has a definite need for detailed knowledge of the atmospheric processes that govern their subsequent dispersal and fate.

Conversion of precursor substances to secondary pollutants such as ozone is an example of chemical transformation in the atmosphere. Transformations, both physical and chemical, affect the ultimate impact of emitted air pollutants. Pollutants emitted to the atmosphere do not remain there forever. Two common deposition (depletion) mechanisms are *dry deposition*, the removal of particles and gases as they come into contact with the surface of the Earth, and *washout*, the uptake of particles and gases by water droplets and snow and their removal from the atmosphere as precipitation that falls to the ground. Acid rain is a form of pollution depletion from the atmosphere. The following sections discuss atmospheric dispersion of air pollutants in greater detail and the main factors associated with this phenomenon, including weather, turbulence, air parcels, buoyancy factors, lapse rates, mixing, topography, inversions, plume behavior, and transport.

Weather

The air contained in Earth's atmosphere is not still. Constantly in motion, air masses warmed by solar radiation rise at the equator and spread toward the colder poles, where they sink and flow downward, eventually returning to the equator. Near the surface of the Earth, as a result of the Earth's rotation, major wind patterns develop. During the day the land warms more quickly than the sea does; at night, the land cools more quickly. Local wind patterns are driven by this differential warming and cooling. Normally, breezes carry cooler, denser air from over land masses out over the water at night. Precipitation is also affected by wind patterns. Warm, moisture-laden air rising from the oceans is carried inland, where the air masses eventually cool, causing the moisture to fall as rain, hail, sleet, or snow. Even though pollutant emissions may remain relatively constant, air quality varies tremendously from day to day. The determining factors have to do with weather.

Weather conditions have a significant impact on air quality and air pollution, both favorable and unfavorable. On hot, sun-filled days, when the weather is calm with stagnating high-pressure cells, air quality suffers because of the buildup of pollutants at ground level. When local weather conditions include cool, windy, stormy weather with turbulent low-pressure cells and cold fronts, these conditions allow the upward mixing and dispersal of air pollutants.

Weather has a direct impact on pollution levels in both mechanical and chemical ways. Mechanically, precipitation works to cleanse the air of pollutants (transferring the pollutants to rivers, streams, lakes, or the soil). Winds transport pollutants from one place to another. Winds and storms often dilute pollutants with cleaner air, making pollution levels less annoying in the area of their release. In a low-pressure cell, air and its accompanying pollution are carried aloft when the air is heated by the sun. When wind accompanies this rising air mass, the pollutants are diluted with fresh air. In a high-pressure cell, the opposite occurs—air and the pollutants it carries sink toward the ground. With no wind, these pollutants are trapped and concentrated near the ground, where serious air pollution episodes may occur.

Chemically, weather can also affect pollution levels. Winds and turbulence mix pollutants together in a sort of giant chemical broth in the atmosphere. Energy from the sun, moisture in the clouds, and the proximity of highly reactive chemicals may cause chemical reactions, which lead to the formation of secondary pollutants. Many of these secondary pollutants may be more dangerous than the original pollutants.

Turbulence

In the atmosphere, the degree of turbulence (which results from wind speed and convective conditions related to the change of temperature with height above the surface of the Earth) is directly related to stability (a function of vertical distribution of atmospheric temperature). The stability of the atmosphere refers to the susceptibility of rising air parcels to vertical motion (attributed to high- and low-pressure systems, air lifting over terrain or fronts, and convection). Consideration of atmospheric stability or instability is essential in establishing the dispersion rate of pollutants. When specifically discussing the stability of the atmosphere, we are referring to the lower boundary where air pollutants are emitted.

The degree of turbulence in the atmosphere is usually classified by stability class: *stable*, *unstable*, and *neutral*. A stable atmosphere is marked by air cooler at the ground than aloft, by low wind speeds, and consequently by a low degree of turbulence. A plume of pollutants released into a stable lower layer of the atmosphere can remain relatively intact for long distances; thus, we can say that stable air discourages the dispersion and dilution of pollutants. An unstable atmosphere is marked by a high degree of turbulence. A plume of pollutants released into an unstable atmosphere may exhibit a characteristic looping appearance produced by turbulent eddies. A neutrally stable atmosphere is an intermediate class between stable and unstable conditions. A plume of pollutants released into a neutral stability condition is often characterized by a coning appearance as the edges of the plume spread out in a V-shape.

The importance of the state of the atmosphere and the effects of stability cannot be overstated. The ease with which pollutants can disperse vertically into the atmosphere is mainly determined by the rate of change of air temperature with height (altitude); therefore, air stability is a primary factor in determining where pollutants will travel and how long they will remain aloft. Stable air discourages the dispersion and dilution of pollutants; conversely, in unstable air conditions, rapid vertical mixing takes place, encouraging pollutant dispersal, which increases air quality.

Air Parcels

Think of air inside a balloon as an analogy for the air parcel. This theoretically infinitesimal parcel is a relatively well-defined body of air (a constant number of molecules) that acts as a whole. Self-contained, it does not readily mix with the surrounding air. The exchange of heat between the parcel and its surroundings is minimal, and the temperature within the parcel is generally uniform.

Buoyancy Factors

Atmospheric temperature and pressure influence the buoyancy of air parcels. Holding other conditions constant, the temperature of air increases as atmospheric pressure increases and conversely decreases as pressure decreases. Where air pressure decreases with rising altitude, the normal temperature profile of the troposphere is one where temperature decreases with height. An air parcel that becomes warmer than the surrounding air (due to heat radiating from the surface of the Earth, for example) begins to expand and cool. As long as the temperature of the parcel is greater than the surrounding air, the parcel is less dense than the cooler surrounding air; therefore, it rises or is buoyant. As the parcel rises, it expands, thereby decreasing its pressure; therefore, its temperature decreases as well. The initial cooling of an air parcel has the opposite effect. In summary, warm air rises and cools, and cool air descends and warms. The extent to which an air parcel rises or falls depends on the relationship of its temperature to that of the surrounding air. As long as the temperature of the parcel is cooler, it will descend. When the temperatures of the parcel and the surrounding air are the same, the parcel will neither rise nor descend unless influenced by wind flow.

Lapse Rate

The lapse rate is defined as the rate of temperature change with height. With an increase in altitude in the troposphere, the temperature of the ambient air usually decreases. Temperature decreases an average of 6 to 7°C/km. This is the normal lapse rate, but it varies widely depending on location and time of day. We define a temperature decrease with height as a *negative lapse rate* and a temperature increase with height as a *positive lapse rate*.

In a dry environment, when a parcel of warm dry air is lifted in the atmosphere, it undergoes adiabatic expansion and cooling. For the most part, a parcel of air does not exchange heat across its boundaries; therefore, an air parcel that is warmer than the surrounding air does not transfer heat to the atmosphere. Any temperature changes that occur within the parcel are caused by increases or decreases in molecular activity within the parcel. Such changes occur adiabatically and are due only to the change in atmospheric pressure as a parcel moves vertically. The term *adiabatic* means "impassable from," corresponding in this instance to an absence of heat transfer. In other words, an adiabatic process is one in which there is no transfer of heat or mass across the boundaries of the air parcel. In an adiabatic process, compression results in heating and expansion results in cooling. A dry air parcel rising in the atmosphere cools at the dry adiabatic rate of 9.8°C/1000 m and has a lapse rate of –9.8°C/1000 m. Likewise, a dry air parcel sinking in the atmosphere heats up at the dry adiabatic rate of 9.8°C/1000 m and has a lapse rate of 9.8°C/1000 m. Air is considered dry, in this context, as long as any water in it remains in a gaseous state.

The *dry adiabatic lapse rate* is a fixed rate, entirely independent of ambient air temperature. A parcel of dry air moving upward in the atmosphere, then, will always cool at the rate of 9.8°C/1000 m, regardless of its initial temperature or the temperature of the surrounding air. When the ambient lapse rate exceeds the adiabatic lapse rate, the ambient rate is said to be *superadiabatic*, and the atmosphere is highly unstable. When the two lapse rates are exactly equal, the atmosphere is said to be *neutral*. When the ambient lapse rate is less than the dry adiabatic lapse rate, the ambient lapse rate is termed *subadiabatic*, and the atmosphere is stable.

The cooling process within a rising parcel of air is assumed to be adiabatic (occurring without the addition or loss of heat). A rising parcel of air (under adiabatic conditions) behaves like a rising balloon, with the air in that distinct parcel expanding as it encounters air of lesser density until its own density is equal to that of the atmosphere that surrounds it. This process is assumed to occur with no heat exchange between the rising parcel and the ambient air (Peavy et al., 1985).

A rising parcel of dry air containing water vapor will continue to cool at the dry adiabatic lapse rate until it reaches its condensations temperature, or dew point. At this point, the pressure of the water vapor equals the saturation vapor pressure of the air, and some of the water vapor begins to condense. Condensation releases latent heat in the parcel, and thus the cooling rate of the parcel slows. This new rate is called the *wet adiabatic lapse rate*. Unlike the dry adiabatic lapse rate, the wet adiabatic lapse rate is not constant but depends on temperature and pressure. In the middle troposphere, however, it is assumed to be approximately –6 to –7°C/1000 m.

Mixing

Within the atmosphere, for effective pollutant dispersal to occur, turbulent mixing is important. Turbulent mixing, the result of the movement of air in the vertical dimension, is enhanced by vertical temperature differences. The steeper the temperature gradient and the larger the vertical air column in which the mixing takes place, the more vigorous the convective and turbulent mixing of the atmosphere.

Topography

On a local scale, topography may affect air motion. In the United States, most large urban centers are located along sea and lake coastal areas. Contained within these large urban centers is much heavy industry. Local air-flow patterns in these urban centers have a significant impact on pollution dispersion processes. Topographic features also affect local weather patterns, especially in large urban centers located near lakes, seas, and open land. Breezes from these features affect vertical mixing and pollutant dispersal. Seasonal differences in heating and cooling land and water surfaces may also precipitate the formation of inversions near the sea or lake shore.

River valley areas are also geographical locations that routinely suffer from industry-related pollution. Many early settlements began in river valleys because of the readily available water supply and the ease of transportation afforded to settlers by river systems within such valleys. Along with settlers came industry—the type of industry that invariably produces air pollutants. These air pollutants, because of the terrain and physical configuration of the valley, are not easily removed from the valley. Winds that move through a typical river valley are called *slope winds*. Slope winds, like water, flow downhill into the valley floor. At the valley floor, slope winds transform to *valley winds*, which flow down-valley with the flow of the river. These winds are lighter than slope winds, and the valley floor becomes flooded with a large volume of air which intensifies the surface inversion that is normally produced by radiative cooling. As the inversion deepens over the course of the night, it often reaches its maximum depth just before sunrise with the height of the inversion layer dependent on the depth of the valley and the intensity of the radiative cooling process. Hills and mountains can also affect local air flow. These natural topographical features tend to decrease wind speed (because of their surface roughness) and form physical barriers that prevent air movement.

Inversions

An inversion occurs when air temperature increases with altitude. Temperature inversions (extreme cases of atmospheric stability) create a virtual lid on the upward movement of atmospheric pollution. This situation occurs frequently but is generally confined to a relatively shallow layer. Plumes emitted into air layers that are experiencing an inversion (inverted layer) do not disperse very much as they are transported with the wind. Plumes that are emitted above or below an inverted layer do not penetrate that layer; rather, these plumes are trapped either above or below that inverted layer. High concentrations of air pollutants are often associated with inversions, as they inhibit plume dispersions. Two types of inversions are important from an air quality standpoint: radiation and subsidence inversions.

Radiation inversions are the most common form of surface inversion and occur when the surface of the Earth cools rapidly. They prompt the formation of fog and simultaneously trap gases and particulates, creating a concentration of pollutants. They are characteristically a nocturnal phenomenon caused by cooling of the surface of the Earth. On a cloudy night, the Earth's radiant heat tends to be absorbed by water vapor in the atmosphere. Some of this is radiated back to the surface. On clear winter nights, however, the surface more readily radiates energy to the atmosphere and beyond, allowing the ground to cool more rapidly. The air in contact with the cooler ground also cools, and the air just above the ground becomes cooler than the air above it, creating an inversion close to the ground, lasting for only a matter of hours. These radiation inversions usually begin to form at the worst time of day in large urban areas—during the late afternoon rush hour, trapping automobile exhaust at ground level and causing elevated concentrations of pollution for commuters. During evening hours, photochemical reactions cannot take place, so the biggest problem can be the accumulation of carbon monoxide. At sunrise, the sun warms the ground and the inversion begins to break up. Pollutants that have been trapped in the stable air mass are suddenly brought back to Earth in a process known as *fumigation*, which can cause a short-lived, high concentration of pollution at ground level (Masters, 2007).

The second type of inversion is the *subsidence inversion*, usually associated with anticyclones (high-pressure systems); they may significantly affect the dispersion of pollutants over large regions. A subsidence inversion is caused by the characteristic sinking motion of air in a high-pressure cell. Air in the middle of a high-pressure zone descends slowly. As the air descends, it is compressed and heated. It forms a blanket of warm air over the cooler air below, thus creating an inversion (located anywhere from several hundred meters above the surface to several thousand meters) that prevents further vertical movement of air.

Plume Behavior

One way to quickly determine the stability of the lower atmosphere is to view the shape of a smoke trail, or *plume*, from a tall stack located on flat terrain. Visible plumes usually consist of pollutants emitted from a smoke stack into the atmosphere. The formation and fate of the plume itself depend on a number of related factors: (1) the nature of the pollutants, (2) meteorological factors (combination of vertical air movement and horizontal air flow), (3) source obstructions, and (4) local topography, especially downwind. Overall, maximum ground-level concentrations will occur in a range from the vicinity of the smokestack to some distance downwind. Air quality problems associated with dispersion of city plumes are compounded by the presence of an already contaminated environment. Even though conventional processes normally work to disperse emissions from point sources, they do occur within the city plume. Because of microclimates within the city and the volume of pollutants that must be handled, conventional processes often cannot disperse the pollutants effectively. Other compounding conditions present in areas where city plumes are generated—topographical barriers, surface inversions, and stagnating anticyclones—work to intensify the city plume and result in high pollutant concentrations.

Many researchers have studied plume rise over the years. The most common plume rise formulas are those developed by Gary A. Briggs, which have been extensively validated with stack plume observations (USEPA, 2005). A formula for buoyancy-dominated plumes is shown in Equation 7.26. Plume rise formulas can be used on plumes with temperatures greater than the ambient air temperature. The *Briggs' plume rise formula* is as follows:

$$\Delta h = \frac{1.6F^{1/3}x^{2/3}}{\bar{u}} \tag{7.26}$$

where

Δh = Plume rise (above stack).

F = Buoyancy flux.

x = Downwind distance from the stack/source.

$\bar{u}$ = Average wind speed.

$$\text{Buoyancy flux} = F = \frac{g}{\pi} V \left(\frac{T_s - T_a}{T_s} \right) \tag{7.27}$$

where

g = Acceleration due to gravity (9.8 m/s^2).

V = Volumetric flow rate of stack gas.

T_s = Temperature of stack gas.

T_a = Temperature of ambient air.

Transport

People living east of the Mississippi River would be surprised to find out that they are breathing air contaminated by pollutants from various sources many miles from their location. Most people view pollution as "out of sight, out of mind." As far as they are concerned, if they don't see it, it doesn't exist. Assume, for example, that a person on a farm heaps together a huge pile of assorted rubbish to be burned. The person preparing this huge bonfire is probably giving little thought to the long-range transport and consequences of any contaminants that might be generated from that bonfire. This person simply has trash, and an easy solution is to burn it. This pile of rubbish, though, is a mixture of discarded rubber tires, old compressed gas bottles, assorted plastic containers, paper, oils, grease, wood, and old paint cans. These are hazardous materials, not just household trash. When the pile of rubbish is set on fire, a huge plume of smoke forms and is carried away by a westerly wind. The firestarter looks downwind and notices that the smoke disappears just a few miles over the property line. The dilution processes and the enormity of the atmosphere work together to dissipate and move the smoke plume away, and the firestarter doesn't give it a second thought. Elevated levels of pollutants from many such fires, though, can occur hundreds to thousands of miles downwind from the combined point sources producing such plumes. The result is that people living many miles from such pollution generators end up breathing contaminated air, transported over some distance to their location. Transport or dispersion estimates are determined by using distribution equations and air quality models. These dispersion estimates are typically valid for the layer of the atmosphere closest to the ground where frequent changes occur in the temperature and distribution of the winds. These two variables have an enormous effect on how plumes are dispersed.

DISPERSION MODELS

Air quality dispersion models consist of a set of mathematical equations that interpret and predict pollutant concentration due to plume dispersal and impaction. They are essentially used to predict or describe the fate of airborne gases, particulate matter, and ground-level concentrations downwind of point sources. To determine the air quality impact on a particular area, the first consideration is normal background concentrations, those pollutant concentrations from natural sources and distant, unidentified manmade sources. Each particular geographical area has a signature, or background, level of contamination considered to be the annual mean background concentration level of certain pollutants. An area, for example, might normally have a particulate matter reading of 30 to 40 $\mu g/m^3$. If particulate matter readings are significantly higher than the background level, this suggests an additional source. To establish background contaminations for a particular source, air quality data related to that site and its vicinity must be collected and analyzed.

The USEPA recognized that, when calculating the atmospheric dispersion of air pollutants, it was important to maintain consistency among air quality analyses; thus, the USEPA published two guidebooks to assist in modeling for air quality analyses: *Guidelines on Air Quality Models (Revised)* (1986) and *Industrial Source Complex (ISC) Dispersion Models User's Guide* (1986). When performing dispersion calculations, particularly for health effect studies, the USEPA and other recognized experts in the field recommend following a four-step procedure (Holmes et al., 1993):

1. Estimate the rate, duration, and location of the release into the environment.
2. Select the best available model to perform the calculations.
3. Perform the calculations and generate downstream concentrations, including lines of constant concentration (isopleths) resulting from the source emissions.
4. Determine what effect, if any, the resulting discharge has on the environment, including humans, animals, vegetation, and materials of construction. These calculations often include estimates of the so-called *vulnerability zones*—that is, regions that may be adversely affected because of the emissions.

Before beginning any dispersion determination activity, the acceptable ground-level concentration of the waste pollutants must be determined. Local meteorological conduits and local topography must be considered, and having an accurate knowledge of the constituents of, for example, waste gas and its chemical and physical properties is paramount.

Air quality models provide a relatively inexpensive means of determining compliance and predicting the degree of emission reduction necessary to attain ambient air quality standards. Under the 1977 Clean Air Act amendments, the use of models is required for the evaluation of permit applications associated with permissible increments under the Prevention of Significant Deterioration (PSD) requirements, which require localities "to protect and enhance" air that is not contaminated (Godish, 1997). Several dispersion models have been developed. These models are mathematical descriptions (equations) of the meteorological transport and dispersion of air contaminants in a particular area that allow estimates of contaminant concentrations, either at ground level or elevated (Carson and Moses, 1969). User-friendly modeling programs are available now that produce quick, accurate results from the operator's pertinent data.

The four generic types of models are Gaussian, numerical, statistical, and physical. The *Gaussian* models use the Gaussian distribution equation and are widely used to estimate the impact of nonreactive pollutants. *Numerical* models are more appropriate than Gaussian models for area sources in urban locations that involve reactive pollutants, but numerical models require extremely detailed source and pollutant information and are not widely used. *Statistical* models are used when scientific information about the chemical and physical processes of a source are incomplete or vague so the use of either Gaussian or numerical models is impractical. Finally, *physical* models require fluid modeling studies or wind tunneling. This approach involves the construction of scaled models and observing fluid flow around these models; it is very complex and requires expert technical support. For large areas with complex terrain, stack downwash, complex flow conditions, or large buildings, this type of modeling may be the best choice.

The selection of an air quality model for a particular air quality analysis is dependent on the type of pollutants being emitted, the complexity of the source, and the type of topography surrounding the facility. Some pollutants are formed by the combination of precursor pollutants; for example, ground-level ozone is formed when volatile organic compounds (VOCs) and nitrogen oxides (NO_x) react in the presence of sunlight. Models to predict ground-level ozone concentrations would use the emission rate of VOCs and NO_x as inputs. Also, some pollutants readily react once emitted into the atmosphere. These reactions deplete the concentrations of these pollutants and may have to be accounted for in the model. Source complexity also plays a role in model selection. Some pollutants may be emitted from short stacks that are subject to aerodynamic downwash. If this is the case, a model must be used that is capable of accounting for this phenomenon. Again, topography plays a major role in the dispersal of plumes and their air pollutants and must be considered when selecting an air quality model. Elevated plumes may impact areas of high terrain. Elevated terrain heights may experience higher pollutant concentrations because they are closer to the plume centerline. A model that considers terrain heights should be used when elevated terrain exists. Probably the best atmospheric dispersion workbook for modeling published to date is that by Turner (1994); most of the air dispersion models used today are based on the Pasquill–Gifford model.

MAJOR AIR POLLUTANTS

The most common and widespread anthropogenic pollutants currently emitted are sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), volatile organic compounds (hydrocarbons), particulates, lead, and a variety of toxic chemicals. Table 7.16 lists important air pollutants and their sources. Recall that, in the United States, the USEPA regulates air quality under the Clean Air Act and amendments that charged the federal government to develop uniform National Ambient Air Quality Standards (NAAQS). These standards include primary standards (covering criteria pollutants) designed to protect health and secondary standards to protect public welfare. Primary standards were to be achieved by 1975 and secondary standards within "a reasonable period of time." In 1971, the USEPA promulgated NAAQS for six classes of air pollutants. Later, in 1978, an air quality standard was also promulgated for lead, and the photochemical oxidant standard was revised to an ozone (O_3) standard (i.e., the ozone permissible level was

TABLE 7.16
Pollutants and Their Sources

Pollutant	Source
Sulfur and nitrogen oxides	Fossil fuel combustion
Carbon monoxide	Primarily motor vehicles
Volatile organic compounds	Vehicles and industry
Ozone	Atmospheric reactions between nitrogen oxides and organic compounds

Source: USEPA, *Environmental Progress and Challenges: EPA's Update*, U.S. Environmental Protection Agency, Washington, DC, 1988.

increased). The particulate matter (PM) standard was revised and redesignated a PM_{10} standard in 1987. This revision reflected the need for a PM standard based on particle sizes (≤10 μm) with the potential for entering the respiratory tract and affecting human health.

Air pollutants were categorized into two groups: primary and secondary. Primary pollutants are emitted directly into the atmosphere, where they exert an adverse influence on human health or the environment. Of particular concern are primary pollutants emitted in large quantities: carbon dioxide, carbon monoxide, sulfur dioxide, nitrogen dioxide, hydrocarbons, and particulate matter. Once in the atmosphere, primary pollutants may react with other primary pollutants or atmospheric compounds such as water vapor to form secondary pollutants. Receiving a lot of press and attention is acid precipitation, which occurs when sulfur or nitrogen oxides react with water vapor in the atmosphere.

SULFUR DIOXIDE

Sulfur enters the atmosphere in the form of corrosive sulfur dioxide (SO_2) gas. Sulfur dioxide is a colorless gas possessing the sharp, pungent odor of burning rubber. On a global basis, natural sources and anthropogenic activities produce sulfur dioxide in roughly equivalent amounts. Natural sources include volcanoes, decaying organic matter, and sea spray, and anthropogenic sources include the combustion of sulfur-containing coal and petroleum products and the smelting of nonferrous ores. In industrial areas, much more sulfur dioxide comes from human activities than from natural sources (MacKenzie and El-Ashry, 1988). Sulfur-containing substances are often present in fossil fuels; SO_2 is a product of combustion that results from burning sulfur-containing materials. The largest single source (65%) of sulfur dioxide is the burning of fossil fuels to generate electricity; thus, near major industrialized areas, it is often encountered as an air pollutant.

In the air, sulfur dioxide converts to sulfur trioxide (SO_3) and sulfate particles (SO_4). Sulfate particles restrict visibility and, in the presence of water, form sulfuric acid (H_2SO_4), a highly corrosive substance that also lowers visibility. The global output of sulfur dioxide has increased sixfold since 1900 (McKenzie and El-Ashry, 1988). Most industrial nations, however, have lowered sulfur dioxide levels by 20 to 60% by shifting away from heavy industry and imposing stricter emission standards. Major sulfur dioxide reductions have come from burning coal with lower sulfur content and from using less coal to generate electricity.

Two major environmental problems have developed in highly industrialized regions of the world, where the atmospheric sulfur dioxide concentration has been relatively high: sulfurous smog and acid rain. Sulfurous smog is the haze that develops in the atmosphere when molecules of sulfuric acid accumulate, growing in size as droplets until they become sufficiently large to serve as light scatterers. The second problem, acid rain, is precipitation contaminated with dissolved acids such as sulfuric acid. Acid rain has posed a threat to the environment by causing certain lakes to become void of aquatic life.

NITROGEN OXIDES

There are seven oxides of nitrogen that are known to occur—NO, NO_2, NO_3, N_2O, N_2O_3, N_2O_4, and N_2O_5—but only two are important in the study of air pollution: nitric oxide (NO) and nitrogen dioxide (NO_2). Nitric oxide is produced by both natural and human actions. Soil bacteria are responsible for the production of most of the nitric oxide that is produced naturally and released to the atmosphere. Within the atmosphere, nitric oxide readily combines with oxygen to form nitrogen dioxide, and together those two oxides of nitrogen are usually referred to as NO_x (nitrogen oxides). NO_x is formed naturally by lightning and by decomposing organic matter. Approximately 50% of anthropogenic NO_x is emitted by motor vehicles, and about 30% comes from power plants, with the other 20% being produced by industrial processes.

Scientists distinguish between two types of NO_x—thermal and fuel—depending on its mode of formation. Thermal NO_x is created when nitrogen and oxygen in the combustion air, such as those within internal combustion engines, are heated to a high enough temperature (above 1000 K) to cause nitrogen (N_2) and oxygen (O_2) in the air to combine. Fuel NO_x results from the oxidation of nitrogen contained within a fuel such as coal. Both types of NO_x generate nitric oxide first, and then, when vented and cooled, a portion of nitric oxide is converted to nitrogen dioxide. Although both thermal NO_x and fuel NO_x can be significant contributors to the total NO_x emissions, fuel NO_x is usually the dominant source, with approximately 50% coming from power plants (stationary sources) and the other half being released by automobiles (mobile sources).

Nitrogen dioxide is more toxic than nitric oxide and is a much more serious air pollutant. Nitrogen dioxide, at high concentrations, is believed to contribute to heart, lung, liver, and kidney damage. In addition, because nitrogen dioxide occurs as a brownish haze (giving smog its reddish-brown color), it reduces visibility. When nitrogen dioxide combines with water vapor in the atmosphere, it forms nitric acid (HNO_3), a corrosive substance that, when precipitated out as acid rain, causes damage to plants and corrosion of metal surfaces. Levels of NO_x rose in several countries and then leveled off or declined during the 1970s. During this same period of time, levels of nitrogen oxide did not drop as dramatically as those of sulfur dioxide, primarily because a large part of total NO_x emissions comes from millions of motor vehicles, while most sulfur dioxide is released by a relatively small number of emission-controlled, coal-burning power plants.

CARBON MONOXIDE

Carbon monoxide is a colorless, odorless, tasteless gas formed when carbon in fuel is not burned completely; it is by far the most abundant of the primary pollutants, as Table 7.17 indicates. When inhaled, carbon monoxide gas restricts the blood's ability to absorb oxygen, causing angina, impaired vision, and poor coordination. Carbon monoxide has little direct effect on ecosystems but has an indirect environmental impact via contributing to the greenhouse effect and depletion of the Earth's protective ozone layer. The most important natural source of atmospheric carbon monoxide is the combination of oxygen with methane (CH_4), which is a product of the anaerobic decay of vegetation. (Anaerobic decay takes place in the absence of oxygen.) At the same time, however, carbon monoxide is removed from the atmosphere by the activities of certain soil microorganisms, so the net result is a harmless average concentration that is less than 0.12 to 15 ppm in the Northern Hemisphere. Because stationary source combustion facilities are under much tighter environmental control than are mobile sources, the principal source of carbon monoxide that is caused by human activities is motor vehicle exhaust, which contributes about 70% of all CO emissions in the United States.

VOLATILE ORGANIC COMPOUNDS

Volatile organic compounds (VOCs) (also listed under the general heading of hydrocarbons) encompass a wide variety of chemicals that contain exclusively hydrogen and carbon. Emissions of volatile hydrocarbons from human resources are primarily the result of incomplete combustion of fossil

TABLE 7.17
U.S. Emission Estimates, 1986

Source	Sulfur Oxide (teragram/yr)	Nitrogen Oxide (teragram/yr)	Volatile Organic Compounds (teragram/yr)	Carbon Monoxide (teragram/yr)	Lead (gigagram/yr)	Particulate Matter (teragram/yr)
Transportation	0.9	8.5	6.5	42.6	3.5	1.4
Stationary source fuel	17.2	10.0	2.3	7.2	0.5	1.8
Industrial processes	3.1	0.6	7.9	4.5	1.9	2.5
Solid waste disposal	0.0	0.1	0.6	1.7	2.7	0.3
Miscellaneous	0.0	0.1	2.2	5.0	0.0	0.8
Total	21.2	19.3	19.5	60.9	8.6	6.8

Source: USEPA, *National Air Pollutant Emission Estimates, 1940–1986*, U.S. Environmental Protection Agency, Washington, DC, 1988.

fuels. Fires and the decomposition of matter are the natural sources. Of the VOCs that occur naturally in the atmosphere, methane (CH_4) is present at the highest concentrations (approximately 1.5 ppm). Even at relatively high concentrations, methane does not interact chemically with other substances, and it causes no ill health effects. In the lower atmosphere, however, sunlight causes VOCs to combine with other gases, such as NO_2, oxygen, and CO, to form secondary pollutants, such as formaldehyde, ketones, ozone, peroxyacetyl nitrate (PAN), and other types of photochemical oxidants. These active chemicals can irritate the eyes, damage the respiratory system, and damage vegetation.

OZONE AND PHOTOCHEMICAL SMOG

By far the most damaging photochemical air pollutant is ozone. Each ozone molecule contains three atoms of oxygen and thus is written O_3. Other photochemical oxidants, such as peroxyacetyl nitrate (PAN), hydrogen peroxide (H_2O_2), and aldehydes, play minor roles. All of these are considered secondary pollutants because they are not emitted but instead are formed in the atmosphere by photochemical reactions involving sunlight and emitted gases, especially NO_x and hydrocarbons. Ozone is a bluish gas, about 1.6 times heavier than air, and relatively reactive as an oxidant. Ozone is present in a relatively large concentration in the stratosphere and is formed naturally by ultraviolet (UV) radiation. At ground level, ozone is a serious air pollutant; it has caused serious air pollution problems throughout the industrialized world, posing threats to human health and damaging foliage and building material. Ozone concentrations in industrialized countries of North America and Europe are up to three times higher than the level at which damage to crops and vegetation begins (MacKenzie and El-Ashry, 1988). Ozone harms vegetation by damaging plant tissues, inhibiting photosynthesis, and increasing susceptibility to disease, drought, and other air pollutants.

In the upper atmosphere, where "good" (vital) ozone is produced, ozone is being depleted by the increased anthropogenic emission of ozone-depleting chemicals on the ground. With this increase, concern has been raised over a potential upset of the dynamic equilibria among stratospheric ozone reactions, with a consequent reduction in ozone concentration. This is a serious situation because stratospheric ozone absorbs much of the incoming solar ultraviolet radiation. As a UV shield, ozone helps to protect organisms on the surface of the Earth from some of the harmful effects of this high-energy radiation. If not interrupted, UV radiation could cause serious damage due to disruption of genetic material, which could lead to increased rates of skin cancers and heritable problems.

In the mid-1980s, a serious problem with ozone depletion became apparent. A springtime decrease in the concentration of stratospheric ozone (ozone holes) was observed at high latitudes, most notably over Antarctica between September and November. Scientists strongly suspected that chlorine atoms or simple chlorine compounds may be playing a key role in this ozone depletion problem.

On rare occasions, it is possible for upper stratospheric ozone (good ozone) to enter the lower atmosphere (troposphere). Generally, this phenomenon only occurs during an event of great turbulence in the upper atmosphere. On rare incursions, atmospheric ozone reaches ground level for a short period of time. Most of the tropospheric ozone is formed and consumed by endogenous photochemical reactions, which are the result of the interaction of hydrocarbons, oxides of nitrogen, and sunlight, which produces a yellowish-brown haze commonly called *smog*.

Although the incursion of stratospheric ozone into the troposphere can cause smog formation, the actual formation of Los Angeles-type smog involves a complex group of photochemical interactions. These interactions are between anthropogenically emitted pollutants (NO and hydrocarbons) and secondarily produced chemicals (peroxyacetyl nitrate, aldehydes, NO_2, and ozone). The concentrations of these chemicals exhibit a pronounced diurnal pattern, depending on their rate of emission and on the intensity of solar radiation and atmospheric stability at different times of the day (Freedman, 1989).

TABLE 7.18
Tropospheric Ozone Budget, Northern Hemisphere (kg/ha/yr)

Transport from stratosphere	13–20
Photochemical production	48–78
Destruction at ground	18–35
Photochemical destruction	48–55

Source: Adapted from Hov, O., *Ambio*, 13, 73–79, 1984.

Historical records show that the presence of various air pollutants in the atmosphere of Los Angeles include NO (emitted as NO_x), which has a morning peak of concentration at 6:00 to 7:00 a.m., largely due to emissions from morning rush-hour vehicles. Hydrocarbons are emitted from both vehicles and refineries; they display a similar pattern to that of NO except that their peak concentration is slightly later. In bright sunlight the NO is photochemically oxidized to NO_2, resulting in a decrease in NO concentration and a peak of NO_2 at 7:00 to 9:00 a.m. Photochemical reactions involving NO_2 produce O atoms, which react with O_2 to form O_3. These result in a net decrease in NO_2 concentration and an increase in O_3 concentration, peaking between 12:00 and 3:00 p.m. Aldehydes, also formed photochemically, peak earlier than O_3. As the day proceeds, the various gases decrease in concentration as they are diluted by fresh air masses or are consumed by photochemical reactions. This cycle is typical of an area that experiences photochemical smog and is repeated daily (Urone, 1976).

A tropospheric ozone budget for the northern hemisphere in shown in Table 7.18. The considerable range of the estimates reflects uncertainty in the calculation of the ozone fluxes. On average, stratospheric incursions account for about 18% of the total ozone influx to the troposphere, while endogenous photochemical production accounts for the remaining 82%. About 31% of the tropospheric ozone is consumed by oxidative reactions in vegetated landscapes at ground level, while the other 69% is consumed by photochemical reactions in the atmosphere (Freedman, 1989).

CARBON DIOXIDE

Carbon-laden fuels, when burned, release carbon dioxide (CO_2) into the atmosphere. Much of this carbon dioxide is dissipated and then absorbed by ocean water, some is taken up by vegetation through photosynthesis, and some remains in the atmosphere. Today, the concentration of carbon dioxide in the atmosphere is approximately 350 ppm and is rising at a rate of approximately 20 ppm every decade. The increasing rate of combustion of coal and oil has been primarily responsible for this occurrence, which may eventually have an impact on global climate.

PARTICULATE MATTER

Atmospheric particulate matter is defined as any dispersed matter, solid or liquid, in which the individual aggregates are larger than single small molecules but smaller than about 500 µm. Particulate matter is extremely diverse and complex; thus, size and chemical composition, as well as atmospheric concentrations, are important characteristics (Masters, 2007). A number of terms are used to categorize particulates, depending on their size and phase (liquid or solid). These terms are listed and described in Table 7.19. Dust, spray, forest fires, and the burning of certain types of fuels are among the sources of particulates in the atmosphere. Even with the implementation of stringent emission controls, which have worked to reduce particulates in the atmosphere, the U.S. Office of Technology Assessment (Postel, 1987) estimated that particulates and sulfates in ambient air may cause the premature death of 50,000 Americans every year.

TABLE 7.19
Atmospheric Particulates

Term	Description
Aerosol	General term for particles suspended in air
Mist	Aerosol consisting of liquid droplets
Dust	Aerosol consisting of solid particles that are blown into the air or are produced from larger particles by grinding them down
Smoke	Aerosol consisting of solid particles or a mixture of solid and liquid particles produced by chemical reactions such as fires
Fume	Generally means the same as smoke but often applies specifically to aerosols produced by condensation of hot vapors, especially of metals
Plume	The geometrical shape or form of the smoke coming out of a stack or chimney
Fog	Aerosol consisting of water droplets
Haze	Any aerosol, other than fog, that obscures the view through the atmosphere
Smog	Popular term originating in England to describe a mixture of smoke and fog; implies photochemical pollution

LEAD

Lead is emitted to the atmosphere primarily from human sources, such as burning leaded gasoline, in the form of inorganic particulates. In high concentrations, lead can damage human health and the environment. Once lead enters an ecosystem, it remains there permanently. In humans and animals, lead can affect the neurological system and cause kidney disease. In plants, lead can inhibit respiration and photosynthesis as well as block the decomposition of microorganisms. Since the 1970s, stricter emission standards have caused a dramatic reduction in lead output.

AIR POLLUTION CONTROL TECHNOLOGY

The two primary motivations behind the utilization of industrial air pollution control technologies are

1. They must be used because of legal or regulatory requirements.
2. They are integral to the economical operation of an industrial process.

Although economists might point out that both of these motivations are really the same (that is, it is less expensive for an industrial user to operate with air pollution control than without), the distinction in application type is an important one. In general, air pollution control is used to describe applications driven by regulations and/or health considerations, whereas applications that deal with product recovery are considered process applications. Nevertheless, the technical issues, equipment design, operation, etc., will be similar if not identical. In fact, what differs between these uses is that the economics that affect the decision-making process will often vary to some degree (Heumann, 1997).

Air pollution control, as with other forms of pollution control, begins with regulation. Regulations (for example, to remediate, reduce, or eliminate a source of emissions) are generated because of community concerns. Regulations often evolve around three considerations (Buonicore and Davis, 1992):

1. Legal limitations imposed for the protection of public health and welfare
2. Social limitations imposed by the community in which the pollution source is or is to be located
3. Economic limitations imposed by marketplace constraints

The responsible party assigned to mitigate an air pollution problem must meet one important goal: ensuring that the design control methodology used will bring the source into full compliance with applicable regulations. Air emissions control design personnel must first understand the problems and then rely heavily on technology to correct the situation to meet regulation standards. Various air pollution control technologies are available for mitigating air pollution source problems. By careful problem analysis and application of the most effective method on a case-by-case basis, responsible persons and designers can ensure that facilities are in full compliance with regulations and that individual pollution sources are brought under control. This section discusses the various air pollution control technologies available to environmental engineers and air pollution control practitioners to mitigate air pollution source problems.

AIR POLLUTION CONTROL CHOICES

Assuming that design engineers have a complete knowledge of the contaminant and the source, have all available physical and chemical data on the effluent from the source, and are aware of the regulations of the control agencies involved, they must then decide which control methodology to employ. Because only a few control methods exist, the choice is limited. Control of atmospheric emissions from a process will generally consist of one of four methods depending on the process, types, fuels, availability of control equipment, etc. The four general control methods are (1) elimination of the process entirely or in part, (2) modifying the operation so it will achieve the desired level of emission, (3) installation of control equipment between the pollutant source and the receptor, and (4) relocation of the operation.

Tremendous costs are involved with eliminating or relocating an entire process, which makes either of these choices the choice of last resort. Eliminating a process is no easy undertaking, especially when the process to be eliminated is the process for which the facility exists, and relocation is not always an answer, either.

Modifying the operation so it will achieve the desired level of emission often looks favorable to those who have weighed the high costs associated with air pollution control systems. Modifying the process to eliminate as much of the pollution problem as possible at the source is generally the first approach to be examined. Often, the easiest way to modify a process for air pollution control is to change the fuel. If a power plant, for example, emits large quantities of sulfur dioxide and fly ash, then conversion to cleaner-burning natural gas is less expensive than installing the necessary control equipment to reduce the pollutant emissions to permitted values. Changing from one fuel to another, however, creates its own problems related to costs, availability, and competition. Today's fuel prices are high, and finding a low-sulfur fuel is not easy, especially as many industries own their own dedicated supplies (which are not available for use in other industries). With regulation compliance looming, everyone wants their share of any available low-cost, low-sulfur fuel, but with limited supplies available the law of supply and demand takes over and prices go up. Some industries employ other process modification techniques. These may include evaluation of alternative manufacturing and production techniques, substitution of raw materials, and improved process control methods (Buonicore and Davis, 1992).

When elimination of the process, entirely or in part, or when relocation of the operation or when modification of the operation is not possible, the only alternative control method left is installation of control equipment between the pollutant source and the receptor. (The purpose of installing pollution control equipment or a control system, obviously, is to remove the pollution from the polluted carrier gas.) To accomplish this, the polluted carrier gas must pass through a control device or system that collects or destroys the pollutant and releases the cleaned carrier gas to the atmosphere (Boubel et al., 1994). The following section focuses on such air pollution control equipment devices and systems.

TABLE 7.20
Factors in Selecting Air Pollution Control Equipment and Systems

1. Best available technology (BAT)
2. Reliability
3. Lifetime and salvage value
4. Power requirements
5. Collection efficiency
6. Capital costs, including operation and maintenance costs
7. Track record of equipment/system and manufacturer
8. Space requirements and weight
9. Power requirements
10. Availability of spare parts and manufacturers' representatives

AIR POLLUTION CONTROL EQUIPMENT AND SYSTEMS

Any selection decision for air pollution control equipment or systems must factor in several considerations. Costs are always worthy of careful consideration (e.g., substituting sodium hypochlorite for chlorine increases costs threefold). Air pollution equipment and systems, are, to no one's surprise, expensive. Selecting or designing equipment and systems to comply with applicable regulatory emission limitations is obviously essential. Assessing the operational and maintenance history (factoring in costs of energy, labor, and repair parts) of each type of equipment or system is important because emission control equipment must be operated continually, without interruption. Any interruption could make the plant subject to severe regulatory penalty—another costly element. Other important factors must also be considered (see Table 7.20).

In addition to the factors listed in Table 7.20, process considerations dealing with gas flow rate and velocity, pollutant concentration, allowable pressure drop, and the variability of gas and pollutant flow rates, including temperature, must all be considered. The type of pollutant is also an important factor that must be taken into consideration: gaseous or particulate. Certain pertinent questions must be asked and answered. If the pollutant, for example, is gaseous, how corrosive, inflammable, reactive, or toxic is it? After these factors have been evaluated, the focus shifts to the selection of the best air pollution control system—one that is affordable, practical, and permitted by regulatory requirements, depending on the type of pollutant to be removed. The following sections discuss two types of pollutants—dry particulates and gaseous pollutants—and the various air pollution control equipment and processes available for their removal.

Removal of Dry Particulate Matter

Constituting a major class of air pollutants, particulates come in a variety of shapes and sizes and as either liquid droplets or dry dust. They have a wide range of physical and chemical characteristics. Dry particulates are emitted from a variety of sources, including both combustion and non-combustion sources due to industry, mining, and construction activities; incinerators; and internal combustion engines. Dry particulates are also emitted from natural sources—volcanoes, forest fires, pollen, and windstorms. All particles and particulate matter exhibit certain important characteristics, which, along with process conditions, must be considered in any engineering strategy to separate and remove them from a stream of carrier gas. Particulate size range and distribution, particle shape, corrosiveness, agglomeration tendencies, abrasiveness, toxicity, reactivity, inflammability, and hygroscopic tendencies must all be examined in light of equipment limitations.

In an air pollution control system, the particulates are separated from the gas stream by the application of one or more forces in gravity settlers, centrifugal settlers, fabric filters, electrostatic precipitators, or wet scrubbers. The particles are then collected and removed from the system. When a flowing fluid (either liquid or gas) approaches a stationary object such as a metal plate, a fabric thread, or a large water droplet, the fluid flow will diverge around that object. Particles in the fluid (because of inertia) will not follow the stream flow exactly but instead will tend to continue in their original directions. If the particles have enough inertia and are located close enough to the stationary object, they will collide with the object and can be collected by it. This is an important phenomenon.

Particles are collected by impaction, interception, and diffusion. *Impaction* occurs when the center of mass of a particle that is diverging from the fluid strikes a stationary object. *Interception* occurs when the particle's center of mass closely misses the object, but, because of its finite size, the particle strikes the object. *Diffusion* occurs when small particulates happen to "diffuse" toward the object while passing near it. Particles that strike the object by any of these means are collected—if short-range forces (chemical, electrostatic, and so forth) are strong enough to hold them to the surface (Cooper and Alley, 1990).

Control technologies for particles focus on capturing the particles emitted by a pollution source. Several factors must be considered before choosing a particulate control device. Typically, particles are collected and channeled through a duct or stack. The characteristics of the particulate exhaust stream affect the choice of the control device. These characteristics include the range of particle sizes, the exhaust flow rate, the temperature, the moisture content, and various chemical properties such as explosiveness, acidity, alkalinity, and flammability.

The most commonly used control devices for controlling particulate emissions include gravity settlers, cyclones, electrostatic precipitators, wet (Venturi) scrubbers, and baghouse (fabric) filters. In many cases, more than one of these devices is used in series to obtain the desired removal efficiencies. For example, a settling chamber can be used to remove larger particles before a pollutant stream enters an electrostatic precipitator. The following text briefly introduces each of the major types of particulate control equipment and points out their advantages and disadvantages.

Gravity Settlers

Gravity settlers (or settling chambers) have long been used by industry for removing solid and liquid waste materials from gaseous streams. Of simple construction, a gravity settler is actually nothing more than an enlarged chamber in which the horizontal gas velocity is reduced, allowing large particles to settle out of the gas by gravity and be recollected in hoppers. Gravity settlers have the advantage of having low initial costs and are relatively inexpensive to operate—there is not a lot that can go wrong. However, because settling chambers are effective in removing only larger particles, they have a relatively low efficiency, especially for removal of small particles (<50 μm). Thus, gravity settlers are used in conjunction with a more efficient control device. In addition, although simple in design, gravity settlers require a large space for installation.

Cyclone Collectors

The cyclone (or centrifugal) collector provides a low-cost, low-maintenance method of removing larger particulates from a gas stream. The cyclone removes particles by inertia separation, causing the entire gas stream to flow in a spiral pattern inside a tube; it is the collector of choice for removing particles greater than 10 μm in diameter. Centrifugal force causes the larger particles to move outward and collide with the narrowing wall of the tube. The particles slide down the wall and fall to the bottom of the cone, where they are removed. The cleaned gas flows out the top of the cyclone. Along with their relatively low construction costs, cyclones have relatively small space requirements for installation. Cyclones are efficient at removing large particles but are not as efficient with smaller particles, especially particles below 10 μm in size—and they do not handle sticky materials well. For this reason, they are used with other particulate control devices. The most serious problems encountered with cyclones are with air flow equalization and their tendency to plug. Cyclones have been used successfully at feed and grain mills, cement plants, fertilizer plants, petroleum refineries, and other applications involving large quantities of gas containing relatively large particles.

Electrostatic Precipitators

An electrostatic precipitator (ESP) is a particle control device that uses electrical forces to move the particles out of the flowing gas stream and onto collector plates. ESPs are usually used to remove small particles from moving gas streams at high collection efficiencies. Widely used in power plants for removing fly ash from the gases prior to discharge, an electrostatic precipitator applies electrical force to separate particles from the gas stream. A high voltage drop is established between electrodes, and particles passing through the resulting electrical field acquire a charge. The charged particles are attracted to and collected on an oppositely charged plate, and the cleaned gas glows through the device. Periodically, the plates are cleaned by rapping them to shake off the layer of dust that accumulates, and the dust is collected in hoppers at the bottom of the device. Although electrostatic precipitators have the advantages of low operating costs, being suitable for operation in high-temperature applications (to 1300°F), low pressure drop, and extremely high particulate (coarse and fine) collection efficiencies, they have the disadvantages of high capital costs and space requirements. The removal efficiencies for ESPs are highly variable; however, for very small particles alone the removal efficiency is about 99%. Typical ESP applications include use in industrial and utility boilers, cement plants, steel mills, petroleum refineries, municipal waste incinerators, hazardous waste incinerators, Kraft pulp and paper mills, and lead, zinc, and copper smelters.

Wet (Venturi) Scrubbers

Wet scrubbers (or collectors) have found widespread use in cleaning contaminated gas streams (e.g., foundry dust emissions, acid mists, furnace fumes) because of their ability to effectively remove particulate and gaseous pollutants. Wet scrubbers vary in complexity from simple spray chambers to remove coarse particles to high-efficiency (Venturi-type) systems to remove fine particles. Whichever system is used, operation employs the same basic principles of inertial impingement or impaction and interception of dust particles by droplets of water. The larger, heavier water droplets are easily separated from the gas by gravity. The solid particles can then be independently separated from the water, or the water can be otherwise treated before reuse or discharge. Increasing either the gas velocity or the liquid droplet velocity in a scrubber increases the efficiency because of the greater number of collisions per unit time. For the ultimate in wet scrubbing, where high collection efficiency is desired, the Venturi scrubber is used. The Venturi operates at extremely high gas and liquid velocities with a very high pressure drop across the Venturi throat. The reduced velocity at the expanded section of the throat allows the droplets of water containing the particles to drop out of the gas stream. Venturi scrubbers are most efficient at removing particulate matter in the size range of 0.5 to 5 μm, with removal efficiencies of up to 99%, which makes them especially effective for the removal of submicron particulates associated with smoke and fumes.

Wet scrubbers have relatively small space requirements, can remove both gases and particles, can neutralize corrosive gases, have low capital costs, and can handle high-temperature, high-humidity gas streams, but their power and maintenance costs are relatively high, they may create wastewater disposal problems, their corrosion problems are more severe than dry systems, and the final product they produce is collected wet. Table 7.21 summarizes theses advantages and disadvantages. Wet scrubbers have been used in a variety of industries such as acid plants, fertilizer plants, steel mills, asphalt plants, and large power plants.

TABLE 7.21
Advantages and Disadvantages of Wet Scrubbers

Advantages	Disadvantages
Small space requirements	Corrosion problems
No secondary dust sources	High power requirements
Handles high-temperature, high-humidity gas streams	Water-disposal problems
Minimal fire and explosion hazards	Difficult product recovery
Ability to collect both gases and particles	Meteorological problems (plume = fog)

Source: USEPA, *Air Pollution Control Orientation Course*, U.S. Environmental Protection Agency, Washington, DC, 2006.

Baghouse (Fabric) Filters

Baghouse filters (or fabric filters) are the most commonly used air pollution control filtration system. In much the same manner as the common vacuum cleaner, fabric filter material capable of removing most particles as small as 0.5 μm and substantial quantities of particles as small as 0.1 μm is formed into cylindrical or envelope bags and suspended in the baghouse. The particulate-laden gas stream is forced through the porous fabric filter, and as the air passes through the fabric particulates accumulate on the cloth, providing a clean air stream. As particulates build up on the inside surfaces of the bags, the pressure drop increases. Before the pressure drop becomes too severe, the bags must be relieved of some of the particulate layer. The particulates are periodically removed from the cloth by shaking or by reversing the air flow. The selection of the fiber material and fabric construction is important to baghouse performance. The fiber material from which the fabric is made must have adequate strength characteristics at the maximum gas temperature expected and adequate chemical compatibility with both the gas and the collected dust. One disadvantage of the fabric filter is that high-temperature gases often have to be cooled before contacting the filter medium. Fabric filters are used in the power generation, incineration, chemical, steel, cement, food, pharmaceutical, metal working, aggregate, and carbon black industries. Fabric filters are relatively simple to operate, provide high overall collection efficiencies up to over 99%, and are very effective in controlling submicrometer particles, but they do have limitations. These include relatively high capital costs, high maintenance requirements (e.g., bag replacement), high space requirements, and flammability hazards for some dusts.

REMOVAL OF GASEOUS POLLUTANTS: STATIONARY SOURCES

In the removal of gaseous air pollutants, the principal gases of concern are the sulfur oxides (SO_x), carbon oxides (CO_x), nitrogen oxides (NO_x), organic and inorganic acid gases, and hydrocarbons (HC). The most common method for controlling gaseous pollutants is the addition of add-on control devices to recover or destroy a pollutant. Four major treatment processes (add-ons) are currently available for the control of these and other gaseous emissions: absorption, adsorption, condensation, and combustion (incineration). The decision as to which single or combined air pollution control technique to use for stationary sources is not always easy. Gaseous pollutants can be controlled by a wide variety of devices, and choosing the most cost-effective, most efficient units requires careful attention to the particular operation for which the control devices are intended. Specifically, the choice of control technology depends on the pollutants to be removed, the removal efficiency required, pollutant and gas stream characteristics, and specific characteristics of the site (USEPA, 2006). Absorption, adsorption, and condensation are all recovery techniques, whereas incineration involves the destruction of the pollutant. When making the difficult and often complex decision

TABLE 7.22
Comparison of Air Pollution Control Technologies

Treatment Technology	Concentration and Efficiency	Comments
Incineration	<100 ppmv; 90–95% efficient >100 ppmv; 95–99% efficient	Incomplete combustion may require additional controls.
Carbon adsorption	>200 ppmv; 90+% efficiency >1000 ppmv; 95+% efficiency	Recovered organics may require additional treatment, which can increase costs.
Absorption	<200 ppmv; 90–95% efficiency >200 ppmv; 95+% efficiency	Can blowdown stream be accommodated at the site?
Condensation	>2000 ppmv; 80+% efficiency	Must have low temperature or high pressure for efficiency.

Note: Typically, only incineration and absorption technologies can consistently achieve greater than 99% gaseous pollutant removal (Buonicore and Davis, 1992).

about which air pollution control technology to employ, it is helpful to follow guidelines based on experience and set forth by Buonicore and Davis (1992) in the prestigious engineering text *Air Pollution Engineering Manual*. Table 7.22 summarizes these.

Absorption

Absorption (or scrubbing), is a major chemical engineering unit operation that involves bringing contaminated effluent gas into contact with a liquid absorbent so that one or more constituents of the effluent gas are selectively dissolved into a relatively nonvolatile liquid. Absorption units are designed to transfer the pollutant from a gas phase to a liquid phase (water is the most commonly used absorbent liquid). The absorption unit accomplishes this by providing intimate contact between the gas and the liquid, thus allowing optimum diffusion of the gas into the solution. The actual removal of a pollutant from the gas stream takes place in three steps: (1) diffusion of the pollutant gas to the surface of the liquid, (2) transfer across the gas/liquid interface, and (3) diffusion of the dissolved gas away from the interface into the liquid (Davis and Cornwell, 1991). Absorption is commonly used to recover products or to purify gas streams that have high concentrations of organic compounds. Absorption equipment is designed to obtain as much mixing between the gas and liquid as possible.

Pollutant gases commonly controlled by absorption include sulfur dioxide, hydrogen sulfide, hydrogen chloride, chlorine, ammonia, and oxides of nitrogen. Absorbers are often referred to as scrubbers, and the types of absorption equipment vary. The principal types of gas absorption equipment include spray towers, packed columns, spray chambers, and Venturi scrubbers. The two most common absorbent units in use today are the plate and packed tower systems. Plate towers contain perforated horizontal plates or trays designed to provide large liquid–gas interfacial areas. The polluted air stream is usually introduced at one side of the bottom of the tower or column and rises up through the perforations in each plate; the rising gas prevents the liquid from draining through the openings rather than through a downpipe. During continuous operation, contact is maintained between air and liquid, allowing gaseous contaminants to be removed, with clean air emerging from the top of the tower.

The packed tower scrubbing system is by far the most commonly used one for the control of gaseous pollutants in industrial applications, where it typically demonstrates a removal efficiency of 90 to 95%. Usually configured in vertical fashion, the packed tower is literally packed with devices that have a large surface-to-volume ratio and a large void ratio offering minimum resistance to gas flow. In addition, packing should provide even distribution of both fluid phases, be sturdy enough to support them in the tower, and be low cost, available, and easily handled (Hesketh, 1991).

The flow through a packed tower is typically countercurrent, with gas entering at the bottom of the tower and liquid entering at the top. Liquid flows over the surface of the packing in a thin film, affording continuous contact with the gases. Though highly efficient for the removal of gaseous contaminants, packed towers may create wastewater disposal problems (converting an air pollution problem to a water pollution problem), become easily clogged when gases with high particulate loads are introduced, and have relatively high maintenance costs.

Adsorption

Adsorption is a mass transfer process that involves passing a stream of effluent gas through the surface of prepared porous solids (adsorbents). The surfaces of the porous solid substance attract and hold (bind) the gas (the adsorbate) by either physical or chemical adsorption. In physical adsorption (a readily reversible process), a gas molecule adheres to the surface of the solid because of an imbalance of electron distribution. In chemical adsorption (not readily reversible), when the gas molecule has adhered to the surface it reacts chemically with it.

Several materials possess adsorptive properties, including activated carbon, alumina, bone char, magnesia, silica gel, molecular sieves, and strontium sulfate, among others. The most important adsorbent for air pollution control is activated charcoal. Activated carbon is the universal standard for purification and removal of trace organic contaminants from liquid and vapor streams. The surface area of activated charcoal will preferentially adsorb hydrocarbon vapors and odorous organic compounds from an air stream.

In an adsorption system (in contrast to the absorption system, where the collected contaminant is continuously removed by flowing liquid), the collected contaminant remains in the adsorption bed. The most common adsorption system is the fixed-bed adsorber, which can be contained in either a vertical or a horizontal cylindrical shell. The adsorbent (usually activated carbon) is arranged in beds or trays in layers about 0.5 inch thick. In multiple-bed systems, one or more beds are adsorbing vapors while the other bed is being regenerated.

The efficiency of most adsorbers is near 100% at the beginning of the operation and remains high until a breakpoint or breakthrough occurs. When the adsorbent becomes saturated with adsorbate, contaminant begins to leak out of the bed, signaling that the adsorber should be renewed or regenerated. By regenerating the carbon bed, the same activated carbon particles can be used again and again. Although adsorption systems are high-efficiency devices that may allow recovery of product, have excellent control and response to process changes, and have the capability of being operated unattended, they also have some disadvantages, including the need for exotic, expensive extraction schemes if product recovery is required; relatively high capital costs; and gas stream prefiltering requirements (to remove any particulate capable of plugging the adsorbent bed).

Condensation

Condensation is a process by which volatile gases are removed from the contaminant stream and changed into a liquid; that is, it is a process that reduces a gas or vapor to a liquid. Condensers condense vapors to a liquid phase either by increasing system pressure without a change in temperature or by decreasing the system temperature to its saturation temperature without a pressure change. The common approach is to reduce the temperature of the gas stream, because increasing the pressure of a gas is very expensive. Condensation is affected by the composition of the contaminant gas stream. When different gases are present in the streams that condense under different conditions, condensation is hindered.

Condensers are widely used to recover valuable products in a waste stream. Condensers are simple, relatively inexpensive devices that normally use water or air to cool and condense a vapor stream. Condensers are typically used as pretreatment devices. They can be used ahead of adsorbers, absorbers, and incinerators to reduce the total gas volume to be treated by more expensive control equipment. Two basic types of condensation equipment are used for pollution control: surface and contact condensers. A surface condenser is normally a shell-and-tube heat exchanger. A surface condenser uses a cooling medium of air or water where the vapor to be condensed is separated from the cooling medium by a metal wall. Coolant flows through the tubes, while the vapor is passed over and condenses on the outside of the tubes and drains off to storage (USEPA, 2006).

In a contact condenser (which resembles a simple spray scrubber), the vapor is cooled by spraying liquid directly on the vapor stream. The cooled vapor condenses, and the water and condensate mixture are removed, treated, and disposed of. In general, contact condensers are less expensive, more flexible, and simpler than surface condensers, but surface condensers require much less water and produce many times less wastewater that must be treated than do contact condensers. Removal efficiencies of condensers typically range from 50% to more than 95%, depending on design and applications. Condensers are used in a wide range of industrial applications, including petroleum refining, petrochemical manufacturing, basic chemical manufacturing, dry cleaning, and degreasing.

Combustion (Incineration)

Even though combustion (incineration) is a major source of air pollution, it is also, if properly operated, a beneficial air pollution control system in which the objective is to convert certain air contaminants (usually carbon monoxide and hydrocarbons) to innocuous substances such as carbon dioxide and water (USEPA, 2006). Combustion is a chemical process defined as rapid, high-temperature, gas-phase oxidation. The combustion equipment used to control air pollution emissions is designed to push these oxidation reactions as close to complete combustion as possible, leaving a minimum of unburned residue. The operation of any combustion operation is governed by four variables: oxygen, temperature, turbulence, and time. For complete combustion to occur, oxygen must be available and put into contact with sufficient temperature (turbulence), and it must be held at this temperature for a sufficient time. These variables are not independent—changing one affects the entire process. Depending on the contaminant being oxidized, equipment used to control waste gases by combustion can be divided into three categories: direct-flame combustion (or flaring), thermal combustion (afterburners), or catalytic combustion. Choosing the proper device depends on many factors, including type of hazardous contaminants in the waste stream, concentration of combustibles in the stream, process flow rate, control requirements, and an economic evaluation.

Direct-Flame Combustion (Flaring)

Direct-flame combustion devices (flares) are the most commonly used air pollution control devices by which waste gases are burned directly, with or without the addition of a supplementary fuel. Common flares include steam-assisted, air-assisted, and pressure-head types. Studies conducted by the USEPA have shown that the destruction efficiency of a flare is about 98%. Flares are normally elevated from 100 to 400 feet to protect the surroundings from heat and flames. When steam is injected at the flare top, the steam provides sufficient turbulence to ensure complete combustion, which prevents the production of visible smoke or soot. Flares are also noisy, which can cause problems for adjacent neighborhoods, and some flares produce oxides of nitrogen, thus creating a new air pollutant.

Thermal Incinerators (Afterburners)

The thermal incinerator or afterburner is usually the unit of choice in cases where the concentration of combustible gaseous pollutants is too low to make flaring practical. Widely used in industry, the thermal combustion system typically operates at high temperatures. Within the thermal incinerator, the contaminant airstream passes around or through a burner and into a refractory-line residence chamber where oxidation occurs. Residence time is the amount of time the fuel mixture remains in the combustion chamber. Flue gas from a thermal incinerator (which is relatively clean) is at a high temperature and contains recoverable heat energy. Thermal incinerators can destroy gaseous pollutants at efficiencies of greater that 99% when operated correctly.

Catalytic Incinerators

Catalytic combustion operates by passing a preheated contaminant-laden gas stream through a catalyst bed, which is usually a thinly coated platinum mesh mat, ceramic honeycomb, or other configuration designed to increase surface area to promote the oxidization reaction at lower temperatures. The metal catalyst is used to initiate and promote combustion at much lower temperatures than those required for thermal combustion (metals in the platinum family are recognized for their ability to promote combustion at low temperature). Catalytic incineration may require 20 to 50 times less residence time than thermal incineration. Other advantages of catalytic incinerators compared to thermal incinerators include the following (Buonicore and Davis, 1992):

1. Catalytic incinerators have lower fuel requirements.
2. Catalytic incinerators have lower operating temperatures.
3. Catalytic incinerators have little or no insulation requirements.
4. Catalytic incinerators have reduced fire hazards.
5. Catalytic incinerators have reduced flashback problems.

Catalytic incinerators normally operate at 700 to 900°F. At this reduced temperature range, a saving in fuel usage and cost is realized; however, this may be offset by the cost of the catalytic incinerator itself. Destruction efficiencies greater than 95% are possible using a catalytic incinerator. Higher efficiencies are possible if larger catalyst volumes or higher temperatures are used.

A heat exchanger is an option for systems with heat transfer between two gas streams (i.e., recuperative heat exchange). The need for dilution air, combustion air, and/or flue gas treatment is based on site-specific conditions. Catalysts are subject to both physical and chemical deterioration, and their usefulness is suppressed by sulfur-containing compounds. For best performance, catalyst surfaces must be clean and active. Catalytic incineration is used in a variety of industries to treat effluent gases, including emissions from paint and enamel bake ovens, asphalt oxidation, coke ovens, formaldehyde manufacturing, and varnish cooking. Catalytic incinerators are best suited for emission streams with low VOC content.

INDOOR AIR QUALITY

The quality of the air we breathe and the attendant consequences for human health are influenced by a variety of factors. These include hazardous material discharges indoors and outdoors, meteorological and ventilation conditions, and pollutant decay and removal processes. Over 80% of our time is spent in indoor environments, so the influence of building structures, surfaces, and ventilation are important considerations when evaluating air pollution exposures (Wadden and Scheff, 1983). Those familiar with *Star Trek* will recognize this most quotable quote: “The air is the air.” However, with regard to the air we breathe, few of us realize that we all face a variety of risks to our health as we go about our day-to-day lives (USEPA, 2001). Driving our cars, flying in planes, engaging in recreational activities, and being exposed to environmental pollutants all pose varying degrees of risk. Some risks are simply unavoidable. Some we choose to accept because to do otherwise would restrict out ability to lead our lives the way we want. And some are risks we might decide to avoid if we had the opportunity to make informed choices. Indoor air pollution is one risk that we can do something about.

A growing body of scientific evidence indicates that the air within homes and other buildings can be more seriously polluted than the outdoor air in even the largest and most industrialized cities. Other research indicates that people spend approximately 90% of their time indoors. A type of climate we do not often think about is the indoor microclimate we spend 80% of our time in—at the office or at home (Wadden and Scheff, 1983). For many people, though, the risks to health due to exposure to air pollution may be greater indoors than outdoors (USEPA, 2001).

Not much attention was paid to indoor microclimates until two significant events occurred. The first was the outbreak of Legionnaires' disease and the second was recognition of sick building syndrome. Also, people who may be exposed to indoor air pollutants for the longest periods of time are often those most susceptible to the effects of indoor air pollution. Such groups include the young, the elderly, and the chronically ill, especially those suffering from respiratory or cardiovascular disease.

The impact of energy conservation on inside environments may be substantial, particularly with respect to decreases in ventilation rates (Hollowell et al., 1979a) and tight buildings constructed to minimize infiltration of outdoor air (Hollowell et al., 1979b; Woods, 1980). The purpose of constructing tight buildings is to save energy—to keep the heat or air conditioning inside the structure. The problem is that not only are indoor air contaminants within these tight structures trapped within but they can also be concentrated, exposing inhabitants to even more exposure.

These topics and others along with causal factors leading to indoor air pollution are covered in this section. What about indoor air quality (IAQ) problems in the workplace? This section also addresses this pervasive but often overlooked problem, covers the basics of indoor air quality as related to the workplace environment, and identifies the major contaminants that currently contribute to this problem. Moreover, mold and mold remediation, although not new to the workplace, are new buzzwords attracting much attention these days. Contaminants such as asbestos, silica, lead, and formaldehyde are also discussed, as are various related remediation practices.

LEGIONNAIRES' DISEASE

Since the infamous outbreak that occurred in Philadelphia in 1976 at the Belleview Stratford Hotel during a convention of American Legion members, with 182 reported cases and 29 deaths, the deadly bacterium *Legionella pneumophila* has become synonymous with the term Legionnaires' disease. The deaths were attributed to colonized bacteria in the air-conditioning system cooling tower. Let's take a look at this deadly killer, one that inhabits the microclimates otherwise known as offices, hotels, homes, and other indoor spaces. Organisms of the genus *Legionella* are ubiquitous in the environment and are found in natural fresh water, potable water, and closed-circuit systems such as evaporative condensers, humidifiers, recreational whirlpools, air-handling systems, and, of course, cooling towers.

The potential for the presence of *Legionella* bacteria is dependent on certain environmental factors: moisture, temperature (50 to 140°F), oxygen, and a source of nourishment such as slime or algae. Not all of the ways in which Legionnaires' disease can be spread are known to us at this time; however, we do know that it can be spread through the air. The Centers for Disease Control and Prevention (CDC, 2013) has stated that there is no evidence that Legionnaires' disease is spread person to person.

Air-conditioning cooling towers and evaporative condensers have been the source of most outbreaks to date, and the bacterium is commonly found in both. Unfortunately, we do not know if this is an important means of spreading Legionnaires' disease because other outbreaks have occurred in buildings that did not have air-conditioning. Not all people are at risk of contacting Legionnaires' disease. The people most at risk include persons

1. With lowered immunological capacity
2. Who smoke cigarettes and abuse alcohol
3. Who are exposed to high concentrations of *Legionella pneumophila*

Legionnaires' disease is most commonly recognized as a form of pneumonia. The symptoms of Legionnaires' disease usually become apparent 2 to 10 days after known or presumed exposure to airborne Legionnaires' disease bacteria. A sputum-free cough is common, but sputum production is sometimes associated with the disease. Within less than a day, the victim can experience rapidly rising fever and the onset of chills. Mental confusion, chest pain, abdominal pain, impaired kidney function, and diarrhea are associated manifestations of the disease. The CDC estimates that around 25,000 people develop Legionnaires' disease annually.

How can Legionnaires' disease be prevented or controlled? The controls currently being used are targeted toward cooling towers and air-handling units (condensate drain pans). Cooling tower procedures used to control bacterial growth vary somewhat in the various regions of a cooling tower system; however, control procedures usually include a good maintenance program requiring repair or replacement of damaged components, routine cleaning, and sterilization. For sterilization, a typical protocol calls for the use of chlorine in a residual solution at about 50 ppm combined with a detergent that is compatible to produce the desired sterilization effect. It is important to ensure that even those spaces that are somewhat inaccessible are properly cleaned of slime and algae accumulations. For air-handling units, control measures for condensate drain pans typically involve keeping the pans clean and checked for proper drainage of fluid. This is important to prevent stagnation and the build up of slime, algae, or bacteria. A cleaning and sterilization program is required any time algae or slime is found in the unit.

SICK BUILDING SYNDROME

The term *sick building syndrome* was coined in 1982 by an international working group under the authorization of the World Health Organization (WHO). The WHO working group studied the literature about indoor climate problems and found that microclimates in buildings can be characterized by the same set of frequently appearing complaints and symptoms. WHO came up with five categories of symptoms exemplified by some complaints reported by occupants apparently suffering from sick building syndrome (SBS):

- *Sensory irritation in eyes, nose, and throat*—Pain, sensation of dryness, smarting feeling, stinging, irritation, hoarseness, voice problems
- *Neurological or general health symptoms*—Headache, sluggishness, mental fatigue, reduced memory, reduced capability to concentrate, dizziness, intoxication, nausea and vomiting, tiredness
- *Skin irritation*—Pain, reddening, smarting or itching sensations, dry skin
- *Nonspecific hypersensitivity reactions*—Running nose and eyes, asthma-like symptoms among nonasthmatics, sounds from the respiratory system
- *Odor and taste symptoms*—Changed sensitivity of olfactory or gustatory sense, unpleasant olfactory or gustatory perceptions

In the past, similar symptoms had been used to define other syndromes known as building disease, building illness syndrome, building-related illness, or tight-fitting office syndrome. In many cases, these names appear to be synonyms for sick building syndrome; thus, WHO efforts to define SBS worked to combine these syndromes into one general definition or summary. A summary compiled by WHO (1982, 1984) and Molhave (1986) of this combined definition includes the five categories of symptoms listed above and the following observations:

- Irritation of mucous membranes in eye, nose, and throat is among the most frequent symptoms.
- Other symptoms (e.g., from lower airways or internal organs) should be infrequent.
- A large majority of occupants report symptoms.
- The symptoms appear especially frequently in one building or in part of it.
- No evident causality can be identified in relation to either exposures or occupant sensitivity.

The WHO group suggested the possibility that SBS symptoms have a common causality and mechanism (WHO, 1982); however, the existence of SBS is still not considered to be confirmed because the descriptions of the symptoms in the literature are anecdotal and unsystematic (Molhave, 1986).

INDOOR AIR POLLUTION

Recognition that the indoor air environment may be a health problem is a relatively recent occurrence. The most significant impacts of indoor air quality include cigarette smoking, stove and oven operation, and emanat ions from certain types of particleboard, cement, and other building materials (Wadden and Scheff, 1983). The significance of the indoor air quality problem became apparent not only because of the Legionnaires' disease outbreak in 1976 and the WHO study of 1982 but also because of another factor that came to the forefront in the mid-1970s: the need to conserve energy. In the early 1970s, when hundreds of thousands of people were standing in line to obtain gasoline for their automobiles, it was not difficult to drive home the need to conserve energy supplies.

The resulting impact of energy conservation on inside environments has been substantial. This is especially the case with regard to building modifications that were made to decrease ventilation rates and new construction practices that were incorporated to ensure tight buildings to minimize infiltration of outdoor air. There is some irony in this development, of course. Although there is a need for proper building design and construction and for effective ventilation guidelines to avoid the exposure of inhabitants to unhealthy environments, a tradeoff arises between energy economics and air quality.

Indoor air quality refers to the effect, good or bad, of the contents of the air inside a structure on its occupants (Byrd, 2003). Stated differently, indoor air quality, in this text, refers to the quality of the air inside workplaces as represented by the concentrations of pollutants and thermal conditions (temperature and relative humidity) that affect the health, comfort, and performance of employees. Usually, temperature (too hot or too cold), humidity (too dry or too damp), and air velocity (too drafty or too still) are considered comfort rather than indoor air quality issues. Unless they are extreme, these conditions may make someone uncomfortable but will not make a person ill. Other factors affecting employees, such as light and noise, are important indoor environmental quality considerations but are not treated as core elements of indoor air quality problems. Nevertheless, most industrial hygienists must take these factors into account when investigating environmental quality situations.

Good indoor air quality can be considered to be present when the air has no unwanted gases or particles in it at concentrations that will adversely affect someone. Poor indoor air quality can result when any gases or particles are at excessive concentrations so as to affect the satisfaction or health of the occupants (Byrd, 2003). In the workplace, poor indoor air quality may be annoying to only one person; however, at the other end of the spectrum, it could be fatal to all the occupants in the workplace. The concentration of the contaminant is crucial. Potentially infectious, toxic, allergenic, or irritating substances are always present in the air, but there is nearly always a threshold level below which no effect occurs.

COMMON INDOOR AIR POLLUTANTS IN THE HOME

This section takes a brief source-by-source look at the most common indoor air pollutants, their potential health effects, and ways to reduce their levels in the home.

Radon

Radon is a noble, nontoxic, colorless, odorless gas produced in the decay of radium-226 and is found everywhere at very low levels. Radon is ubiquitous in the soil and air near the surface of the Earth. As radon undergoes radioactive decay, it releases an alpha particle, gamma ray, and progeny that quickly decay to release alpha and beta particles and gamma rays. Because radon progeny are electrically charged, they readily attach to particles, producing a radioactive aerosol. It is when radon becomes trapped in buildings and concentrations build up in indoor air that exposure to radon becomes of concern. This is the case because aerosol radon-contaminated particles may be inhaled and deposited in the bifurcations of respiratory airways. Irradiation of tissue at these sites poses a significant risk of lung cancer (depending on exposure dose).

The most common way in which radon enters a house is through the soil or rock upon which the house is built. The most common source of indoor radon is uranium, which is common to many soils and rocks. As uranium breaks down, it releases soil or radon gas, and radon gas breaks down into radon decay products or progeny (commonly called *radon daughters*). Radon gas is transported into buildings by pressure-induced convective flows. Other sources of radon include well water and masonry materials. Radon levels in a house vary in response to temperature-dependent and wind-dependent pressure differentials and to changes in barometric pressures. When the base of a house is under significant negative pressure, radon transport is enhanced.

Studies indicate that as many as 10% of all American homes, or about 9 million homes, may have elevated levels of radon, and the percentage may be higher in geographic areas with certain soils and bedrock formations (USEPA, 1988a). Exposure to radon in the home can be reduced by taking the following steps (USEPA, 1988b, 2009):

- Measure levels of radon in the home.
- Obtain information from state radiation protection offices on the availability of detection devices or services.
- Refer to USEPA guidelines in deciding whether and how quickly to take action based on test results.
- Learn about control measures.
- Take precautions not to draw larger amounts of radon into the house.
- Select a qualified contractor to draw up and implement a radon mitigation plan.
- Stop smoking and discourage smoking in your home.
- Treat radon-contaminated well water by aerating or filtering through granulated activated charcoal.

Environmental Tobacco Smoke

The use of tobacco products by approximately 45 million smokers in the United States results in significant indoor contamination from combustion byproducts that expose millions of people who do not smoke but breathe contaminated indoor air. Side-stream smoke, which comes from the burning end of a cigarette, and smoke that is exhaled by the smoker contain a complex mixture of over 4700 compounds, including both gases and particles. Environmental tobacco smoke has been found to cause diseases such as lung cancer in both smokers and healthy nonsmokers. Environmental tobacco smoke may also increase the lung cancer risk associated with exposures to radon. To reduce exposure to environmental tobacco smoke in the home or office,

- Give up smoking and discourage smoking in your home and place of work or require smokers to smoke outdoors.
- Provide ventilation, which is a common way to reduce exposure to indoor air pollutants such as environmental tobacco smoke; ventilation works to reduce but not eliminate exposure.

Biological Contaminants

A variety of biological contaminants can cause significant illness and health risks. These include mold and mildew, viruses, animal dander and cat saliva, mites, cockroaches, pollen, and infections from airborne exposures to viruses that cause colds and influenza and bacteria that cause Legionnaires' disease and tuberculosis. To reduce exposure to biological contaminants in the home or office,

- Install and use exhaust fans that are vented to the outdoors in kitchens and bathrooms, and vent clothes dryers to the outdoors.
- Ventilate attics and crawl spaces to prevent moisture buildup.

- Keep water trays in cool-mist or ultrasonic humidifiers clean and filled with fresh distilled water daily.
- Thoroughly dry and clean water-damaged carpets and buildings materials within 24 hours.
- Maintain good housekeeping practices in both the home and office.

Combustion Byproducts

Combustion byproducts are released into indoor air from a variety of sources. These include unvented kerosene and gas space heaters, woodstoves, fireplaces, gas stoves, and hot-water heaters. The major pollutants released from these sources are carbon monoxide, nitrogen dioxide, and particles. To reduce exposure to combustion products in the home or office,

- Operate fuel-burning unvented space heaters with great care and take special safety precautions.
- Install and use exhaust fans over gas cooking stoves and ranges and keep the burners properly adjusted.
- Inspect furnaces, flues, and chimneys annually, and promptly make any needed repairs.
- Keep woodstove emissions to a minimum.

Household Products

A large variety of organic compounds are widely used in household products because of their useful characteristics, such as the ability to dissolve substances and evaporate quickly. Cleaning, disinfecting, cosmetic, degreasing, and hobby products all contain organic solvents, as do paints, varnishes, and waxes. All of these products can release organic compounds while being used and when they are stored. To reduce exposure to household organic compounds,

- Always follow label instructions carefully.
- Throw away partially full containers of chemicals safely.
- Limit the amount you buy.

Pesticides

Pesticides represent a special case of chemical contamination of buildings, where it has been estimated that 80 to 90% of most people's exposure in the air occurs. These products are extremely dangerous if not used properly. To reduce exposure to pesticides in the home,

- Read the label and follow directions.
- Use pesticides only in well-ventilated areas.
- Dispose of unwanted pesticides safely.

Asbestos in the Home

Asbestos became a major indoor air quality concern in the United States in the late 1970s. Asbestos is a mineral fiber commonly used in a variety of building materials and has been identified as having the potential, when friable, to cause cancer in humans. To reduce exposure to asbestos in the home or office,

- Do not cut, rip, or sand asbestos-containing materials.
- When you need to remove or clean up asbestos, use a professional, trained contractor.

BUILDING FACTORS AFFECTING INDOOR AIR QUALITY

Building factors affecting indoor air quality can be grouped into two factors:

- *Factors affecting indoor climate*—The thermal environment (temperature, relative humidity, and airflow) are important dimensions of indoor air quality for several reasons. First, many complaints of poor indoor air may be resolved by simply altering the temperature or relative humidity. Second, people that are thermally uncomfortable will have a lower tolerance to other building discomforts. Third, the rate at which chemicals are released from building materials is usually higher at higher building temperatures. Thus, if occupants are too warm, it is also likely that they are being exposed to higher pollutant levels.
- *Factors affecting indoor air pollution*—Much of the building fabric, its furnishings and equipment, its occupants, and the occupants' activities produce pollution. In a well-functioning building, some of these pollutants will be directly exhausted to the outdoors and some will be removed as outdoor air enters that building and replaces the air inside. The air outside may also contain contaminants that will be brought inside in this process. This air exchange is brought about by the mechanical introduction of outdoor air (outdoor air ventilation rate), the mechanical exhaust of indoor air, and the air exchanged through the building envelope (infiltration and exfiltration).

Pollutants inside can travel through the building as air flows from areas of higher atmospheric pressure to areas of lower atmospheric pressure. Some of these pathways are planned and deliberate so as to draw pollutants away from occupants, but problems arise when unintended flows draw contaminants into occupied areas. In addition, some contaminants may be removed from the air through natural processes, such as with the adsorption of chemicals by surfaces or the settling of particles onto surfaces. Removal processes may also be deliberately incorporated into the building systems. Air filtration devices, for example, are commonly incorporated into building ventilation systems. Thus, the factors most important to understanding indoor pollution are (1) indoor sources of pollution, (2) outdoor sources of pollution, (3) ventilation parameters, (4) airflow patterns and pressure relationships, and (5) air filtration systems.

TYPES OF WORKPLACE AIR POLLUTANTS

Common pollutants or pollutant classes of concern in commercial buildings along with common sources of these pollutants are provided in Table 7.23.

TABLE 7.23
Indoor Pollutants and Potential Sources

Pollutant or Pollutant Class	Potential Sources
Environmental tobacco smoke	Lighted cigarettes, cigars, pipes
Combustion contaminants	Furnaces, generators, gas or kerosene space heaters, tobacco products, outdoor air, vehicles
Biological contaminants	Wet or damp materials, cooling towers, humidifiers, cooling coils or drain pans, damp duct insulation or filters, condensation, re-entrained sanitary exhausts, bird droppings, cockroaches or rodents, dust mites on upholstered furniture or carpeting, body odors
Volatile organic compounds (VOCs)	Paints, stains, varnishes, solvents, pesticides, adhesives, wood preservatives, waxes, polishes, cleansers, lubricants, sealants, dyes, air fresheners, fuels, plastics, copy machines, printers, tobacco products, perfumes, drycleaned clothing
Formaldehyde	Particleboard, plywood, cabinetry, furniture, fabrics
Soil gases (radon, sewer gas, VOCs, methane)	Soil and rock (radon), sewer drain leak, dry drain traps, leaking underground storage tanks, landfill
Pesticides	Termiticides, insecticides, rodenticides, fungicides, disinfectants, herbicides

TABLE 7.24
Indoor Sources of Contaminants

Common Sources	Mitigation and Control
Housekeeping and Maintenance	
Cleansers	Use low-emitting products.
Waxes and polishes	Avoid aerosols and sprays.
Disinfectants	Dilute products to the proper strength.
Air fresheners	Use proper protocol when diluting and mixing.
Adhesives	Do not overuse; use during unoccupied hours.
Janitor/supply closets	Store products properly with containers closed and lids on tight.
Wet mops	Use exhaust ventilation for storage spaces (eliminate return air).
Drain cleaners	Clean mops; store mop top up to dry.
Vacuuming	Avoid the use of air fresheners; clean and exhaust instead.
Paints and coatings	Use high-efficiency vacuum bags and filters.
Solvents	Use integrated pest management.
Pesticides	
Lubricants	
Occupant-Related Sources	
Tobacco products	Enforce a smoking policy.
Office equipment	Use exhaust ventilation with pressure control for major local sources.
Cooking/microwave use	Use low-emitting art supplies and marking pens.
Art supplies	Avoid paper clutter.
Marking pens	Educate occupants and staff.
Paper products	
Personal products (e.g., perfume)	
Tracked-in dirt or pollen	
Building Uses as Major Sources	
Print/photocopy shop	Use exhaust ventilation and pressure control.
Drycleaning	Use exhaust hoods where appropriate; check hood air flows.
Science laboratory	
Medical office	
Hair or nail salon	
Cafeteria	

(Continued)

SOURCES OF WORKPLACE AIR POLLUTANTS

Air quality is affected by the presence of various types of contaminants in the air. Some are in the form of gases. These would be generally classified as toxic chemicals. The types of interest are combustion products (carbon monoxide, nitrogen dioxide), volatile organic compounds (e.g., formaldehyde, solvents, perfumes and fragrances), and semivolatile organic compounds (pesticides). Other pollutants are in the form of animal dander; soot; particles from buildings, furnishings, and occupants (e.g., fiberglass, gypsum powder, paper dust, lint from clothing, carpet fibers); and dirt (sandy and earthy material), among others. Specific sources for contaminants that result in adverse health effects in the workplace include the workers themselves, who can have contagious diseases or can carry allergens or other agents on their clothing; building compounds containing VOCs, particles, or fibers; contaminated building components that contain allergens, microbial agents, or pesticides; and outdoor air, which can carry microorganisms, allergens, and chemical air pollutants (Burge and Hoyer, 1998).

Table 7.24 identifies indoor sources of contaminants commonly found in the workplace and offers some measures for maintaining control of these contaminants. Table 7.25 identifies common sources of contaminants that are introduced from outside buildings. These contaminants frequently

TABLE 7.24 (Continued)
Indoor Sources of Contaminants

Common Sources	Mitigation and Control
Building-Related Sources	
Plywood/compressed wood	Use low-emitting sources.
Construction adhesives	Air out an open or ventilated area before installing.
Asbestos products	Increase ventilation rates during and after installing.
Insulation	Keep material dry prior to enclosing.
Wall/floor coverings (vinyl/plastic)	
Carpets and carpet adhesives	
Wet building products	
Transformers	
Upholstered furniture	
Renovation or remodeling	
HVAC Systems	
Contaminated filters	Perform HVAC preventive maintenance.
Contaminated duct linings	Change filter and clean drain pans; provide proper slope and drainage.
Dirty drain pans	Use potable water for humidification.
Humidifiers	Keep duct lining dry; move lining outside of duct if possible.
Lubricants	Fix leaks and clean spills.
Refrigerants	Maintain spotless mechanical rooms (they are not storage areas).
Mechanical room	Avoid backdrafting.
Maintenance activities	Check and maintain flues from boilers to the outside.
Combustion appliances (boilers, furnaces, stoves, generators)	Keep combustion appliances properly tuned.
	Do not allow the use of unvented combustion appliances.
	Perform polluting activities during unoccupied hours.
Moisture	
Mold	Keep building dry.
Vehicles	
Underground or attached garage	Use exhaust ventilation.
	Maintain garage under negative pressure relative to the building.
	Check air-flow patterns frequently.
	Monitor carbon monoxide levels.

find their way inside through the building shell, openings, or other pathways to the inside. When workers complain of indoor air quality problems, industrial hygienists are called upon to determine if the problem really is an indoor air quality problem. If they determines that some form of contaminant is present in the workplace, proper remedial action is required. This usually includes removing the source of the contamination.

INDOOR AIR CONTAMINANT TRANSPORT

Air contaminants reach worker breathing zones by traveling from the source to the worker by various pathways. Normally, the contaminants travel with the flow of air. Air moves from areas of high pressure to areas of low pressure, which is why controlling workplace air pressure is an integral part of controlling pollution and enhancing building indoor air quality performance. Air movements should be from occupants, toward a source, and out of the building rather than from the source to the occupants and out of the building. Pressure differences will control the direction of air motion and the extent of occupant exposure. *Driving forces* change pressure relationships and create airflow. Common driving forces are identified in Table 7.26.

TABLE 7.25
Outdoor Sources of Contaminants

Common Sources	Mitigation and Control
Ambient Outdoor Air	
Air quality in the general area	Filter or clean intake air.
Vehicular Sources	
Local vehicular traffic	Locate air intake away from source.
Vehicle idling areas	Require engines to be shut off at loading docks.
Loading docks	Pressurize building or zone.
	Add vestibules or sealed doors near sources.
Commercial or Manufacturing Sources	
Laundry or drycleaning	Locate air intake away from source.
Paint shops	Pressurize building relative to the outdoors.
Restaurants	Consider air cleaning options for outdoor air intakes.
Photo processing	Use landscaping to block or redirect flow of contaminants.
Automotive shops or gas stations	
Electronics manufacturers or assemblers	
Various industrial operations	
Utilities or Public Works	
Utility power plants	Locate air intake away from source.
Incinerators	Pressurize building relative to the outdoors.
Water treatment plants	Consider air cleaning options for outdoor air intakes.
	Use landscaping to block or redirect flow of contaminants.
Agricultural	
Pesticide spraying	Locate air intake away from source.
Processing or packing plants	Pressurize building relative to the outdoors.
Ponds	Consider air cleaning options for outdoor air intakes.
	Use landscaping to block or redirect flow of contaminants.
Construction and Demolition	Pressurize building.
	Use walk-off mats.
Building Exhaust	
Bathroom exhaust	Separate exhaust or relief from air intake.
Restaurant exhaust	Pressurize building.
Air handler relief vent	
Exhaust from major tenant (e.g., drycleaner)	
Water Sources	
Pools of water on roof	Provide proper roof drainage.
Cooling tower mist	Separate air intake from source of water.
	Treat and maintain cooling tower water.
Birds and Rodents	
Fecal contaminants	Bird-proof intake grills.
Bird nesting	Consider vertical grills.
Building Operations and Maintenance	
Trash and refuse areas	Separate source from air intake.
Chemicals, fertilizers, groundskeeping, and storage	Keep source area clean with lids on tight.
Painting, roofing, or sanding	Isolate storage areas from occupied areas.
Ground Sources	
Soil gas	Depressurize soil.
Sewer gas	Seal foundation and penetrations to foundations.
Underground fuel storage tanks	Keep air ducts away from ground sources.

TABLE 7.26
Major Driving Forces

Driving Force	Effect
Wind	Positive pressure is created on the windward side causing infiltration, and negative pressure on the leeward size causing exfiltration, although wind direction can be varied due to surrounding structures.
Stack effect	When the air inside is warmer than that outside it rises, sometimes creating a column that rises up stairwells, elevator shafts, vertical pipe chases, etc. This buoyant force of the air results in positive pressure on the higher floors, negative pressure on the lower floors, and a neutral pressure plane somewhere in between.
HVAC/fans	Fans are designed to push air in a directional flow, resulting in positive pressure in front and negative pressure behind the fan.
Flues and exhaust	Exhausted air from a building will reduce the building air pressure relative to the outdoors. Air exhausted will be replaced either through infiltration or through planned outdoor air intake vents.
Elevators	The pumping action of a moving elevator can push air out of or draw air into the elevator shaft as it moves.

INDOOR AIR DISPERSION PARAMETERS

Several parameters, some of which characterize observed patterns of contaminant distribution and others of which characterize flow features, such as stability, are used to characterize the dispersion of a contaminant inside a room:

- *Contaminant concentration* is an indicator of contaminant distribution in a room—that is, the mass of contaminant per unit volume of air (measured in kg/m^3).
- *Local mean age of air* is the average time it takes for air to travel from the inlet to any point in the room (Di Tommaso et al., 1999).
- *Purging effectiveness of inlets* is a quantity that can be used to identify the relative performance of each inlet in a room where there are multiple inlets.
- *Local specific contaminant-accumulating index* is a general index capable of reflecting the interaction between the ventilation flow and a specific contaminant source.
- *Air change effectiveness (ACE)* is a measure of how effectively the air present in a room is replaced by fresh air from the ventilation system (Di Tommaso et al., 1999). It can be defined as the age of air that would occur throughout the room if the air was perfectly mixed divided by the average age of air where the occupants breathe.
- *Ventilation effectiveness factor (VEF)* is the ratio of two contaminant concentration differentials: the contaminant concentration in the supply air (typically zero) and the contaminant concentration in the room under complete mixing conditions (Zhang et al., 2001).
- *Relative ventilation efficiency* is the ratio of the local mean age that would exist if the air in the room were completely mixed to the local mean age that is actually measured at a point.
- *Air diffusion performance index (ADPI)* is primarily a measure of occupant comfort rather than an indicator of contaminant concentrations. It expresses the percentage of locations in an occupied zone that meet air movement and temperature specifications for comfort.
- *Temperature effectiveness* is similar in concept to ventilation effectiveness and reflects the ability of a ventilation system to remove heat.
- *Effective draft temperature* indicates the feeling of coolness due to air motion.
- *Reynolds number* expresses the ratio of the inertial forces to viscous forces.
- *Rayleigh number* characterizes natural convection flows.

- *Grashof number* is equivalent to the Rayleigh number divided by the Prandtl number (a dimensionless number approximating the ratio of viscosity and thermal diffusity).
- *Froude number* is a dimensionless number used to characterize flow through corridors and doorways and in combined displacement and wind ventilation cases.
- *Richardson number* characterizes the importance of buoyancy.
- *Flux Richardson number* characterizes the stabilizing effect of stratification on turbulence.
- *Buoyancy flux* is used to characterize buoyancy-driven flows.
- *Archimedes number* characterizes conditions of the supplied air; it expresses the ratio of the buoyancy forces to momentum forces or the strength of natural convection to forced convection.

COMMON AIRFLOW PATHWAYS

Contaminants travel along pathways—sometimes over great distances. Pathways may lead from an indoor source to an indoor location or from an outdoor source to an indoor location. The location experiencing a pollution problem may be close by, in the same, or in an adjacent area, but it may be a great distance from, or on a different floor from a contaminant source. Knowledge of common pathways helps to track down the source and prevent contaminants from reaching building occupants (see Table 7.27).

TABLE 7.27
Common Airflow Pathways for Contaminants

Common Pathway	Comment
Indoors	
Stairwells Elevator shafts Vertical electrical or plumbing chases	The stack effect brings about air flow by drawing air toward these chases on the lower floors and away from these chases on the higher floors, affecting the flow of contaminants.
Receptacles, outlets, openings	Contaminants can easily enter and exit building cavities and thereby move from space to space.
Duct or plenum	Contaminants are commonly carried by the HVAC system throughout the occupied spaces.
Duct or plenum leakage	Duct leakage accounts for significant unplanned air flow and energy loss in buildings.
Flue or exhaust leakage	Leaks from sanitary exhausts or combustion flues can cause serious health problems.
Room spaces	Air and contaminants move within a room or through doors and corridors to adjoining spaces.
Outdoors to Indoors	
Indoor air intake	Polluted outdoor air or exhaust air can enter the building through the air intake.
Windows or doors	A negatively pressurized building will draw air and outside pollutants into the building through any cracks and crevices or available opening.
Substructure or slab penetrations	Radon and other soil gases and moisture-laden air or microbial-contaminated air often travel through crawlspaces and other substructures into the building.

MAJOR INDOOR AIR QUALITY CONTAMINANTS

Environmental engineers and industrial hygienists spend a large portion of their time working with and mitigating air contaminant problems in the workplace. The list of potential contaminants workers might be exposed to while working is extensive. Other than those poisonous gases and materials that are automatically top priorities for engineers and industrial hygienists to investigate and mitigate, there are a few major chemical- and material-derived air contaminants that are considered extremely hazardous. These also attract an industrial hygienist's immediate attention and require remedial actions. This section focuses on asbestos, silica, formaldehyde, and lead as examples of such hazardous contaminants requiring the immediate attention of industrial hygienists.

ASBESTOS EXPOSURE

Asbestos is the name given to a group of naturally occurring minerals widely used in certain products, such as building materials and vehicle brakes, to resist heat and corrosion. Asbestos includes chrysoltile, amosite, crocidolite, tremolite asbestos, anthophyllite asbestos, actinolite asbestos, and any of these materials that have been chemically treated or altered. Typically, asbestos appears as a whitish, fibrous material that may release fibers that range in texture from coarse to silky; however, airborne fibers that can cause health damage may be too small to be seen with the naked eye. An estimated 1.3 million employees in construction and general industry face significant asbestos exposure on the job. Heaviest exposures occur in the construction industry, particularly during the removal of asbestos during renovation or demolition (abatement). Employees are also likely to be exposed during the manufacture of asbestos products (such as textiles, friction products, insulation, and other building materials) and automotive brake and clutch repair work.

The inhalation of asbestos fibers by workers can cause serious diseases of the lungs and other organs that may not appear or manifest themselves until years after the exposure has occurred. For instance, asbestosis can cause a buildup of scar-like tissue in the lungs and result in a loss of lung function that often progresses to disability and death. Smokers are at higher risk of developing some asbestos-related diseases. In addition to asbestosis, exposure to asbestos can cause mesothelioma, which is a cancer affecting the membranes lining the lungs and abdomen; lung cancer; and cancers of the esophagus, stomach, colon, and rectum. The Occupational Safety and Health Administration (OSHA) has issued the following three standards to assist industrial hygienists with compliance and to protect workers from exposure to asbestos in the workplace:

- 29 CFR 1926.1101 covers construction work, including alteration, repair, renovation, and demolition of structures containing asbestos.
- 29 CFR 1915.1001 covers asbestos exposure during work in shipyards.
- 29 CFR 1910.1001 applies to asbestos exposure in general industry, such as exposure during brake and clutch repair, custodial work, and manufacture of asbestos-containing products.

The standards for the construction and shipyard industries classify the hazards of asbestos work activities and prescribe particular requirements for each classification:

- Class I is the most potentially hazardous class of asbestos jobs and involves the removal of thermal system insulation and sprayed-on or troweled-on asbestos-containing surfacing materials or presumed asbestos-containing materials.
- Class II includes the removal of other types of asbestos-containing materials that are not thermal system insulation, such as resilient flooring and roofing materials containing asbestos.

- Class III focuses on repair and maintenance operations where asbestos-containing materials are disturbed.
- Class IV pertains to custodial activities where employees clean up asbestos-containing waste and debris.

There are equivalent regulations in states with OSHA-approved state plans.

Permissible Exposure Limits

Employee exposure to asbestos must not exceed 0.1 fibers per cubic centimeter (f/cm^3) of air, averaged over an 8-hour work shift. Short-term exposure must also be limited to not more than 1 f/c^3, averaged over 30 minutes. Rotation of employees to achieve compliance with either permissible exposure limit (PEL) is prohibited.

Exposure Monitoring

In construction and shipyard work, unless the industrial hygienist is able to demonstrate that employee exposures will be below the PELs (a "negative exposure assessment"), it is generally a requirement that monitoring for workers in Class I and II regulated areas be conducted. For workers in other operations where exposures are expected to exceed one of the PELs, periodic monitoring must be conducted. In general industry, for workers who may be exposed above a PEL or above the excursion limit, initial monitoring must be conducted. Subsequent monitoring at reasonable intervals must be conducted, and in no case at intervals greater than 6 months for employees exposed above a PEL.

Competent Person

In all operations involving asbestos removal (abatement), employers must name a "competent person" qualified and authorized to ensure worker safety and health, as required by Subpart C, "General Safety and Health Provisions for Construction" (29 CFR 1926.20). Under the requirements for safety and health prevention programs, the competent person must frequently inspect job sites, materials, and equipment. A fully trained and licensed industrial hygienist often fills this role. In addition, for Class I jobs the competent person must inspect onsite at least once during each work shift and upon employee request. For Class II and III jobs, the competent person must inspect often enough to assess changing conditions and upon employee request.

Regulated Areas

In general industry and construction, regulated areas must be established where the 8-hour TWA or 30-minute excursions values for airborne asbestos exceed the PELs. Only authorized persons wearing appropriate respirators can enter a regulated area. In regulated areas, eating, smoking, drinking, chewing tobacco or gum, and applying cosmetics are prohibited. Warning signs must be displayed at each regulated area and must be posted at all approaches to regulated areas.

Methods of Compliance

In both general industry and construction, employers must control exposures using engineering controls, to the extent feasible. Where engineering controls are not feasible to meet the exposure limit, they must be used to reduce employee exposures to the lowest levels attainable and must be supplemented by the use of respiratory protection.

Respirators

In general industry and construction, the level of exposure determines what type of respirator is required; the standards specify the respirator to be used. Keep in mind that respirators must be used during all Class I asbestos jobs. Refer to 29 CFR 1926.103 for further guidance on when respirators must be worn.

Labels

Caution labels must be placed on all raw materials, mixtures, scrap, waste, debris, and other products containing asbestos fibers.

Protective Clothing

For any employee exposed to airborne concentrations of asbestos that exceed the PEL, the employer must provide and require the use of protective clothing such as coveralls or similar full-body clothing, head coverings, gloves, and foot coverings. Wherever the possibility of eye irritation exists, face shields, vented goggles, or other appropriate protective equipment must be provided and worn.

Training

For employees involved in each identified work classification, training must be provided. The specific training requirements depend upon the particular class of work being performed. In general industry, training must be provided to all employees exposed above a PEL. Asbestos awareness training must also be provided to employees who perform housekeeping operations covered by the standard. Warning labels must be placed on all asbestos products, containers, and installed construction materials when feasible.

Recordkeeping

The employer must keep an accurate record of all measurements taken to monitor employee exposure to asbestos. This record is to include the date of measurement, operation involving exposure, sampling and analytical methods used, and evidence of their accuracy; number, duration, and results of samples taken; type of respiratory protective devices worn; name and Social Security number; and the results of all employee exposure measurements. This record must be kept for 30 years.

Hygiene Facilities and Practices

Clean change rooms must be furnished by employers for employees who work in areas where exposure is above the TWA and/or excursion limit. Two lockers or storage facilities must be furnished and separated to prevent contamination of the employee's street clothes from protective work clothing and equipment. Showers must be furnished so that employees may shower at the end of the work shift. Employees must enter and exit the regulated area through the decontamination area. The equipment room must be supplied with impermeable, labeled bags and containers for the containment and disposal of contaminated protective clothing and equipment. Lunchroom facilities for those employees must have a positive-pressure, filtered air supply and be readily accessible to employees. Employees must wash their hands and face prior to eating, drinking, or smoking. The employer must ensure that employees do not enter lunchroom facilities with protective work clothing or equipment unless surface fibers have been removed from the clothing or equipment. Employees may not smoke in work areas where they are occupationally exposed to asbestos.

Medical Exams

In general industry, exposed employees must have a preplacement physical examination before being assigned to an occupation exposed to airborne concentrations of asbestos at or above the action level or the excursion level. The physical examination must include chest x-ray, medical and work history, and pulmonary function tests. Subsequent exams must be given annually and upon termination of employment, although chest x-rays are required annually only for older workers whose first asbestos exposure occurred more than 10 years ago. In construction, examinations must be made available annually for workers exposed above the action level or excursion limit for 30 or more days per year or who are required to wear negative pressure respirators; chest x-rays are at the discretion of the physician.

SILICA EXPOSURE

Crystalline silica (SiO_2) is a major component of the Earth's crust. In pure, natural form, SiO_2 crystals are minute, very hard, translucent, and colorless. Most mined minerals contain some SiO_2. "Crystalline" refers to the orientation of SiO_2 molecules in a fixed pattern as opposed to a nonperiodic, random molecular arrangement defined as amorphous (e.g., diatomaceous earth). Silica exposure occurs in a wide variety of settings, such as mining, quarrying, and stone-cutting operations; ceramics and vitreous enameling; and in use of filters for paints and rubber. The wide use and multiple applications of silica in industrial applications combine to make silica a major occupational health hazard that can lead to death. Silicosis is a disabling, nonreversible, and sometimes fatal lung disease caused by overexposure to respirable crystalline silica. More than a million U.S. workers are exposed to crystalline silica, and each year more than 250 die from silicosis (see Table 7.28). There is no cure for the disease, but it is 100% preventable if employers, workers, and health professionals work together to reduce exposures.

Guidelines for Control of Occupational Exposure to Silica

In accordance with the Occupational Safety and Health Administration's (OSHA) standard for air contaminants (29 CFR 1910.1000), employee exposure to airborne crystalline silica shall not exceed an 8-hour time-weighted average (TWA) limit as stated in 29 CFR 1910.1000, Table Z-3, or a limit set by a state agency whenever a state-administered Occupational Safety and Health Plan is in effect. As mandated by OSHA, the first mandatory requirement is that employee exposure be eliminated through the implementation of feasible engineering controls (e.g., dust suppression, ventilation). After all such controls are implemented and they do not control to the permissible exposure, each employer must rotate its employees to the extent possible in order to reduce exposure. Only when all engineering or administrative controls have been implemented, and the level of respirable silica still exceeds permissible exposure limits, may an employer rely on a respirator program pursuant to the mandatory requirements of 29 CFR 1910.134. Generally where working conditions or other practices constitute recognized hazards likely to cause death or serious physical harm, they must be corrected.

FORMALDEHYDE EXPOSURE

Formaldehyde (HCHO) is a colorless, flammable gas with a pungent, suffocating odor. Formaldehyde is common to the chemical industry. It is the most important aldehyde produced commercially and is used in the preparation of urea-formaldehyde and phenol-formaldehyde resins. It is also produced during the combustion of organic materials and is a component of smoke. The major sources in workplace settings are in manufacturing processes (used in the paper, photographic, and clothing industries) and building materials. Building materials may contain phenol, urea, thiourea, or melamine resins that contain HCHO. Degradation of HCHO resins can occur when these materials become damp from exposure to high relative humidity, if the HCHO materials are saturated with water during flooding, or when leaks occur. The release of HCHO occurs when the acid catalysts involved in the resin formulation are reactivated. When temperatures and relative humidity increase, outgassing increases (Washington State Department of Health, 2003).

Formaldehyde exposure is most common through gas-phase inhalation; however, it can also occur through liquid-phase skin absorption. Workers can be exposed during direct production, treatment of materials, and production of resins. Healthcare professionals, pathology and histology technicians, and teachers and students who handle preserved specimens are potentially at high risk. Studies indicate that formaldehyde is a potential human carcinogen. Airborne concentrations above 0.1 ppm can cause irritation of the eyes, nose, and throat. The severity of irritation increases as the concentration increases; at 100 ppm it is immediately dangerous to life and health. Dermal contact causes various skin reactions, including sensitization, which might force persons thus sensitized to

TABLE 7.28
Deaths from Silica in the Workplace

Occupation	Proportionate Mortality Ratio (PMR)[a]
Miscellaneous metal and plastic machine operators	168.44
Hand molders and shapers, except jewelers	64.12
Crushing and grinding machine operators	50.97
Hand molding, casting, and forming occupations	35.70
Molding and casting machine operators	30.60
Mining machine operators	19.61
Mining occupations (not elsewhere classified)	15.33
Construction trades (not elsewhere classified)	14.77
Grinding, abrading, buffing, and polishing machine operators	8.47
Heavy equipment mechanics	7.72
Miscellaneous material moving equipment operators	6.92
Millwrights	6.56
Crane and tower operators	6.02
Brick masons and stone masons	4.71
Painters, construction and maintenance	4.50
Furnace, kiln, oven operators, except food	4.10
Laborers, except construction	3.79
Operating engineers	3.56
Welders and cutters	3.01
Machine operators, not specified	2.86
Not specified mechanics and repairers	2.84
Supervisors, production occupations	2.73
Construction laborers	2.14
Machinists	1.79
Janitors and cleaners	1.78
Industry	**Proportionate Mortality Ratio (PMR)[a]**
Metal mining	69.51
Miscellaneous nonmetallic mineral and stone products	55.31
Nonmetallic mining and quarrying, except fuel	49.77
Iron and steel foundries	31.15
Pottery and related products	30.73
Structural clay products	27.82
Coal mining	9.26
Blast furnaces, steelworks, rolling and finishing mills	6.49
Miscellaneous fabricated metal products	5.87
Miscellaneous retail stores	4.63
Machinery, except electrical, (not elsewhere classified)	3.96
Other primary metal industries	3.63
Industrial and miscellaneous chemicals	2.72
Not specified manufacturing industries	2.67
Construction	1.82

Sources: OSHA, *Deaths from Silica in the Workplace*, Occupational Safety and Health Administration, Washington, DC, 2015 (https://www.osha.gov/dsg/etools/silica/determine_exposure/silicadeaths/silicadeaths.html).

[a] Observed number of deaths from silicosis per occupation divided by expected number of deaths. A value of 1 indicates no additional risk; a value of 10 indicates a risk 10 times greater than the normal risk of silicosis.

find other work. OSHA requires that the employer conduct initial monitoring to identify all employees who are exposed to formaldehyde at or above the action level or short-term exposure-limit (STEL) and to accurately determine the exposure of each employee so identified. If the exposure level is maintained below the STEL and the action level, employers may discontinue exposure monitoring, until there is a change that could affect exposure levels. The employer must also monitor employee exposure promptly upon receiving reports of formaldehyde-related signs and symptoms.

With regard to exposure control, the best prevention is provided by source control whenever possible. The selection of HCHO-free or low-emitting products, such as exterior-grade plywood, which use phenol HCHO resins for indoor use is the best starting point. Secondary controls include filtration, sealants, and fumigation treatments. Filtration can be achieved using selected adsorbents. Sealants involve coating the materials in question with two or three coats of nitrocellulose varnish or water-based polyurethane. Three coats of these materials can reduce outgassing by as much as 90%. Training is required at least annually for all employees exposed to formaldehyde concentrations of 0.1 ppm or greater. The training will increase employees' awareness of specific hazards in their workplace and of the control measures employed. The training also will assist successful medical surveillance and medical removal programs. These provisions will only be effective if employees know what signs or symptoms are related to the health effects of formaldehyde and are periodically encouraged to do learn them.

LEAD EXPOSURE

Lead has been poisoning workers for thousands of years. Most occupational over exposures to lead have been found in the construction trades, such as plumbing, welding, and painting. In plumbing, soft solder (banned for many uses in the United States), used chiefly for soldering tinplate and copper pipe joints, is an alloy of lead and tin. The use of lead-based paint in residential applications has been banned, but because lead-based paint inhibits the rusting and corrosion of iron and steel, it is still used on construction projects. Significant lead exposures can also arise from removing paint from surfaces previously coated with lead-based paint. According to OSHA 93-47, the operations that generate lead dust and fumes include the following:

- Flame-torch cutting, welding, the use of heat guns, or sanding, scraping, and grinding of lead-based painted surfaces during repair, reconstruction, dismantling, and demolition work
- Abrasive blasting of structures containing lead-based paints
- Use of torches and heat guns, and sanding, scraping, and grinding of lead-based painted surfaces during remodeling or abating lead-based paint
- Maintaining process equipment or exhaust duct work

Health Effects of Lead

Lead can enter the body through several routes of entry. When absorbed into the body in certain doses, lead is a toxic substance. Lead can be absorbed into the body by inhalation and ingestion. Except for certain organic lead compounds not covered by OSHA's lead standard (29 CFR 1926.62), such as tetraethyl lead, when scattered in the air as a dust, fume, or mist lead can be absorbed into the body by inhalation. A significant portion of the lead that can be inhaled or ingested gets into the blood stream. Once in the blood stream, lead is circulated throughout the body and stored in various organs and tissues. Some of this lead is quickly filtered out of the body and excreted, but some remains in the blood and other tissues. As exposure to lead continues, the amount stored in the body will increase if more lead is being absorbed than is being excreted. Cumulative exposure to lead, which is typical in construction settings, may result in damage to the blood, nervous system, kidneys, bones, heart, and reproductive system and contributes to high blood pressure. Some of the symptoms of lead poisoning include the following:

- Poor appetite
- Dizziness
- Pallor
- Headache
- Irritability or anxiety
- Constipation
- Sleeplessness
- Weakness
- Insomnia
- “Lead line” in gums
- Fine tremors
- Hyperactivity
- Wrist drop (weakness of extensor muscles)
- Excessive tiredness
- Numbness
- Muscle and joint pain or soreness
- Nausea
- Reproductive difficulties

Lead Standard Definitions

The OSHA lead standard defines the following terms:

- *Action level* is the employee exposure, without regard to the use of respirators, to an airborne concentration of lead of 30 micrograms per cubic meter of air (30 μg/m^3), averaged over an 8-hour period.
- *Permissible exposure limit (PEL)* is the concentration of airborne lead to which an average person may be exposed without harmful effects. OSHA has established a PEL of 50 micrograms per cubic meter of air (50 μg/m^3) averaged over an 8-hour period. If an employee is exposed to lead for more than 8 hours in any work day, the permissible exposure limit, a time-weighted average (TWA) for that day shall be reduced according to the following formula:

  $$\text{Maximum permissible limit } (\mu g/m^3) = 400 \times \text{Hours worked in the day.}$$

  When respirators are used to supplement engineering and administrative controls to comply with the PEL and all the requirements of the lead standard’s respiratory protection rules have been met, employee exposure, for the purpose of determining whether the employer has complied with the PEL, may be considered to be at the level provided by the protection factor of the respirator for those periods the respirator is worn. Those periods may be averaged with exposure levels during periods when respirators are not worn to determine the employee’s daily TWA exposure.
- *μg/m^3* is micrograms per cubic meter of air. A microgram is 1 millionth of a gram. There are 454 grams in a pound.

Worker Lead Protection Program

The employer is responsible for the development and implementation of a worker lead protection program. This program is essential to minimizing worker risk of lead exposure. The most effective way to protect workers is to minimize exposure through the use of engineering controls and good work practices. At a minimum, the following elements should be included in the employer’s worker protection program for employees exposed to lead:

- Hazard determination, including exposure assessment
- Engineering and work practice controls
- Respiratory protection
- Protective work clothing and equipment (PPE)
- Housekeeping
- Hygiene facilities and practices
- Medical surveillance and provisions for medical removal
- Employee information and training
- Signs
- Recordkeeping

MOLD CONTROL

Molds can be found almost anywhere; they can grow on virtually any organic substance, as long as moisture and oxygen are present. The earliest known writings that appear to discuss mold infestation and remediation are found in Leviticus, Chapter 14, Old Testament. Where is mold typically found? Name the spot or place; they have been found growing in office buildings, schools, automobiles, private homes, and any location where water and organic matter are left unattended. Mold is not a new issue—just one that, until recently, has received little attention by regulators in the United States. That is, there are no state or federal statutes or regulations regarding molds and indoor air quality.

Molds reproduce by making spores that usually cannot be seen without magnification. Mold spores waft through the indoor and outdoor air continually. When mold spores land on a damp spot indoors, they may begin growing and digesting whatever they are growing on in order to survive. Molds generally destroy the things they grow on (USEPA, 2001).

The key to limiting mold exposure is to prevent the germination and growth of mold. Because mold requires water to grow, it is important to prevent moisture problems in buildings. Moisture problems can have many causes, including uncontrolled humidity. Some moisture problems in workplace buildings have been linked to changes in building construction practices beginning in the 1970s. Some of these changes have resulted in buildings that are tightly sealed and lack adequate ventilation, potentially leading to moisture buildup. Building materials, such as drywall, may not allow moisture to escape easily. Moisture problems may also be due to roof leaks, landscaping, or gutters that direct water into or under the building, as well as by unvented combustion appliances. Delayed maintenance or insufficient maintenance is also associated with moisture problems in buildings. Moisture problems in temporary structures have frequently been associated with mold problems.

Building maintenance personnel, architects, and builders need to know effective means of avoiding mold growth that might arise from maintenance and construction practices. Locating and cleaning existing growths are also paramount to reducing the health effects of mold contamination. Using proper cleaning techniques is important because molds are incredibly resilient and adaptable (Davis, 2001).

Molds can elicit a variety of health responses in humans. The extent to which an individual may be affected depends on their state of health, susceptibility to disease, the organisms with which they came in contact, and the duration and severity of exposure (Ammann, 2000). Some people experience temporary effects that disappear when they vacate infested areas (Burge, 1997). In others, the effects of exposure may be long term or permanent (Yang, 2001). It should be noted that systemic infections caused by molds are not common. Normal, healthy individuals can resist systemic infection from airborne molds. Those at risk for system fungal infection are severely immunocompromised individuals such as those with HIV/AIDS, individuals who have had organ or bone marrow transplants, and persons undergoing chemotherapy.

In 1994, an outbreak of the mold *Stachybotrys chartarum* in Cleveland, Ohio, was believed by some to have caused pulmonary hemorrhage in infants. Sixteen of the infants died. The CDC sponsored a review of the cases and concluded that the scientific evidence provided did not warrant the conclusion that inhaled mold was the cause of the illnesses in the infants; however, the panel also stated that further research was warranted, as the study design for the original research appeared to be flawed (CDC, 1999). Below is a list of mold components known to elicit a response in humans:

- *Volatile organic compounds*—"Molds produce a large number of volatile organic compounds. These chemicals are responsible for the musty odors produced by growing molds" (McNeel and Kreutzer, 1996). VOCs also provide the odor in cheeses, and the "off" taste of mold-infested foods. Exposure to high levels of volatile organic compounds affects the central nervous system, producing such symptoms as headaches, attention deficit, inability to concentrate, and dizziness (Ammann, 2000). At present, the specific contribution of mold volatile organic compounds to building-related health problems has not been studied (McNeel and Kreutzer, 1996). Also, mold volatile organic compounds are likely responsible for only a small fraction of total VOCs indoors (Davis, 2001).
- *Allergens*—All molds, because of the presence of allergens on spores, have the potential to cause an allergic reaction in susceptible humans (Rose, 1999). Allergic reactions are believed to be the most common exposure reaction to molds. These reactions can range from mild, transitory responses such as runny eyes, runny nose, throat irritation, coughing, and sneezing to severe, chronic illnesses such as sinusitis and asthma (Ammann, 2000).
- *Mycotoxins*—These natural organic compounds are capable of initiating a toxic response in vertebrates (McNeel and Kreutzer, 1996). Some molds are capable of producing mycotoxins. Molds known to potentially produce mycotoxins and which have been isolated in infestations causing adverse health effects include certain species of *Acremonium*, *Alternaria*, *Aspergillus*, *Caldosporium*, *Chaetomium*, *Fusarium*, *Paecilomyces*, *Penicillium*, *Stachybotrys*, and *Trichoderma* (Yang, 2001). Although a certain type of mold or mold strain type may have the genetic potential for producing mycotoxins, specific environmental conditions are believed to be necessary for the mycotoxins to be produced. In other words, although a given mold might have the potential to produce mycotoxins, it will not produce them if the appropriate environmental conditions are not present (USEPA, 2001). Currently, the specific conditions that cause mycotoxin production are not fully understood. The USEPA recognizes that mycotoxins have a tendency to concentrate in fungal spores and that there is limited information currently available regarding the process involved in fungal spore release. As a result, the USEPA is currently conducting research in an effort to determine the environmental conditions required for the sporulation, emission, aerosolization, dissemination, and transport of *Stachybotrys* into the air (USEPA, 2001).

Mold Prevention

The key to mold control is moisture control; in other words, solve moisture problems before they become mold problems. Several mold prevention tips are listed below:

- Fix leaky plumbing and leaks in the building envelope as soon as possible.
- Watch for condensation and wet spots. Fix sources of moisture problems as soon as possible.
- Prevent moisture due to condensation by increasing surface temperature or reducing the moisture level in air (humidity). To increase surface temperature, insulate or increase air circulation. To reduce the moisture level in air, repair leaks, increase ventilation (if outside air is cold and dry), or dehumidify (if outdoor air is warm and humid).
- Keep heating, ventilation, and air conditioning (HVAC) drip pans clean, flowing properly, and unobstructed.

- Perform regular HVAC inspections and maintenance as scheduled.
- Vent moisture-generating appliances, such as dryers, to the outside where possible.
- Maintain a low indoor humidity, below 60% relative humidity (RH) but ideally 30 to 50%, if possible.
- Clean and dry wet or damp spots within 48 hours.
- Don't let foundations stay wet. Provide drainage and slope the ground away from the foundation.

Mold Remediation

At the present time, there are no standardized recommendations for mold remediation; however, the USEPA is working on guidelines. There are certain aspects of mold cleanup, though, that have been agreed upon by many practitioners in the field. A common-sense approach should be taken when assessing mold growth. For example, it is generally believed those small amounts of growth, such as those commonly found on shower walls, pose no immediate health risk to most individuals. Persons with respiratory problems, a compromised immune system, or fragile health, should not participate in cleanup operations. Cleanup crews should be properly attired. Mold should not be allowed to touch bare skin. Eyes and lungs should be protected from aerosol exposure. Adequate ventilation should be provided while, at the same time, containing the infestation in an effort to avoid spreading mold to other areas. The source of moisture must be stopped and all areas infested with mold thoroughly cleaned. If thorough cleaning is not possible due to the nature of the material (porous vs. semi- and nonporous), al contaminated areas should be removed. Safety tips that should be followed when remediating moisture and mold problems include

- Do not touch mold or moldy items with bare hands.
- Do not get mold or mold spores in your eyes.
- Do not breathe in mold or mold spores.
- Consider using personal protective equipment (PPE) when disturbing mold. The minimum PPE is a respirator, gloves, and eye protection.

Mold Cleanup Methods

A variety of mold cleanup methods are available for remediating damage to building materials and furnishings caused by moisture control problems and mold growth. These include wet vacuum, damp wipe, HEPA vacuum, and the removal of damaged materials and sealing them off in plastic bags. The specific method or group of methods used will depend on the type of material affected.

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8 Water Pollution

The average American uses more than 180 gallons of fresh, clean water a day, while many rural villagers in the Third World nations spend up to 6 hours a day obtaining their water from distant, polluted streams. Nearly 10 million people die each year as a result of intestinal diseases caused by unsafe water. While the magnitude of water use in most Western countries gives the appearance of an unlimited supply, it is only an illusion. In the 30-year period between 1950 and 1980, the U.S. population grew by 50 percent. During the same time period, water consumption increased by 150 percent. The Water Resources Council projects that of the 106 water supply regions in the United States, water supplies to 17 of them will be seriously inadequate in the next decades.

—Boyce (1997)

INTRODUCTION TO WATER

Let's look at some basic concepts or facts about water—facts that we may or may not be familiar with:

- Life as we know it cannot exist without water. A lack of water first enervates, then prostrates, then kills. Most of us are familiar with this fact.
- When literally dying from lack of water, any fear of drowning in the first river, lake, stream, or deep depression containing water that we stumble upon leaves us instantly. Why? Simply, we do not fear drowning when we intend to drink it all—every last drop.
- The leading cause of accidental death in desert regions is drowning.
- In a rainstorm, we know that when lightning streaks like gunfire through clouds dense as wool and volleys of thunder roar like cannonballs tumbling down a stone staircase, shaking air permeated with the smell of ozone, that rain—hard rain, rain that splatters on rock like pellets, knocking berries off junipers, leaves off trees, limbs off oaks—is on its way, driven by wind perhaps capable of knocking down the oak itself.

These things we know or imagine about water, about rain, about the results of water or rain events. We know these things—some through instinct, some through experience. We have knowledge of many facts concerning water, but of course there is much more that we do not know about water that we *should* know. Most important, though, as our Native American friends would tell us if we bothered to ask, is that we need to learn to respect water. Why? Simply put, water is the essence of life.

Now let's take a look at some other facts about water that we might not be familiar with at all but should be

- If we took all the available supplies of water on Earth from every ocean, every lake, every stream, every river, every brook, every well, every tiny puddle, and from the atmosphere itself, the quantity would all add up to an overwhelming volume of more than 333 million cubic miles, making water the most common substance on Earth.
- Of this 333 million cubic miles of water, about 97% (or about 323 million cubic miles) is salty, residing mostly in the oceans but also in glaciers and ice caps. Note that, although saltwater is more plentiful than freshwater, freshwater is what concerns us in this text. Saltwater fails the most vital test: It does not provide us the vital refreshment we require.

- Freshwater makes up only a small fraction of the Earth's water, about 3%. Only 1% of Earth's water is usable by humans. Freshwater is contained in lakes, rivers, streams, bays, and the atmosphere and under the ground.
- Most living organisms depend on water for survival. Human bodies contain about 60% water. To survive, we need to take in about 2-1/2 liters of water a day; 1-1/2 liters come from the liquids we drink and the rest from the water content in our foods. We put our lives in jeopardy if we lose 12% or more of our body water.

Water covers almost three-quarters of the Earth's surface. Although it is our most abundant resource, water is present on Earth in only a thin film, and almost 97% of it is saltwater. Earth's water performs many functions essential to life on Earth: helping to maintain climate, diluting environmental pollution, and, of course, supporting all life. Freshwater sources include groundwater and surface water. In this chapter, we focus on surface water—rivers, lakes, streams, wetlands, and coastal waters. More specifically, we focus our attention on surface water pollution; however, we limit our discussion to only the freshwater bodies upon which life is so dependent. Later in the chapter we discuss groundwater pollution.

Most human settlements evolved and continue to develop along the shores of many freshwater bodies, mainly rivers. The obvious reason for this is threefold: accessibility, a plentiful source of drinking water, and, later, a source of energy (water power) for our earliest machines. When human populations began to spread out and leave the watercourses, we found that some areas have too little water and others too much. Human beings (being the innovative and destructive creatures we are) have, with varying degrees of success, attempted to correct these imbalances by capturing freshwater in reservoirs behind dams, transferring freshwater in rivers and streams from one area to another, tapping underground supplies, and endeavoring to reduce water use, waste, and contamination. Water pollution can be defined in a general way as the presence of unwanted substances in water beyond levels acceptable for health or aesthetics. In some of these efforts to modify Nature we have been successful; in others (when gauged against the current condition of our water supplies) we are still learning—and we have much more to learn. Unfortunately, only a small proportion (about 0.5%) of all water on Earth is found in lakes, rivers, streams, or in the atmosphere. Even this small amount, though, is more than enough, if it is kept free of pollution and distributed evenly, to provide for the drinking, food preparation, and agricultural needs of all Earth's people. We simply need to learn how to better manage and conserve the freshwater readily available to us.

SURFACE WATER

Precipitation that does not infiltrate into the ground or return to the atmosphere is surface water. When the water is freshly fallen and still mobile, not having yet reached a body of water, we call it *runoff*—water that flows into nearby lakes, wetlands, streams, rivers, and reservoirs. Before continuing our discussion of surface water, let us review the basic concepts of the hydrological cycle.

Actually a manifestation of an enormous heat engine, the water cycle raises water from the oceans in warmer latitudes by a prodigious transformation of solar energy. Transferred through the atmosphere by the winds, the water is deposited far away over sea or land. Water taken from the Earth's surface to the atmosphere (either by evaporation from the surface of lakes, rivers, streams, and oceans or through transpiration of plants) forms clouds that condense to deposit moisture on the land and sea as rain or snow. The water that collects on land flows back to the oceans in streams and rivers. The water that we see is surface water. The U.S. Environmental Protection Agency (USEPA) defines surface water as all water open to the atmosphere and subject to runoff. Surface freshwater can be broken down into four components: lakes, rivers and streams, estuaries, and wetlands.

Limnology is the study of bodies of open freshwater (lakes, rivers, and streams) and of their plant and animal biology and physical properties. Freshwater systems are grouped or classified as either lentic or lotic. Lentic (*lenis*, for "calm") systems are represented by lakes, ponds, impoundments,

DID YOU KNOW?

Lentic (standing or still) water systems—Natural lentic water systems include lakes, ponds, bogs, marshes, and swamps. Other standing freshwater bodies, including reservoirs, oxidation ponds, and holding basins, are usually constructed.

Lotic (flowing) water systems—The human circulatory system can be compared to the earth's water circulation system. The hydrological cycle pumps water as our hearts pump blood, continuously circulating water through air, water bodies, and various vessels. As our blood vessels are essential to the task of carrying blood throughout our bodies, water vessels (rivers) carry water, fed by capillary creeks, brooks, streams, rills, and rivulets.

reservoirs, and swamps—standing water systems. Lotic (*lotus*, for "washed") systems are represented by rivers, streams, brooks, and springs—running water systems. On occasion, distinguishing between these two different systems is difficult. In old, wide, and deep rivers where water velocity is quite low, for example, the system becomes similar to that of a pond. Surface water (produced by melting snow or ice or from rainstorms) always follows the path of least resistance. In other words, water doesn't run uphill. Beginning with droplets and ever increasing, runoff is carried by rills, rivulets, brooks, creeks, streams, and rivers from elevated land areas that slope down toward one primary water course—a topographically defined drainage area. Drainage areas, known as *watersheds* or *drainage basins*, are surrounded by a ridge of high ground called the *watershed divide*. Watershed divides separate drainage areas from each other.

SURFACE WATER POLLUTANTS

Before we discuss surface water pollution, we must define several important terms related to water pollution. One of these is point source. A *point source* is, as defined by the Clean Water Act (CWA), any discernible, confined, and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation (CAFO), or vessel or other floating craft, from which pollutants are discharged. For example, the outfalls of industrial facilities or wastewater treatment plants are point sources. A *nonpoint source*, in contrast, is more widely dispersed. An example of a nonpoint source of pollution is rainwater carrying topsoil (sediments), animal waste (feces), and chemical contaminants into a stream. Nonpoint pollution includes water runoff from farming, urban areas, forestry, and construction activities. Nonpoint sources comprise the largest source or water pollution, contributing an estimated 70% or more of the contamination in quality-impaired surface waters. Note that atmospheric deposition of pollutants is also a nonpoint source of acid, nutrients, metals, and other airborne pollutants.

Another important term associated with nonpoint sources is *runoff*, which is a nonpoint source that originated on land. The USEPA considers polluted runoff to be the most serious water pollution problem in the United States. Runoff occurs because of human intervention with landscapes. When land is disturbed by parking lots, tarmac, roads, factories, homes, and buildings, rainwater is not free to percolate through the soil, which absorbs and detoxifies many pollutants. Instead, when there is little if any soil, contaminated rainwater runs off into area water bodies, polluting them.

Surface water pollutants can harm aquatic life, threaten human health, or result in the loss of recreational or aesthetic potential. Surface water pollutants come from industrial sources, nonpoint sources, municipal sources, background sources, and other/unknown sources. The eight chief pollutants are biochemical oxygen demand, nutrients, suspended solids, pH, oil and grease, pathogenic microorganisms, toxic pollutants, and nontoxic pollutants.

Biochemical Oxygen Demand (BOD)

Organic matter (dead plants and animal debris; wild animal and bird feces), human sewage, food-processing wastes, chemical plant wastes, slaughterhouse wastes, pulp- and paper-making wastes, and tannery wastes discharged to a water body are degraded by oxygen-requiring microorganisms. The amount of oxygen consumed during microbial utilization of organics is called the biochemical oxygen demand (BOD). BOD is classified as a *conventional pollutant* because it is amendable to treatment by a municipal sewage treatment plant. Although some natural BOD is almost always present, BOD is often an indication of the presence of sewage and other organic waste. High levels of BOD can deplete the oxygen in water. Fish and other aquatic organisms present in such waters with low oxygen conditions may die.

Nutrients

Elements such as carbon, nitrogen, phosphorus, sulfur, calcium, iron, potassium, manganese, cobalt, and boron are called *nutrients* (or biostimulants); they are essential to the growth and reproduction of aquatic plants and animals that depend on the surrounding water to provide their nutrients. Just as too much of any good thing can have serious side affects for all of us, so is the case with too many nutrients in water. For example, when fertilizers composed of nutrients enter surface water systems, over-enrichment with nitrogen and phosphorus may result. A rich supply of such nutrients entering a lake may hasten *eutrophication*, which the USEPA defines as a process during which a lake evolves into a bog or marsh and eventually disappears. Excess nutrients also can stimulate a very abundant dense growth of aquatic plants (bloom), especially algae.

pH

pH refers to the acidity or alkalinity of water; when it exceeds regulatory limits it is considered to be a conventional pollutant. A low pH may mean a water body is too acidic to support life optimally. Some water bodies are naturally acidic, but others are made so by acid deposition or acid runoff from mining operations.

Suspended Solids

Suspended solids are physical pollutants and may consist of inorganic or organic particles or of immiscible liquids. Inorganic solids such as clay, silt, and other soil constituents are common in surface water. Organic materials—plant fibers and biological solids—are also common constituents of surface waters. These materials are often natural contaminants resulting from the erosive action of water flowing over surfaces. Fine particles from soil runoff can remain suspended in water and increase its turbidity or cloudiness. This can stunt the growth of aquatic plants by limiting the amount of sunlight reaching them. Effluents from wastewater treatment and industrial plants and runoff from forestry and agricultural operations are sources of suspended solids. Note that because of the filtering capacity of the soil, suspended solids are seldom a constituent of groundwater.

Oil and Grease

Oil spills in or near surface water bodies that eventually reach the water body can have a devastating effect on fish, other aquatic organisms, and birds and mammals. Note that spills are not the only source of oil in water; oil leaking from automobiles and other vehicles or released during accidents is washed off roads with rainwater and into water bodies. Improper disposal of used oil from vehicles is another source; motor and other recreational boats release unburned fuel into water bodies.

Pathogenic Organisms

From the perspective of human use and consumption, the biggest concern associated with microorganisms is infectious disease. Microorganisms are naturally found in water (and elsewhere in the environment) and can cause infections; however, organisms that are not native to aquatic systems are of greatest concern—native or not, they can be transported by natural water systems. These organisms usually require an animal host for growth and reproduction. Nonpoint sources of these microorganisms include runoff from livestock operations and stormwater runoff. Point sources include improperly operating sewage treatment plants. When the surface water body functions to provide drinking water to a community, the threat of infectious microorganism contamination is very real and may be life threatening. People who live in industrial nations with generally safe water supplies think of pathogenic contamination as a third-world problem; however, several problems in industrial nations (Sydney, Australia, for example, had serious problems with their local water supply over the summer of 1998) have alerted us to the very real possibility of dangerous contamination in our own water supplies.

Toxic Pollutants

There are hundreds of potentially toxic water pollutants. Of these, USEPA, under the Clean Water Act, regulates more than 100 pollutants of special concern. These include arsenic and the metals mercury, lead, cadmium, nickel, copper, and zinc. Organic toxic pollutants include benzene, toluene, and many pesticides, herbicides, and insecticides.

Nontoxic Pollutants

Nontoxic pollutants include chemicals such as chlorine, phenols, iron, and ammonia. Color and heat are also nontoxic pollutants regulated under the CWA. Pure water is colorless, but water in natural water systems is often colored by foreign substances; for example, many facilities discharge colored effluents into surface water systems. Colored water is not aesthetically acceptable to the general public, however, so the intensity of the color that can be released is regulated by law. Heat or thermal nontoxic pollution can cause problems but is not ordinarily a serious pollutant, although in localized situations it can cause problems with temperature-sensitive organism populations.

EMERGING CONTAMINANTS

It has been suggested that humans and domestic and wildlife species have suffered adverse health consequences resulting from exposure to environmental chemicals that interact with the endocrine system. However, considerable uncertainty exists regarding the relationships between adverse health outcomes and exposure to environmental contaminants. Collectively, chemicals with the potential to interfere with the function of endocrine systems are called endocrine disrupting chemicals (EDCs). EDCs have been broadly defined as exogenous agents that interfere with the production, release, transport, metabolism, binding, action, or elimination of the natural hormones in the body responsible for the maintenance of homeostasis and the regulation of developmental processes. It is important to point out that EDCs, along with, in a broader sense, pharmaceuticals and personal care products (PPCPs), fall into the category of "emerging contaminants." Emerging contaminants can fall into any of a wide range of groups defined by their effects, uses, or key chemical or microbiological characteristics. These compounds are found in the environment, often as a result of human activities.

We are quickly approaching a time when we will enter into the fifth generation of people exposed to toxic chemicals from before conception to adulthood. In a few cases, we have identified the hazards of certain chemicals and their compounds and have implemented restrictions. One well-known chemical compound that comes to mind in regard to its environmental harm and subsequent banning is dichlorodiphenyltrichloroethane (DDT). Let's take a look at DDT.

The insecticide DDT was initially produced in the 1920s and was developed as the first of the modern synthetic insecticides in the 1940s. It was extensively used between 1945 and 1965 to great effect to control and eradicate insects that were responsible for malaria, typhus, and other insect-borne human diseases among both military and civilian populations, as well as for insect control in crop and livestock production, institutions, homes, and gardens. DDT was an excellent insecticide because even at low levels it was very effective at killing a wide variety of insects. The quick success of DDT as a pesticide and its broad use in the United States and other countries led to the development of resistance by many insect pest species. Moreover, the chemical properties that made this a good pesticide also made it persist in the environment for a long time.

This persistence led to accumulation of the pesticide in non-target species, especially raptorial birds (e.g., falcons, eagles). Due to the properties of DDT, the concentration of DDT in birds could be much higher than concentrations in insects or soil. Birds at the top of the food chain (e.g., pelicans, falcons, eagles, grebes) had the highest concentrations of DDT. Although the amount of DDT did not kill the birds, it interfered with calcium metabolism, which led to thin eggshells. As a result, eggs would crack during development, allowing bacteria to enter, which killed the developing embryos. This had a great impact on the population levels of these birds. Peregrine falcons and brown pelicans were placed on the endangered species list in the United States, partially due to the declining reproductive success of the birds due to DDT exposure.

Rachel Carson, that unequaled environmental journalist of profound vision and insight, published *Silent Spring* in 1962, which helped to draw public attention to this problem and to the need for better pesticide controls. This was the very beginning of the environmental movement in the United States and is an excellent example of reporting by someone affiliated with the media that identified a problem and warned of many similar problems that could occur unless restrictions were put in place related to chemical pesticide use. Partially as a result of Carson's flagship book, scientists documented the link between DDT and eggshell thinning. This resulted in the U.S. Department of Agriculture, the federal agency responsible for regulating pesticides before formation of the U.S. Environmental Protection Agency in 1970, initiating regulatory actions in the later 1950s and 1960s to prohibit many uses of DDT because of mounting evidence of the pesticide's declining benefits and environmental and toxicological effects.

In 1972, the USEPA issued a cancellation order for DDT based on adverse environmental effects of its use, such as those to wildlife (the known effects on other species, such as raptors), as well as the potential human health risks posed by DDT. Since then, studies have continued, and a causal relationship between DDT exposure and reproductive effects is suspected. Today, DDT is classified as a probable human carcinogen by U.S. and international authorities. This classification is based on animal studies in which some animals developed liver tumors.

Known to be very persistent in the environment, DDT will accumulate in fatty tissues and can travel long distances in the upper atmosphere. Since the use of DDT was discontinued in the United States, its concentration in the environment and animals has decreased, but because of its persistence residues of concern from historical use still remain. Moreover, DDT is still used in developing countries because it is inexpensive and highly effective. Other alternatives are too expensive for these other countries to use (USEPA, 2012).

The approximately 13,500 chemical manufacturing facilities in the United States are owned by more than 9000 companies. There are 84,000 chemicals in use in the United States, and approximately 700 new ones are added each year. Manufacturers generally manufacture chemicals classified into two groups: commodity chemicals and specialty chemicals. Commodity chemical manufacturers produce large quantities of basic and relatively inexpensive compounds in large plants, often built specially to make one chemical. Commodity plants often run continuously, typically shutting down only a few weeks a year for maintenance. Specialty-batch or performance chemical manufacturers produce smaller quantities of more expensive chemicals that are used less frequently on an as-needed basis. Facilities are located all over the country, with many companies in Texas, Ohio, New Jersey, Illinois, Louisiana, Pennsylvania, and North and South Carolina.

In the United States, under the Toxic Substances Control Act (TSCA), five chemicals were banned—only five. This may seem odd because, when the TSCA was passed in 1976, 60,000 chemicals were included in the inventory of existing chemicals. Since that time, the USEPA has only successfully restricted or banned five chemicals and has only required testing on another 200 existing chemicals. An additional 24,000 chemicals have entered the marketplace, so the TSCA inventory now includes more than 84,000 chemicals. The chemical industry is an essential contributor to the U.S. economy, with shipments valued at about $555 billion per year. If we know several chemicals are dangerous or harmful to us and our environment, why have only five of them been banned? The best answer is that under the TSCA it is difficult to ban a chemical that predated the Rule and thus has been grandfathered.

So, which five chemicals has the TSCA banned? If you were a knowledgeable contestant on the television show *Jeopardy*, you might respond with, "What are PCBs, chlorofluorocarbons, dioxin, hexavalent chromium, and asbestos?" An easy question with a straightforward answer, right? Well, not so fast. Technically, you would be incorrect with that answer. Even though the USEPA did initially ban most asbestos-containing products in the United States, in 1991 the rule was vacated and remanded by the Fifth Circuit Court of Appeals. As a result, most of the original bans on the manufacture, importation, processing, or distribution in commerce for most asbestos-containing product categories originally covered in the 1989 final rule were overturned. Only the bans on corrugated paper, rollboard, commercial paper, specialty paper, and flooring felt and any new uses of asbestos remained banned under the 1989 rule. Most asbestos-containing products can still be legally manufactured, imported, processed, and distributed in the United States, even though more than 45,000 Americans have died from asbestos exposure in the past three decades. According to the U.S. Geological Survey, the production and use of asbestos have declined significantly (USEPA, 2014b).

ENDOCRINE DISRUPTORS*

A growing body of evidence suggests that humans and wildlife species have suffered adverse health effects after exposure to endocrine disrupting chemicals (also referred to as *environmental endocrine disruptors*). Environmental endocrine disruptors can be defined as exogenous agents that interfere with the production, release, transport, metabolism binding, action, or elimination of natural hormones in the body responsible for maintaining homeostasis and regulating developmental processes. The definition reflects a growing awareness that the issue of endocrine disruptors in the environment extends considerably beyond that of exogenous estrogens and includes antiandrogens and agents that act on other components of the endocrine system such as the thyroid and pituitary glands (Kavlock et al., 1996). Disrupting the endocrine system can occur in various ways. Some chemicals can mimic a natural hormone, fooling the body into over-responding to the stimulus (e.g., a growth hormone that results in increased muscle mass) or responding at inappropriate times (e.g., producing insulin when it is not needed). Other endocrine disrupting chemicals can block the effects of a hormone from certain receptors. Still others can directly stimulate or inhibit the endocrine system, causing overproduction or underproduction of hormones. Certain drugs are used to intentionally cause some of these effects, such as birth control pills. In many situations involving environmental chemicals, an endocrine effect may not be desirable.

In recent years, some scientists have proposed that chemicals might inadvertently be disrupting the endocrine system of humans and wildlife. Reported adverse effects include declines in populations, increases in cancers, and reduced reproductive function. To date, these health problems have been identified primarily in domestic or wildlife species with relatively high exposures to organochlorine compounds, including DDT and its metabolites, polychlorinated biphenyls (PCBs), and dioxides, or to naturally occurring plant estrogens (phytoestrogens). However, the relationship of human diseases of the endocrine system and exposure to environmental contaminants is poorly understood and scientifically controversial.

Although domestic and wildlife species have demonstrated adverse health consequences from exposure to elements in the environment that interact with the endocrine system, it is not known if similar effects are occurring in the general human population, but again there is evidence of adverse

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* Adapted from Spellman, F.R., *Personal Care Products and Pharmaceuticals in Wastewater and the Environment*, DEStech Publishers, Lancaster, PA, 2014.

effects in populations with relatively high exposures. Several reports of declines in the quality and decrease in the quantity of sperm production in humans over the last five decades and the reported increase in incidences of certain cancers (breast, prostate, testicular) that may have an endocrine-related basis have led to speculation about environmental etiologies (Kavlock et al., 1996). There is increasing concern about the impact of the environment on public health, including reproductive ability, and controversy has arisen from some reviews claiming that the quality of human semen has declined (Carlson et al., 1992). However, little notice has been paid to these warnings, possibly because they have been based on data on selected groups of men recruited from infertility clinics, from among semen donors, or from candidates for vasectomy. Furthermore, the sampling of publications used for review was not systematic, thus implying a risk of bias. Because a decline in semen quality may have serious implications for human reproductive health, it is of great importance to elucidate whether the reported decrease in sperm count reflects a biological phenomenon or, rather, is due to methodological errors.

Data on semen quality collected systematically from reports published worldwide indicate clearly that sperm density declined appreciably from 1938 to 1990, although we cannot conclude whether or not this decline is continuing today. Concomitantly, the incidence of some genitourinary abnormalities including testicular cancer and possibly also maldescent (faulty descent of the testicle into the scrotum) and hypospadias (abnormally placed urinary meatus) has increased. Such remarkable changes in semen quality and the occurrence of genitourinary abnormalities over a relatively short period are more probably due to environmental rather than genetic factors. Some common prenatal influences could be responsible both for the decline in sperm density and for the increase in cancer of the testis, hypospadias, and cryptorchidism (one or both testicles fail to move to scrotum). Whether estrogens or compounds with estrogen-like activity or other environmental or endogenous factors damage testicular function remains to be determined (Carlson et al., 1992). Even though we do not know what we do not know about endocrine disruptors, it is known that the normal functions of all organ systems are regulated by endocrine factors, and small disturbances in endocrine function, especially during certain stages of the life cycle such as development, pregnancy, and lactation, can lead to profound and lasting effects. The critical issue is whether sufficiently high levels of endocrine disrupting chemicals exist in the ambient environment to exert adverse health effects on the general population.

Current methodologies for assessing, measuring, and demonstrating human and wildlife health effects (e.g., the generation of data in accordance with testing guideline) are in their infancy. The USEPA has developed testing guidelines and the Endocrine Disruption Screening Program, which is mandated to use validated methods for screening the testing chemicals to identify potential endocrine disruptors, to determine adverse effects and dose–response, to assess risk, and ultimately to manage risk under current laws.

Biological Effects

In this section, we discuss what we know about the carcinogenic effects of endocrine disrupting agents in humans and wildlife, the major classes of chemicals thought to be responsive for these effects, and the uncertainties associated with the reported effects. Numerous field studies of teleost (bony) fishes in localized highly contaminated areas (i.e., hot spots) have shown high prevalences of liver tumors (Baumann et al., 1990; Harshbarger and Clark, 1990; Meyers et al., 1994). The predominant risk factor that has been associated with these liver tumors is exposure to polyaromatic hydrocarbons (PAHs) and, to a lesser degree, PCBs and DDT. Certain species such as carp and fathead minnows are more resistant, while trout are more sensitive. There has been no indication that the liver tumors in fish involve an endocrine modulation mechanism. Other than for localized areas of high contamination, field studies have shown no increasing trends for tumors of any type in fish. Two tumor registries for wildlife species exist in the United States (Smithsonian Registry of Tumors in Lower Animals and Armed Forces Institute of Pathology's Registry of Comparative Pathology). A variety of dose-related tumors can be produced in fish given carcinogens under experimental laboratory conditions (Couch and Harshbarger, 1985). Again, let's be clear that there is no specific evidence that the development of these tumors involves a hormonal disruption mechanism. Research has shown that estradiol and certain hormone precursors (e.g., dehydroepiandrosterone [DHEA]) act as promoters after treatment of fishes with carcinogenic substances such as aflatoxin and *N*-methyl-*N*-nitroso-*N′*-nitroguanidine (MNNG). Toxicopathic liver lesions have been associated with contaminant exposure in some marine fish (Meyers et al., 1994).

There is a paucity of carcinogenicity data for other forms of wildlife. One study of beluga whales in the St. Lawrence seaway found that approximately 50% of dead whales examined had neoplasms (i.e., abnormal masses of tissue), of which about 25% were malignant (Beland et al., 1993; DeGuise et al., 1995). In 1996, Theo Colborn, together with science writers Dianne Dumanoski and John Peterson Myers, compiled various observations concerning chemical exposure and wildlife health into the book *Our Stolen Future* (often compared to Rachel Carson's *Silent Spring*) and drew a straight line between the effects observed in wild animals and human health effects, including breast and prostate cancer and decreasing male fertility caused by decreasing sperm counts, cryptorchidism (where one or both testicles fail to descend from the body), and hypospadias (deformation of the phallus) (Breithaupt, 2004).

Is this animal-to-humankind endocrine disrupter exposure connection to ill health effects an old-style fishing expedition or is it food for thought? Is it enough to drive maximum effort by scientific researchers? Conversely, one can ask: When it comes to researching and determining the causal factors related to human disease, is there a limiting factor, or should there be one?

The hypothesis that endocrine disruption can cause cancer in humans is based on the causal association between DES exposure of pregnant women and clear-cell adenocarcinoma of the vagina and cervix in their female offspring, hormone-related risk factors for breast and uterine cancer, and limited evidence of an association between body burden levels of 1,1-dichloro-2.2-bis(*p*-chlorophenyl)ethylene (DDE) or PCBs and breast cancer risk (Kavlock et al., 1996). Young women who developed cancer of the vagina were more likely to have had mothers who used diethylstilbestrol (DES) during pregnancy to avoid miscarriage than mothers who did not use the drug (Herbst et al., 1971). The finding has led to a number of important conclusions. First, maternal exposures during gestation can lead to cancer in offspring, and, second, it demonstrates that a synthetic estrogen can cause cancer. Some of the male offspring of women who took DES display pseudohermaphroditism (Kaplan, 1959) and genital malformations, including epididymal cysts, testicular abnormalities such as small testes and microphallus, and reduced semen quality (Driscoll and Taylor, 1980; Gill et al., 1979; Penny, 1982). Follow-up surveys of DES-exposed male offspring, however, did not show impairment in fertility or sexual function (Leary et al., 1984; Wilcox et al., 1995), nor is there evidence of increased risk of testicular cancer (Leary et al., 1984).

According to the CDC (2013) and based on U.S. cancer statistics from 1999 to 2009, the three most common cancers among women of all races and Hispanic origins in the United States are

- Breast cancer (123.1 per 100,000)
- Lung cancer (54.1 per 100,000) (second among white, black, and American Indian/Alaska Native women; third among Asian/Pacific Islander and Hispanic women)
- Colorectal cancer (37.1 per 100,000) (second among Asian/Pacific Islander and Hispanic women; third among white, black, and American Indian/Alaska Native women)

The leading causes of cancer death among women are

- Lung cancer (38.6 per 100,000 women of all races) (first among white, black, Asian/Pacific Islander, and American Indian/Alaska Native women; second among Hispanic women)
- Breast cancer (22.2 per 100,00 women of all races) (first among Hispanic women; second among white, black, Asian/Pacific Islander, and American Indian/Alaska Native women)
- Colorectal cancer (13.1 per 100,000 women of all races (third among women of all races and Hispanic origin populations)

The most common cancer among women in the United States is breast cancer. A number of epidemiological studies have examined the risk factors for breast cancer. Identified risk factors include several that relate to hormonal activity: decreased parity, age at first delivery, age at menarche (the beginning of the menstruation), age, race, and unopposed estrogen therapy. In addition, breast tumors can be characterized as to their degree of estrogen-receptor positivity resulting in relevant prognostic information. The evidence supports a causal relationship between female breast cancer and hormonal activity.

A number of organochlorine pesticides or pesticidal metabolites are found in breast milk and human adipose tissue (Jensen and Slorach, 1991; Sonawane, 1995). Several cross-sectional studies have suggested a possible relationship between levels of some organohalide residues in human tissues and breast cancer risk, although the observations are not entirely consistent across studies, and no clear relationship has been established (Austin et al., 1989; DeWally et al., 1994; Falck et al., 1992; Henderson et al., 1995; Krieger et al., 1994; Mussalo-Rauhamaa et al., 1990; Unger et al., 1984; Wolff et al., 1993). In general, these studies suggested that levels of *p,p′*-DDE and total PCBs were higher in the fat or serum of woman who had breast cancer than in comparison groups. The meaning of these findings is unclear, in part because *op,p′*-DDE and the few PCB congeners that have been tested have little or no discernible estrogenic activity, while the short-lived forms of DDT, *o,p′*-DDT and *o,p′*-DDE, have only very weak estrogenic properties. Further, a 1994 case-control study with historical data from serum DDE and PCBs conflicts with earlier findings (Krieger et al., 1994). This study showed no overall effect of serum residue levels on breast cancer risk, although subcategorical analysis did suggest a possible increase in risk among black women with higher levels of serum *p,p′*-DDE. The women in these studies, except those in the study by Henderson et al. (1995), were not exposed to high levels of PCBs or DDE, and the actual differences in levels measured between cases and controls were not large. Studies of women occupationally exposed to high levels of PCBs have not demonstrated an excess risk of breast cancer mortality (Brown, 1987; Sinks, 1992). The results of these studies, therefore, are equivocal and further research is needed (including examination of effects in subsequent generations for parental exposures).

The bottom line is that examination of the USEPA database on pesticide registration or organochlorines showed no correlation of the spectrum of tumor types observed in laboratory animals with the assertion that the organochlorines are related to human breast cancer. Organochlorines frequently increased the incidence of liver tumors in rates but did not increase the incidence of mammary tumors (Kavlock et al., 1996). One subclass of herbicides, the chloro-*S*-triazines, produces an earlier onset of mammary tumors in Sprague–Dawley rats (Stevens, 1994; Wetzel et al., 1994), but there are no epidemiological studies that suggest a relationship between exposure to triazine herbicide and human breast cancer. An examination of the National Toxicology Program (NTP) database involving approximately 450 animal studies showed increased incidences of mammary tumors in approximately 10% of the studies. However, based on evaluation of chemical structures and other available information, this subset of test substances is not likely to be estrogenic (Dunnick et al., 1995). This analysis only considered the possibility that the chemicals were direct estrogen agonists. It is obvious that other possible mechanisms exist for induction of endocrine-mediated tumors. Moreover, good animal or cellular models do not yet exist for the study of some endocrine-mediated tumors (e.g., testicular) that are reported to be on the increase in the human population, but such models would be useful in testing cause-and-effect relationships.

The previous discussion addressed the potential for endocrine disruptors to cause breast cancer in women. What about men? What is the potential for men to contract various cancers via exposure to certain endocrine disruptors? The jury is still out on this question, but many studies have been conducted on the subject and many researchers have attempted to show a possible straight-line connection between the two; for example, the possible link between endocrine disruptors and prostate cancer has been studied extensively.

Reproductive Effects

Some of the major questions currently being asked about the reproductive effects of endocrine disruptors include the following: What do we know about the reproductive and developmental effects of endocrine disrupting agents in humans and wildlife? What are the major classes of chemicals thought responsible for these effects? What are the uncertainties associated with the reported effects? In this section, we provide both speculative opinions and authoritative answers for these questions.

Field and laboratory studies of wildlife populations and individuals have revealed effects in offspring that appear to be the result of endocrine disruption. Examples include reproductive problems in wood ducks (*Aix sponsa*) from Bayou Meto, Arkansas, which is downstream from a hazardous waste site in central Arkansas (White and Hoffman, 1995); wasting and embryonic deformities in Great Lakes colonial fish-eating birds (i.e., herring gulls, common terns, and double-crested cormorants) (Bowerman et al., 1995; Colborn, 1991; Fox et al., 1991a,b; Giesy et al., 1995; Gilbertson et al., 1991; Hoffman et al., 1987; Peakall and Fox, 1987); feminization and demasculinization of gulls (Boss and Witschi, 1943; Fox et al., 1978; Fry and Toone, 1981; Fry et al., 1987); developmental effects in Great Lakes snapping turtles (*Chelydra serpentina*) (Bishop et al., 1991); embryonic mortality and developmental dysfunction in lake trout and other salminiods in the Great Lakes (Leatherland, 1993; Mac and Edsall, 1991; Mac et al., 1993); abnormalities of sexual development in Lake Apopka alligators (Guillette et al., 1994, 1995); reproductive failure in mink from the Great Lakes area (Wren, 1991); and reproductive impairment in the Florida panther (Facemire et al., 1995). In each case, detectable concentrations of chemicals with known endocrine disruption effects have been reported in the animals or in their environment, but an etiological link has been established for only a few of these observations. In ecological studies, these effects were not recognized until the populations began to decline. However, the observation that a population is stable is not an assurance that endocrine disrupting chemicals are not affecting reproduction, development, or growth of individuals.

Neurological Effects

Some of the major questions currently being asked about the neurological effects of endocrine disruptors include the following: What do we know about the neurological effects of endocrine disrupting agents in humans and wildlife? What are the major classes of chemicals thought to be responsible for these effects? What are the uncertainties associated with the reported effects? In this section, we provide both speculative opinions and authoritative answers for these questions.

Current knowledge indicates that neuroendocrine disruption can be induced by multiple mechanisms. Direct effects on endocrine glands (e.g., the thyroid) may alter the hormonal milieu, which in turn can affect the nervous system, resulting in neurotoxicity. Conversely, EDCs may initially act on the central nervous system (CNS) (e.g., neuroendocrine disruptors), which in turn can influence the endocrine system. Simply, exposure to chemicals can adversely affect the structure and function of the nervous system without any endocrine system involvement. Moreover, alterations in the following would be indicative of neuroendocrine disruption: reproductive behaviors mediated by alterations in the hypothalamic–pituitary axis (e.g., courtship and parental behavior in avian species); alterations in metabolic rate, which could indirectly affect behavior; altered sexual differentiation in the brain, which could affect sexually dimorphic reproductive and nonreproductive neural end points; and some types of neuroteratogenic effects. There are clear examples in the human and animal literature in which exposure to endocrine disruptors had occurred and effects on behavior, learning and memory, attention, sensory function, and psychomotor development were observed (Colborn et al., 1993; Fox et al., 1978; McArthur et al., 1983). Some of these effects, however, can also be produced by developmental neurotoxicants having little or no known endocrine disrupting properties and, therefore, cannot be regarded as specific to the endocrine disrupting class of chemicals. It is known that exposures to a number of nonchemical factors (e.g., food or oxygen deprivation, infections, temperature) could also adversely affect the nervous system, resulting in effects similar to those produced by endocrine disruptors. These nonchemical factors may also interact in as yet unpredictable ways with chemical stressors. Therefore, considerable care should be taken to eliminate nonchemical causes before concluding that neurotoxicity is causally related to the effects of a chemical acting on the endocrine system.

There are several examples of chemicals or classes of chemicals that produce neurotoxicity by an endocrine mechanism. Environmental toxicologist should consider the dose at which neuroendocrine dysfunctions are produced relative to the concentrations existing in the environment and relative to dose levels at which other toxic effects occur, the relationship between exposure and effect, and the role of naturally occurring chemicals with endocrine-mimicking properties. With these caveats in mind, examples of directly or indirectly acting neuroendocrine disruptors include some PCBs, dioxins, DDT and related chlorinated pesticides and their metabolites, some metals (methylmercury, lead, organotins), insect growth regulators, dithiocarbamates, synthetic steroids, tamoxifen, phytoestrogen, and triazine herbicides. Identification of chemicals as neuroendocrine disruptors should be based on mechanistic information at the cellular or molecular level in the endocrine system or defined functionally in terms of activity on response known to be mediated by or dependent on hormones. All definitions of neuroendocrine disruptors should be interpreted specifically with respect to gender, hormonal status, and developmental stage, because the expression of toxicities for chemicals may change significantly depending on these variables.

A number of uncertainties critical to understand the significance and effects of neuroendocrine disruptors have been identified:

1. Chemicals occur as mixtures in the environment, thereby making it difficult to assign cause and effect for specific agents. It is possible that the parent chemical may not affect the endocrine system but is metabolized to an active form. The toxicokinetics of and relative tissue distribution into the nervous system are generally unknown for most chemicals; little is known about the metabolic interaction between chemicals in mixtures.
2. There are ranges of possible specific and nonspecific effects that could be measured. Research to date has used only a small number of techniques and methods, and it is likely that many neuroendocrine effects may be subtle and not easily detected with currently available procedures. It is also a concern that the functions most sensitive to chemically induced alterations in neuroendocrine function are the most difficult to measure in the field.
3. It is critical to know when exposure occurred relative to when the effects are measured. Observed effects could be dependent on a number of intrinsic factors such as seasonal variability and intrinsic facts such as hormonal status. In addition, the nervous system is known to be differently sensitive to chemical perturbation at various stages of development. A chemical may have a significant effect on neuroendocrine function if exposure occurs at a critical period of development but have little or no effect at other stages of maturation.
4. Several issues related to extrapolation are critical to understanding neuroendocrine disruptors. For example, it is difficult to evaluate the significance to human health of a chemically induced change in a behavior that does not naturally occur in humans; that is, there are concerns about the appropriateness of some animal models for toxicologic studies. In addition, there are uncertainties about extrapolating from one species to another and from experiments conducted in the laboratory to those performed in the field.
5. There are uncertainties about the shape of the respective dose–response curves for many neuroendocrine effects. It is likely that some chemicals may have multiple effects occurring at different points on the dose–response curve.
6. Basic information concerning the mechanism of action of chemicals on the developing nervous system and the neurological role of hormones during development would greatly reduce uncertainties about risk of exposure to neuroendocrine disruptors. Furthermore, it is also important to understand the consistency of the effects relative to the hypothesis that chemicals are affecting the nervous system.

Immunological Effects

Some of the questions currently being asked about the immunological effects of endocrine disrupters include the following: What do we know about the immunological effects of endocrine disrupting agents in humans and wildlife? What are the major classes of chemicals thought responsible for these effects? What are the uncertainties associated with the reported effects? In this section, both speculative opinions and authoritative answers are provided for these questions.

Published studies have demonstrated associations between autoimmune syndromes and DES exposures (Noller et al., 1988). A relationship has been well established between physiological estrogen levels and autoimmune diseases in women (Grossman, 1985; Homo-Delarche et al., 1991; Schuurs and Veheul, 1990). The observations that exposure of humans to DES, TCDD, PCBs, carbamates, organochlorines, organometals, and certain heavy metals alters immune phenotypes or function are suggestive of immunosuppression (Davis and Safe, 1990; Dean et al., 1994b; Luster et al., 1990; McKinney et al., 1976). Experimental animal studies support these observations (e.g., Loose et al., 1977), although dose–response information is needed to clarify whether these are directly or indirectly acting agents. With respect to fish and wildlife, it was also noted that several of the agents listed above induce immune suppression or hyperactivity similar to that reported in experimental animals and humans. Embryonic exposure of trout to aflatoxin has led to alterations in adult immune capacity (Arkoosh, 1989; Arkoosh and Kaattari, 1987; Kaattari et al., 1994). With regard to disease susceptibility and exposure, there have been examples such as the dolphin epizootic of 1987 to 1988 (Aguilar and Raga, 1983). In this case, there was an association with PCBs and DDT in the blood, decreased immune function, and increased incidence of infections among affected individuals (Swenson et al., 1994). Impairment in immune function has been reported in bottlenose dolphins exposed to PCBs and DDT (Lahvis et al., 1995) and in harbor seals fed fish from polluted waters (deSwart et al., 1994; Ross et al., 1995). From 1991 to 1993, specific immune functions and general hematologic parameters were measured in herring gull and Caspian tern chicks from a number of study sites in the Great Lakes chosen across a wide range of organochlorine contamination (primarily PCBs). As the hepatic activity of ethoxinyresorufin-*O*-deethylase (EROD), an index of exposure, increased, thymus mass decreased. At highly contaminated sites, both gull and tern chicks showed marked reductions in T-cell-mediated immunity as measured by the phytohemagglutinin skin test (Grassman and Scanlon, 1995).

A variety of immunoassays have been used to demonstrate effects in experimental laboratory animals, humans, fish, and wildlife. These include modulation of antibody response (both *in vivo* and *in vitro*), the phytohemagglutinin skin test, mitogenesis, phagocytosis, levels of complement or lack of acute phase reactants, cytotoxic T-lymphocyte reactivity, and natural killer cell activity (Bowser et al., 1994; Dean et al., 1994a; Grassman and Scanlon, 1995; Luster et al., 1988; Schrank et al., 1990; Zelikoff et al., 1991, 1995).

Evidence of an increased rate of autoimmunity associated with prenatal DES exposure suggests the possibility that other endocrine disrupting chemicals may induce a similar pathologic state. Studies are needed to determine if there has been an increase in cases of immune dysregulation in areas or sites where EDC exposures have occurred. Evidence indicates that the incidences of allergy and asthma (forms of hypersensitivity) is increasing in humans (Buist and Vollmer, 1990; Gergen and Weiss, 1990; Weiss and Wagener, 1990). It is not known whether EDC exposures are responsible for some part of this development. Alteration of sex-steroid balance has been shown to lead to increased or accelerated onset of autoimmune syndromes in mice (Homo-Delarche et al., 1991). In rats and mice, heavy metals such as lead, mercury, and gold enhance autoimmune syndromes (Zelikoff et al., 1994; Pelletier et al., 1994). There have also been reports of exposures of fish to EDCs in the environment that led to immune enhancement. Although autoantibodies have been reported in sharks and trout (Gonzalez et al., 1989; Marcholonis et al., 1993; Michel et al., 1990), no attempts have been made to correlate exposure to EDCs with incidences of autoantibodies. In trout, embryonic exposure to aflatoxin B_1 can lead to immune stimulation or suppression in the adult, depending on the immune parameter analyzed (Kaattari et al., 1994). Other data suggest that small changes in physiologic levels of estrogens can affect the immune system, and studies in gull and tern chicks in the Great Lakes clearly indicate that the findings are associated with developmental exposures (Grassman, 1995).

Concerning direct-acting EDCs, although it would appear that these agents directly affect the immune system, it is unknown whether there may be disruptive effects on the endocrine–immune axis. Because the immune and endocrine systems are linked via various cytokine signaling processes (IL-1, ACTH, catecholamines, prolactin, and endorphins), it is likely that EDC effects on the immune system modulate elements of the endocrine or nervous systems or *vice versa*. Too little is known about the dose–response curves for immunotoxicity, neurotoxicity, or endocrine effects to decipher the independent or interactive effects on these systems. Because of the high degree of intercommunication between these systems, there is a need for coordinated and cooperative studies among laboratories in all of these disciplines.

Although the most forceful arguments for the overall consequences of immune dysfunction would be increased disease incidence, this is difficult to assess in humans or wildlife populations. Furthermore, only certain subpopulations (the very young or elderly) may be affected. Disease may only be manifested as a population decline. Disease trials can be undertaken, but they require controlled laboratory experiments employing populations of wild animals or fish that can easily be maintained in the laboratory. In humans, the variability within a population makes it difficult to decipher exogenously triggered effects.

The fact that employment of a variety of *in vitro* assays has been successful in correlative exposure studies leads to the question of whether those immune parameters can be correlated with the increased risk of disease. A number of immune parameters operate independently (e.g., lysozyme levels, complement activity, phagocytosis, induction of cytotoxic T-lymphocytes, plaque-forming cells). Which combination of these assessments would make for an optimal predictive suite of assays? Knowledge of normal baseline values for wildlife species, and in most cases humans, is lacking. If these populations are to be screened for perturbations in immune function, control populations must be defined and standardized control values obtained. Also, the types of exposures must be well documented (i.e., dose, length of exposure, and timing).

PHARMACEUTICALS AND PERSONAL CARE PRODUCTS*

Pharmaceuticals and personal care products were first referred to as PPCPs (Figure 8.1) only a few years ago, but these bioactive chemicals (substances that have an effect on living tissue) have been around for decades. Their effect on the environment is now recognized as an important area of research. PPCPs include the following:

- Prescription and over-the-counter therapeutic drugs
- Veterinary drugs
- Fragrances
- Cosmetics
- Sunscreen products
- Diagnostic agents
- Nutraceuticals (e.g., vitamins)

Sources of PPCPs include the following:

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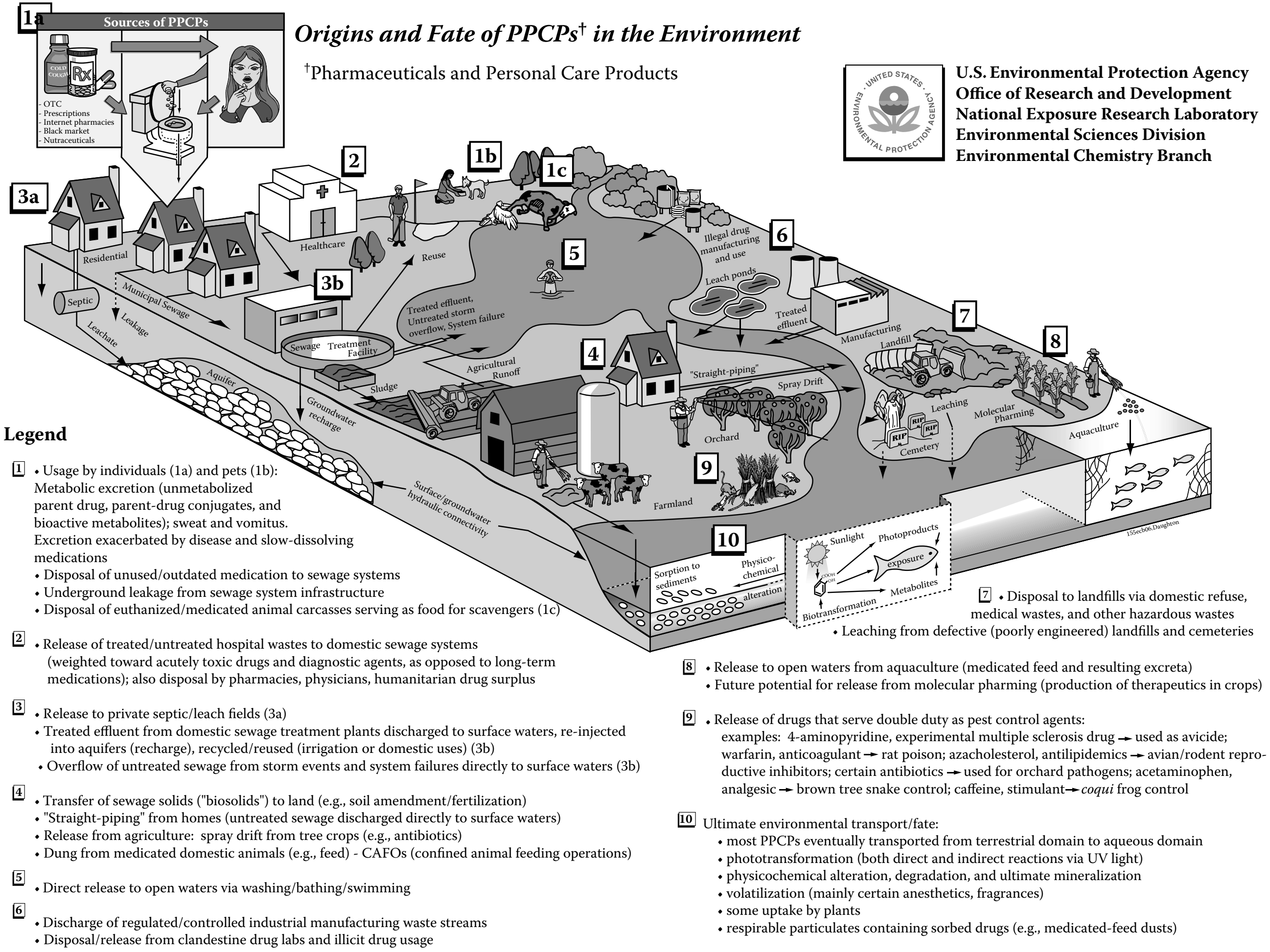
* Adapted from Daughton, C.G. and Ternes, T.A., Pharmaceuticals and personal care products in the environment: agents of subtle change?, *Environ. Health Perspect.*, 107(Suppl. 6), 907–938, 1999; Daughton, C.G., *Drugs and the Environment: Stewardship and Sustainability*, U.S. Environmental Protection Agency, Las Vegas, NV, 2010.



Origins and Fate of PPCPs† in the Environment

†Pharmaceuticals and Personal Care Products

U.S. Environmental Protection Agency
Office of Research and Development
National Exposure Research Laboratory
Environmental Sciences Division
Environmental Chemistry Branch

Legend

1
- Usage by individuals (1a) and pets (1b): Metabolic excretion (unmetabolized parent drug, parent-drug conjugates, and bioactive metabolites); sweat and vomitus. Excretion exacerbated by disease and slow-dissolving medications
- Disposal of unused/outdated medication to sewage systems
- Underground leakage from sewage system infrastructure
- Disposal of euthanized/medicated animal carcasses serving as food for scavengers (1c)

2
- Release of treated/untreated hospital wastes to domestic sewage systems (weighted toward acutely toxic drugs and diagnostic agents, as opposed to long-term medications); also disposal by pharmacies, physicians, humanitarian drug surplus

3
- Release to private septic/leach fields (3a)
- Treated effluent from domestic sewage treatment plants discharged to surface waters, re-injected into aquifers (recharge), recycled/reused (irrigation or domestic uses) (3b)
- Overflow of untreated sewage from storm events and system failures directly to surface waters (3b)

4
- Transfer of sewage solids ("biosolids") to land (e.g., soil amendment/fertilization)
- "Straight-piping" from homes (untreated sewage discharged directly to surface waters)
- Release from agriculture: spray drift from tree crops (e.g., antibiotics)
- Dung from medicated domestic animals (e.g., feed) - CAFOs (confined animal feeding operations)

5
- Direct release to open waters via washing/bathing/swimming

6
- Discharge of regulated/controlled industrial manufacturing waste streams
- Disposal/release from clandestine drug labs and illicit drug usage

7
- Disposal to landfills via domestic refuse, medical wastes, and other hazardous wastes
- Leaching from defective (poorly engineered) landfills and cemeteries

8
- Release to open waters from aquaculture (medicated feed and resulting excreta)
- Future potential for release from molecular pharming (production of therapeutics in crops)

9
- Release of drugs that serve double duty as pest control agents: examples: 4-aminopyridine, experimental multiple sclerosis drug → used as avicide; warfarin, anticoagulant → rat poison; azacholesterol, antilipidemics → avian/rodent reproductive inhibitors; certain antibiotics → used for orchard pathogens; acetaminophen, analgesic → brown tree snake control; caffeine, stimulant → *coqui* frog control

10 Ultimate environmental transport/fate:
- most PPCPs eventually transported from terrestrial domain to aqueous domain
- phototransformation (both direct and indirect reactions via UV light)
- physicochemical alteration, degradation, and ultimate mineralization
- volatilization (mainly certain anesthetics, fragrances)
- some uptake by plants
- respirable particulates containing sorbed drugs (e.g., medicated-feed dusts)

FIGURE 8.1 Origins and fate of PPCPs in the environment. (From Daughton, C.G., *Origins and Fate of PPCPs in the Environment*, U.S. Environmental Protection Agency, Las Vegas, NV, 2006.)

- Human activity
- Residues from pharmaceutical manufacturing
- Residues from hospitals
- Illicit drugs
- Veterinary drug use, especially antibiotics and steroids
- Agribusiness

The significance of individuals directly contributing to the combined load of chemicals in the environment has gone largely unrecognized, but the presence of PPCPs in the environment illustrates the immediate connection of the actions and activities of individuals with their environment. Individuals add PPCPs to the environment through excretion (the elimination of waste material from the body) and bathing, as well as the disposal of unwanted medications to sewers and trash. Some PPCPs are easily broken down and processed by the human body or degrade quickly in the environment, but others are not easily broken down and processed, so they enter domestic sewers. Excretion of biologically unused and unprocessed drugs depends on

- *Individual drug composition*—Certain excipients, or inert ingredients, can minimize absorption and therefore maximize excretion.
- *Ability of individual bodies to break down drugs*—This ability depends on age, sex, health, and individual idiosyncrasies.

Because they dissolve easily and do not evaporate at normal temperatures or pressure, PPCPs make their way into the soil and into aquatic environments via sewage, treated sewage biosolids (sludge), and irrigation with reclaimed water.

For the purposes of this text and the following discussion, pharmaceutical, veterinary, and illicit drugs and the ingredients in cosmetics, food supplements, and other personal care products, together with their respective metabolites and transformation products, are collectively referred to as PPCPs and more appropriately called *micropollutants*. PPCPs are commonly infused into the environment via sewage treatment facilities, outhouses, septic tanks, cesspools, concentrated animal feeding operations (CAFOs), human and animal excretion into the environment (water and soil), and wet weather runoff (e.g., stormwater runoff). In many instances, untreated sewage is discharged into receiving waters by flood overload events, domestic straight-piping, bypassing due to interceptor and pumping failures, or sewage waters lacking municipal treatment. In the United States alone, possibly more than a million homes do not have sewage systems but instead rely on direct discharge of raw sewage into streams by straight-piping or by outhouses not connected to leach fields (Pressley, 1999).

Note that, even with wastewater treatment, many of the micropollutants in the sewage waste stream remain in the effluent that is discharged into the receiving waters, because many treatment processes are not designed to remove low concentrations of PPCP micropollutants. The big unknown is whether the combined low concentrations from each of the numerous PPCPs and their transformation products have any significance with respect to ecologic function, while recognizing that immediate effects could escape detection if they are subtle and that long-term cumulative consequences could be insidious. Another question is whether the pharmaceuticals remaining in water used for domestic purposes pose long-term risks for human health after lifetime ingestion via potable waters multiple times a day of very low, subtherapeutic doses of numerous pharmaceuticals; however, this issue is not addressed in this text.

The problem is further complicated by the fact that, although the concentration of individual drugs in the aquatic environment could be low (subparts per billion or subnanomolar, often referred to as micropollutants), the presence of numerous drugs sharing a specific mode of action could lead to significant effects through additive exposures. It is also significant that, until very recently, drugs, unlike pesticides, have not been subject to the same scrutiny regarding possible adverse environmental effects. They have therefore enjoyed several decades of unrestricted discharge to the environment, mainly via wastewater treatment works. This is surprising, especially because certain pharmaceuticals are designed to modulate endocrine and immune systems and cellular signal transduction. As such, they have obvious potential to act as endocrine disruptors in the environment, which is especially true for aquatic organisms, whose exposures may be of a more chronic nature because PPCPs are constantly infused into the environment wherever humans live or visit, whereas pesticide fluxes are more sporadic and have greater spatial heterogeneity. At the present time, it is quite apparent that little information exists from which to construct comprehensive risk assessments for the vast majority of PPCPs having the potential to enter the environment.

Although little is known of the occurrence and effects of pharmaceuticals in the environment, more data exist for antibiotics than for any other therapeutic class. This is the result of their extensive use in both human therapy and animal husbandry, their more easily deterred effects end points (e.g., via microbial and immunoassays), and their greater chances of introduction into the environment, not just by wastewater treatment plants but also by runoff and groundwater contamination, especially from confined animal feeding operations. The literature on antibiotics is much more developed because of the obvious issues of direct effects on native microbiota (and consequent alteration of microbial community structure) and development of resistance in potential human pathogens. Because of the considerably larger literature on antibiotics, this text only touches on this issue; for the same reason, it only touches on steroidal drugs purposefully designed to modulate endocrine systems.

Pharmaceuticals and the Environment

The fact that pharmaceuticals have been entering the environment from a number of different routes and possibly causing untoward effects in biota has been noted in the scientific literature for several decades, but until recently its significance has gone largely unnoticed. This is due in large part to the international regulation of drugs by human health agencies, which usually have limited expertise in environmental issues. In the past, drugs were rarely viewed as potential environmental pollutants, and there was seldom serious consideration given to their fates once they were excreted from the user. Then again, until the 1990s, any concerted efforts to look for drugs in the environment would have met with limited success because the chemical analysis tools required to identify the presence of drugs with low detection limits (i.e., nanograms per liter or parts per trillion) amid countless other substances, native and anthropogenic alike, were not commonly available. Other obstacles that still exist to a large degree are that many pharmaceuticals and cosmetic ingredients and their metabolites are not available in the widely used environmentally oriented mass spectral libraries. They are available in such specialty libraries such as Pfleger (Maurer et al., 2011), which are not frequently used by environmental chemists. Analytical reference standards, when available, are often difficult to acquire and are quite costly. The majority of drugs are also highly water soluble. This precludes the application of straightforward, conventional sample clean-up/preconcentration methods, coupled with direct gas chromatographic separation, that have been used for years for conventional pollutants, which tend to be less polar and more volatile.

Drugs in the environment did not capture the attention of the scientific or popular press until recently. Some early overviews and reviews were presented by Halling-Sorenson et al. (1998), Raloff (1998), Roembke et al. (1996), Ternes et et al. (1998, 1999), and Velagaleti (1998); more recently, by USEPA's Christian G. Daughton (2010). The evidence supports the case that PPCPs refractory to degradation and transformation do indeed have the potential to reach the environment. What is not known, however, is whether these chemicals and their transformation products can elicit physiologic effects on biota at the low concentrations at which they are observed to occur. Another unknown is the actual quantity of each of the numerous commercial drugs that is ingested or disposed of. With respect to determining the potential extent of the problem, this contrasts sharply with pesticides, for which usage is much better documented and controlled.

When discussing disposal or wastage of pharmaceuticals, one thing seems certain—namely, we must understand the terminology currently used in discussing drug disposal or drug wastage. Daughton (2010) pointed out that discussions of drug disposal are complicated enough, but sometimes it is not even clear as to what is meant by the various terms used to describe drugs that are subject to disposal. Terms used in the literature include *unused*, *unwanted*, *unneeded*, *expired*, *wasted*, and *leftover*. The distinctions between these can be subtle or ambiguous. For instance, "unused" and "expired" are not good descriptors, as they represent only subsets of the total spectrum of medications that can require disposal. "Unused" omits those medications requiring disposal but which have indeed already been used (such as used medical devices). Just because a medication container or package has been opened does not necessarily mean that it has been used. "Unused" can also mean to patients that they are literally no longer using the medication (for its intended purpose), despite the fact that many patients continue using medications on a self-medicating basis—that is, administering the medication for a condition or duration not originally intended, one of the many forms of noncompliance. The term "expired" omits the preponderance of drugs that are discarded before expiry, often soon after they are dispensed. The term "leftover" is sufficiently expansive, as it includes all medications no longer begin used for the original prescribed condition or intended use—or even unintended purpose. Another term often used to refer to unused consumer pharmaceuticals is *home-generated pharmaceuticals* (or *home-generated pharmaceutical waste*), but this too is not a rigorous term, as many drugs for consumer use are not kept in the home but are dispersed in countless locations throughout society (Ruhoy and Daughton, 2008).

A major obstacle in any discussion of drug wastage is what exactly is meant by "wastage." A definition of wastage is notoriously difficult, especially because the topic involves countless variables and perspectives. A simple definition for drug waste is medications dispensed to—or purchased by—a consumer that are never used for the original intended purpose. But, on closer examination, this is not as straightforward as it might first appear. A better term might be *leftover* medications, as this avoids any inference of whether the medications were actually wasted (that is, served no purpose) but does not infer a reason for why the medications accumulated unused or unwanted. Would a medication intended for emergency contingency purposes (and now expired) be considered wasted? After all, such medications served their purpose of being available for possible emergencies. How about medications intended for unscheduled consumption as the situation arises or as needed? These scenarios show that it would not be possible to completely eliminate leftover medications—only to reduce them to a necessary minimum. It could be argued whether or not the basic premise that medications experience undue wastage is even valid. No one really knows how much drug waste occurs in commerce (at the consumer level or in the healthcare setting) in terms of either the total quantity or the cost. In one review of medication wastage, White (2010) observed that traditional estimates for the United Kingdom are that 1 to 10% of the total cost of medications are wasted, but estimates in the United Kingdom are usually based on the quantities of medications returned to pharmacies by consumers, omitting the quantities that are disposed of at home, stored indefinitely, or shared with others.

Many statements regarding drug wastage are based on rates of patient compliance, which is an enormously complex and controversial topic by itself. Noncompliance rates, however, include not only the frequency with which drugs go unused but also the frequency with which prescriptions are *not* filled or with which they are consumed incorrectly. Neither of the latter contributes to any need for disposal. Failure to fill a prescription may even reduce the need for disposal, so noncompliance does not necessarily lead to leftover drugs. Few make this distinction in the literature. One example is a report by White (2009), who discussed the many nuances and points of confusion regarding the data on drug wastage.

Table 8.1 lists various PPCPs, together with their use or origin and some representative environmental occurrence and effects data. These chemicals, together with their synthetic precursors and transformation products, are continually released into the environment in enormous quantities as a result of their manufacture and use (via excretion, mainly in urine and feces) and the disposal

TABLE 8.1
PPCPs Identified in Environmental Samples or That Have Significance for Aquatic Life

Compound	Use/Origin	Environmental Occurrence	Refs.
Acetaminophen	Analgesic/ antiinflammatory	Efficiently removed by POTW. POTW maximum effluent, 6.0 μg/L; not detected in surface waters.	Ternes (1998)
Acetylsalicylic acid	Analgesic/ antiinflammatory	Ubiquitous. One of the first pharmaceuticals identified in sewage influent/effluent. POTW removal efficiency, 81%; POTW maximum effluent, 1.5 μg/L; maximum in surface waters, 0.34 μg/L. Sewage effluent, 1 μg/L.	Richardson and Bowron (1985); Ternes (1998)
Betaxolol	Beta-blocker (antihypertensive, antiglaucoma)	POTW maximum effluent, 0.19 μg/L; maximum in surface waters, 0.028 μg/L.	Hirsch et al. (1996)
Bezafibrate	Lipid regulator	Loading of ~300 g/day in German POTW. POTW removal efficiency, 83%; POTW maximum effluent, 4.6 μg/L; maximum in surface waters, 3.1 μg/L. Influent concentration of 1.2 μg/L in Brazilian sewage treatment works (STWs), with removal efficiencies ranging from 27 to 50%.	Stumpf (1999); Ternes (1998)
Biphenylol	Antiseptic, fungicide	In POTWs in Germany, biphenylol was routinely found in both influents (up to 2.6 μg/L) and effluents, but removal was extensive.	Ternes et al. (1998)
Bisoprolol	Beta-blocker (antihypertensive)	POTW maximum effluent, 0.37 μg/L; maximum in surface waters, 2.9 μg/L.	Hirsch et al. (1996)
Carazolol	Beta-blocker (antihypertensive, antianginal, antiarrhythmic)	POTW maximum effluent, 0.12 μg/L; maximum in surface waters, 0.11 μg/L.	Hirsch et al. (1996)
Carbamazepine	Analgesic; antiepileptic	Loading of over 100 g/day in German POTW, but load in effluent can be 114 g/day. POTW removal efficiency, 7%; POTW maximum effluent, 6.3 μg/L; maximum in surface waters, 1.1 μg/L.	Ternes (1998)
4-Chlor-3,5-xylenol (chloroxylenol)	Antiseptic	In POTWs in Germany, 4-chloroxylenol was occasionally found in both influents and effluents (<0.1 μg/L).	Ternes et al. (1998)
Chlorophene	Antiseptic	In POTWs in Germany, chlorophene was routinely found in both influents (up to 0.71 μg/L) and effluents; removal was not as extensive as for biphenylol.	Ternes et al. (1998)
Clenbuterol	Bronchodilator	POTW maximum effluent, 0.08 μg/L; maximum in surface waters, 0.05 μg/L.	Ternes (1998)
Clofibrate	Lipid regulator	Not detected in POTW effluent and not detected in surface waters; river water, ~40 ng/L.	Richardson and Bowron (1985); Ternes (1998)

Continued

TABLE 8.1 (Continued)
PPCPs Identified in Environmental Samples or That Have Significance for Aquatic Life

Compound	Use/Origin	Environmental Occurrence	Refs.
Clofibric acid	Polar, active metabolite of lipid regulators (clofibrate, etofyllin clofibrate, etofibrate)	One of the first prescription drugs/ metabolites ever reported in sewage influent/effluent. Missouri STW effluent averaged 2.1 kg/day; 0.8 to 2.0 µg/L in raw sewage and activated sludge effluent. Loading of over 50 g/day in German POTW; POTW removal efficiency, 51%; POTW maximum effluent, 1.6 µg/L; maximum in surface waters, 0.55 µg/L. In Swiss rural/urban lakes, 1 to 9 ng/L (ppt); in North Sea, up to 7.8 ng/L; in Brazilian STWs, influent concentration of 1 µg/L, with removal efficiencies ranging from 15 to 34%; in German tap waters, up to 270 ng/L.	Buser and Muller (1998); Garrison et al. (1976); Heberer et al. (1998); Hignite and Azanoff (1977); Stumpf et al. (1999); Ternes (1998)
Cyclophosphamide	Antineoplastic	POTW maximum effluent: 0.02 µg/L; not detected in surface waters. Hospital sewage, 146 ng/L and 19 ng/L to 4.5 µg/L; POTW receiving hospital waste, influent up to 143 ng/L and effluent up to 17 ng/L.	Steger-Hartmann et al. (1996); Ternes (1998)
Diatrizoate (Na)	X-ray contrast media	Resistant to biodegradation and yields refractory, unidentified metabolites. In German surface waters, median concentration of 0.23 µg/L. Isolated maximum values above 100 µg/L indicate that locally very high concentrations can occur, especially in small streams containing a high percentage of STW discharges.	Kalsch (1999); Ternes and Hirsch (2000)
Diazepam	Psychiatric drug (anxiolytic; muscle relaxant)	POTW maximum effluent, 0.04 µg/L; not detected in surface waters. In groundwater from a Superfund site near Atlantic City, NJ, 10 to 40 µg/L.	Genicola (1999); Ternes (1998)
Dicofenac-Na	Analgesic/ antiinflammatory	Loading of ~100 g/day in German POTW; POTW removal efficiency, 69%; POTW maximum effluent, 2.1 µg/L; maximum in surface waters, 1.2 µg/L. Influent to Swiss STWs, 500 to 1800 ng/L and effluents more than 50% as much. In Swiss lakes and rivers, 1 to 12 ng/L, with lower order streams at 11 to 310 ng/L. In Brazilian STWs, influent concentrations of 0.8 µg/L with removal efficiencies ranging from 9 to 75%.	Buser et al. (1998); Stumpf et al. (1999); Ternes (1998)
Dimethylaminophenazone (aminopyrine)	Analgesic/ antiinflammatory	Loading of over 50 g/day in German POTW; POTW removal efficiency, 38% POTW maximum effluent, 1.0 µg/L; maximum in surface waters, 0.34 µg/L.	Ternes (1998)

Continued

TABLE 8.1 (Continued)
PPCPs Identified in Environmental Samples or That Have Significance for Aquatic Life

Compound	Use/Origin	Environmental Occurrence	Refs.
17α-Ethinyl estradiol	Oral contraceptive	Up to 7 ng/L in POTW effluent. Not detected in German surface water above 0.5 ng/L but found in Dutch Rhine water up to 4.3 ng/L.	Belfroid et al. (1999); Routledge et al. (1998); Ternes et al. (1999)
Etofibrate	Lipid regulator	Not detected in POTW effluent; not detected in surface waters.	Ternes (1998)
Fenfluramine	Sympathomimetic amine (anorexic)	Although no one has looked for fenfluramine in sewage, it is known to enhance the release of serotonin (5-HT), and in the crayfish 5-HT in turn triggers release of ovary-stimulating hormone, resulting in larger oocytes with enhanced amounts of vitellin (consequences unknown). Similarly, in fiddler crabs, fenfluramine (dose of 125 nmol) stimulates (through 5-HT) the production of gonad-stimulating hormone, accelerating testicular maturation.	Kulkarni et al. (1992); Sarojini et al. (1993)
Fenofibrate	Lipid regulator	Efficiently removed by POTW; POTW maximum effluent, 0.03 µg/L; not detected in surface waters.	Ternes (1998)
Fenofibric acid	Polar, active metabolite of fenofibrate	Loading of over 50 g/day in German POTW; POTW removal efficiency, 64%; POTW maximum effluent, 1.2 µg/L; maximum in surface waters, 0.28 µg/L. In Brazilian STWs, influent concentration of 0.4 µg/L, with removal efficiencies ranging from 6 to 45%.	Stumpf et al. (1999); Ternes (1998)
Fenoprofen	Analgesic/anti-inflammatory	Not detected in POTW effluent or surface waters.	Stumpf et al. (1996); Ternes (1998)
Fenoterol	Bronchodilator	POTW maximum effluent, 0.06 µg/L; maximum in surface waters, 0.061 µg/L.	Ternes (1998)
Fluoroquinolone carboxylic acids	Antibiotics	As one of many classes of pharmaceuticals, antibiotics in general have been investigated for their occurrence in the environment more than any other class of PPCPs. Their ubiquitous occurrence in the environment is a leading proposed cause of the rise in resistance among pathogenic bacteria. Strongly sorbs to soil. Highly active in hospital wastewaters.	Burhenne et al. (1997a,b); Hartmann et al. (1998, 1999)
Fluoxetine	Antidepressant	No data available.	—
Fluvoxamine	Antidepressant	No data available.	—

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TABLE 8.1 (Continued)
PPCPs Identified in Environmental Samples or That Have Significance for Aquatic Life

Compound	Use/Origin	Environmental Occurrence	Refs.
Gemfibrozil	Lipid regulator	Loading of over 50 g/day in German POTW; POTW removal efficiency, 69%; POTW maximum effluent, 1.5 µg/L; maximum in surface waters, 0.51 µg/L. In Brazilian STWs, influent concentration of 0.3 µg/L with removal efficiencies ranging from 16 to 46%	Stumpf et al. (1999); Ternes (1998)
Gentisic acid	Hydroxylated metabolite of acetylsalicylic acid	Efficiently removed by POTW; POTW maximum effluent: 0.59 µg/L; maximum in surface waters, 1.2 µg/L. Average gentisic acid concentrations in POTW influents of 4.6 µg/L, with no detectable amounts in the effluents.	Ternes (1998); Ternes et al. (1998)
o-Hydroxyhippuric	Metabolite of acetylsalicylic acid	Efficiently removed by POTW; not detected in POTW effluent or surface waters; average *o*-hydroxyhippuric acid concentrations in POTW influent of 6.8 µg/L; no detectable amounts in effluents.	Ternes (1998); Ternes et al. (1998)
Ibuprofen	Analgesic/ antiinflammatory	Loading of over 200 g/day in German POTW; POTW removal efficiency, 90%; POTW maximum effluent, 3.4 µg/L; maximum in surface waters, 0.53 µg/L. In Brazilian STWs, influent concentration of 0.3 µg/L, with removal efficiencies ranging from 22 to 75%. STW influents up to 3.3 µg/L. POTW removal, >95%, surface waters up to 8 ng/L. One of the few studies to look at metabolites is Buser et al. (1999).	Buser et al. (1999); Stumpf et al. (1999); Ternes (1998)
Ifosfamide	Antineoplastic	POTW maximum effluent, 2.9 µg/L; not detected in surface waters. Hospital sewage, 24 ng/L. Hospital maximum effluent, 1.91 µg/L; median, 109 ng/L. POTW influent/effluent maximum, 43 ng/L; median, 6.5 to 9.3 ng/L. Found to be totally refractory to removal by POTW.	Kummerer et al. (1997); Steger-Hartmann et al. (1996); Ternes (1998)
Indomethacine	Analgesic/ antiinflammatory	Loading of ~10 g/day in German POTW; POTW removal efficiency, 75%; POTW maximum effluent, 0.60 µg/L; maximum in surface waters, 0.20 µg/L. In Brazilian STWs, influent concentration of 0.95 µg/L, with removal efficiencies ranging from 71 to 83%.	Stumpf et al. (1999); Ternes (1998)
Iohexol	X-ray contrast	Very low toxicity reported.	Steger-Hartmann et al. (1998)

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TABLE 8.1 (Continued)
PPCPs Identified in Environmental Samples or That Have Significance for Aquatic Life

Compound	Use/Origin	Environmental Occurrence	Refs.
Iopamidol	X-ray contrast	Concentrations as high as 15 µg/L in municipal STW effluents, and median concentration of 0.49 µg/L.	Ternes and Hirsch (2000)
Iopromide	X-ray contrast	Resistant to biodegradation and yields refractory, unidentified metabolites. Reported in rivers. Concentrations as high as 11 µg/L in municipal STW effluents.	Kalsch (1999); Ternes and Hirsch (2000)
Iotrolan	X-ray contrast	Very low aquatic toxicity reported.	Steger-Hartmann et al. (1998)
Ketoprofen	Analgesic/ antiinflammatory	POTW maximum effluent: 0.38 µg/L; maximum in surface waters, 0.12 µg/L. In Brazilian STWs, influent concentration of 0.5 µg/L, with removal efficiencies ranging from 48 to 69%.	Stumpf et al. (1999); Ternes (1998)
Meclofenamic acid	Analgesic/ antiinflammatory	Not detected in POTW effluent or surface waters.	Stumpf et al. (1999); Ternes (1998)
Metoprolol	Beta-blocker	Loading of nearly 400 g/day in German POTW; POTW removal efficiency, 83%; POTW maximum effluent, 2.2 µg/L; maximum in surface waters, 2.2 µg/L.	Ternes (1998)
Musks			
Musk ambrette, musk xylene, musk ketone, musk moskene, musk tibetene	Nitro musk	Synthetic musks first began to be identified in environmental samples almost 30 years ago.	—
Galaxolide, tonalide, celestolide	Polycyclic musk	Widely used in a wide array of fragrances for cosmetics and other personal care products. Introduced to commerce in 1950s.	—
Musk xylene	Transformation products of nitro musks, resulting from microbial reduction of the nitro groups	Identified in sewage influent/effluent.	Behechti et al. (1998); Gatermann et al. (1998)
Nadolol	Beta-blocker	POTW maximum effluent, 0.06 µg/L; not detected in surface waters.	Ternes (1998)
Naproxen	Analgesic/ antiinflammatory	Loading of over 50 g/day in German POTW; POTW removal efficiency, 66%; POTW maximum effluent, 0.52 µg/L; maximum in surface waters, 0.39 µg/L. In Brazilian STWs, influent concentration of 0.6 µg/L, with removal efficiencies ranging from 15 to 78%.	Ternes (1998); Stumpf et al. (1999)

Continued

TABLE 8.1 (Continued)
PPCPs Identified in Environmental Samples or That Have Significance for Aquatic Life

Compound	Use/Origin	Environmental Occurrence	Refs.
Paroxetine	Antidepressant	No data.	—
Phenazone	Analgesic	Loading of ~10 g/day in German POTW; POTW removal efficiency, 33%; POTW maximum effluent, 0.41 µg/L; maximum in surface waters, 0.95 µg/L.	Ternes (1998)
Propranolol	Beta-blocker	Loading of over 500 g/day in German POTW; POTW removal efficiency, 96%; POTW maximum effluent, 029 µg/L; maximum in surface waters, 059 µg/L.	Ternes (1998)
Propyphenazone	Analgesic/ antiinflammatory	General (Denmark) landfill leachates, 0.3 to 4.0 mg/L directly beneath and declining depending on depth and distance along plume; prevalent in Berlin waters.	Heberer et al. (1998); Holm et al. (1995)
Salbutamol	Bronchodilator	POTW maximum influent, 0.17 µg/L; maximum in surface waters, 0.035 µg/L.	Ternes (1998)
Salicylic acid	Primary hydrolytic metabolite of acetylsalicylic acid; keratolytic, dermatice, food preservative	Up to 54 µg/L in POTW effluent but efficiently removed in effluent; POTW maximum effluent, 0.14 µg/L; maximum in surface waters, 4.1 µg/L. Average salicylic acid concentrations in POTW influents of 55 µg/L and in effluents of 0.5 µg/L.	Ternes (1998); Ternes et al. (1998)
Sulfonamides	Antibiotics	Grinstead (Denmark) landfill leachates, 0.04 to 6.47 mg/L directly beneath and declining depending on depth and distance along plume.	Holm et al. (1995)
Terbutaline	Bronchodilator	POTW maximum effluent, 0.12 µg/L; not detected in surface waters.	Ternes (1998)
3,4,5,6-Tetrabromo-*o*-cresol	Antiseptic, fungicide	POTWs in Germany: tertabromo-*o*-cresol found in both influents and effluents (<0.1 µg/L).	Ternes et al. (1998)
Timolol	Beta-blocker (antihypertensive)	POTW maximum effluent, 0.07 µg/L; maximum in surface waters, 0.01 µg/L.	Ternes (1998)
Triclosan	Antiseptic	In water, 0.05 to 0.15 µg/L. Antibacterial widely used for 30 years in a vast array of consumer products. Its usage as a preservative and disinfectant continues to grow. Tricolosan's use in commercial products spans footwear (in hosiery and insoles of shoes called "odor-eaters"), hospital hand soap, acne creams (e.g., Clearasil), and as a slow-release product called Microban, which is incorporated in a wide variety of plastic products (ranging from children's toys to kitchen utensils, such as cutting boards).	Okumura and Nishikawa (1996)
Verapamil	Cardiac drug	No data available	—

of unused/unwanted or expired drugs directly into the domestic sewage system and via burial in landfills. Although largely unknown, there is evidence that large quantities of prescription and nonprescription, over-the-counter (OTC) drugs are never consumed (for any number of reasons) (Bosch, 1998), and many of these are undoubtedly eventually disposed down toilets or via domestic refuse.

A striking difference between pharmaceuticals and pesticides with respect to environmental release is that pharmaceuticals have the potential for ubiquitous direct release into the environment worldwide—anywhere that humans live or visit. Even areas considered relatively pristine (e.g., national parks) are subject to pharmaceutical exposures, especially given that some parks have very large, aging sewage treatment systems, some of which discharge into park surface waters and some which overflow during wet weather events and infrastructure failures. Other possible sources include disposal of unwanted illicit drugs and synthesis byproducts into domestic sewage systems by clandestine drug operations. The disposal of raw products and intermediates (e.g., ephedrine) via toilets is not uncommon in illegal laboratories. Also, in contrast to pesticides, pharmaceuticals in any stage of clinical testing (not yet approved for dispensing by the Food and Drug Administration) are subject to release into the environment, although their overall concentrations would be very low.

Some drugs are excreted essentially unaltered in their free form (e.g., methotrexate, platinum antineoplastics), often with the help of active cellular multidrug transporters for moderately lipophilic drugs. Others are metabolized to various extents, which is partly a function of the individual patient and the circadian timing of the dose (the P450 microsomal oxidase system is a major route of formation of more polar, more easily excreted metabolites). Still others are converted to more soluble forms by the formation of conjugates (with sugars or peptides). The subsequent transformation products—metabolites and conjugates from eukaryotic and prokaryotic metabolism and from physicochemical alteration—add to the already complex picture of thousands of highly bioactive chemicals. The FDA refers to all metabolites and physicochemical transformation products, such as those that range from the dissociated parent compound to photolysis products, for a given drug as structurally related substances (SRSs), which can have greater or lesser physiological activity than the parent drug.

As in mammals, the metabolic disposition of lipophilic xenobiotics, such as numerous drugs, in vertebrate aquatic species is largely governed by what is referred to as Phase I and Phase II reactions (James, 1986); less is known about invertebrate metabolism. Phase I makes use of monooxygenases (e.g., cytochrome P450), reductases, and hydrolases (for esters and epoxides) to add reactive functional groups to the molecule. Phase II uses covalent conjugation (glucuronidation) to make the molecule hydrophilic and more excretable. These reactions are catalyzed by glycosyltransferases and sulfotransferases (for hydroxyaromatics and carboxy groups), glutathione *S*-transferases (for electrophilic functional groups such as halogens, nitro groups, or unsaturated/conjugated sites), acetyltransferases (for primary amines or hydrazines), and aminoacyltransferases (for forming peptides from carboxy groups using free amino acids). This metabolic strategy creates metabolites successively more polar than the parent compound, thereby enhancing excretion. Considerable interspecies and intraspecies diversity, however, can be observed in actual metabolic potentials.

The introduction of drugs into the environment is partly a function of the quantity of drugs manufactured, the dosage frequency and amount, the excretion efficiency of the parent compound and metabolites, propensity of the drug to sorb to solids, and the metabolic transformation capability of subsequent sewage treatment (or landfill) microorganisms. Publicly owned treatment works (POTW) receive influent from domestic, municipal, and industrial (including pharmaceutical manufacture) sewage systems. The processed liquid effluents from primary and secondary treatments are then discharged to surface waters and the residual solids (biosolids) to landfills/farms. Land disposal, including manure from treated animals at CAFOs, creates the potential for introduction into groundwaters or surface waters (via wet weather runoff). Theoretically, PPCPs in sewage biosolids applied to crop lands could be taken up by plants.

Compounds surviving the various phases of metabolism and other degradative or sequestering actions (i.e., display environmental persistence) can then pose an exposure risk for organisms in the environment. Even the less/nontoxic conjugates (glucuronides) can later be converted back to the original bioactive compounds via enzymatic (β-glucuronidases) or chemical hydrolysis (e.g., acetylsalicylic acid can be hydrolyzed to the free salicylic acid).

Some degradation products can even be more bioactive than the parent compound; therefore, conjugates can essentially act as storage reservoirs from which the free drugs can later be released into the environment. Up to 90% of certain drugs can become conjugated (Ternes, 1998), with conjugations varying as a function of chemical class. These pathways of introduction into the environment have been summarized by Velagaleti (1998).

Wastewater Treatment and PPCPs

Treatment facilities, primarily POTWs or wastewater treatment plants (WWTPs), which also include privately owned works, play a key role in the introduction of pharmaceuticals into the environment. (See Rogers, 1996, for a review of the fate of synthetic chemicals in wastewater treatment plants.) WWTPs were designed to handle human waste of mainly natural origin, primarily via the acclimated degradative action of microorganisms (the efficiency of metabolism of a given drug can increase with duration of treatment because of enzyme induction and cellular adaptation) and the coagulation/flocculation of suspended solids; sometimes, tertiary treatment (e.g., chemical or ultraviolet oxidation) is used. Most anthropogenic chemicals introduced along with this normal waste suffer unknown fates. Two primary mechanisms remove substances from the incoming waste stream: (1) microbial degradation to lower molecular weight products, leading sometimes to complete mineralization—CO_2 and H_2O; and (2) sorption to filterable solids which are later removed with the biosolids.

Although the microbiota of wastewater treatment systems may have been exposed to many PPCPs for a number of years, two factors work against the effective microbial removal of these substances for WWTPs. First, the concentrations of most drugs are probably so low that the lower limits for enzyme affinities may not be met. For example, the daily loadings of PPCPs into WWTPs are largely a function of the serviced human population, the dosages/duration of medications consumed, and the metabolic or excretory half-lives, all of which are large variables. As an example, the daily load of a subset of pharmaceuticals to a particular POTW near Frankfurt, Germany, ranged from tens to hundreds of grams, with approximate individual removal efficiencies varying widely from 10 to 100% but trending to around 60% (Ternes, 1998). This particular POTW serviced about a third of a million people at a flow rate of roughly 60,000 m^3/day. Despite the number of studies on treatment efficiencies, a widespread investigation is still lacking for the differences in removal efficiencies for distinct types of WWTPs as well as for individual treatment techniques. The extent to which a particular plant uses primary, secondary, and tertiary technologies will greatly influence removal efficiencies; the technologies employed vary widely among cities. The biodegradative fate of most compounds in WWTPs is governed by non-growth-limiting (enzyme-saturating) substrate concentrations (copiotrophic metabolism, which means they thrive in nutrient-rich environments). In contrast, PPCPs are present in WWTPs at concentrations at enzyme-subsaturating levels, which necessitates oligotrophic metabolism (nutrient-poor environments). These micropollutants might be handled by only a small subset of specialist oligotrophic organisms whose occurrence is probably more prevalent in native environments (e.g., lakes) characterized by low-carbon fluxes (e.g., sediments and associated pore waters, where desorption mass transfer is limiting) than in WWTPs.

For clarity of the preceding discussion and for the discussion that follows, let's look at *oligotrophic* (meaning "few foods") *lakes*. They are young, deep, crystal-clear, nutrient-poor lakes with little biomass productivity. Only a small quantity of organic matter grows in an oligotrophic lake; the phytoplankton, the zooplankton, attached algae, macrophytes (aquatic weeds), bacteria, and fish are all present as small populations. "It's like planting corn in sandy soil, not much growth" (Kevern et al., 1999). Lake Superior is an example from the Great Lakes. The bottom line on degradation of PPCPs in WWTPs is that their degradation may occur more prevalently in the receiving waters or sediments (especially in the case of running waters such as streams and rivers) than in WWTPs.

Many new drugs are introduced to the market each year; some of these drugs are from entirely new classes never seen before by the microbiota of a WWTP. Each of these presents a new challenge to biodegradation. A worst-case scenario may not be unusual—the concentration of a drug leaving a WWTP in the effluent could essentially be the same as that entering. Only a several-fold to multiple order of magnitude dilution when the effluent is mixed into the receiving water, assuming a sufficiently high natural flow, serves to reduce the concentration; obviously, smaller streams have increased potential for having higher concentrations of any PPCP that has been introduced. In general, most pharmaceuticals resist extensive microbial degradation (e.g., mineralization); although some parent drugs often show poor solubility in water, leading to preferential sorption of suspended particles, they can thereby sorb to colloids and therefore be discharged in the aqueous effluent (Velagaleti, 1998). Metabolites, including breakdown products and conjugates, will partition mainly to the aqueous effluent. Some published data demonstrate that many parent drugs do make their way into the environment.

In a 2004–2009 study, scientists found and reported that pharmaceutical manufacturing facilities can be a significant source of pharmaceuticals to the environment. Effluents from two wastewater treatment plants that receive discharge from pharmaceutical manufacturing facilities (PMFs) had 10 to 1000 times higher concentrations of pharmaceuticals than effluents from four WWTPs across the nation that do not receive PMF discharge. The effluents from these two WWTPs are discharged to streams where the measured pharmaceuticals were traced downstream, and as far as 30 kilometers (18 miles) from one plant's outfall. This was the first study to assess PMFs as a potential source of pharmaceuticals in the environment. The PMFs investigated are pharmaceutical formulation facilities, where ingredients are combined to form final drug products and products are packaged for distribution. Although pharmaceuticals have been measured in many streams and aquifers across the nation, levels are generally lower than 1 part per billion (ppb); however, concerns persist in 23 other plants that higher levels may occur in environmental settings where wastewaters are released to the environment.

In this study, 35 to 38 effluent samples were collected from each of three WWTPs in New York State and one effluent sample was collected from each of 23 strategically selected WWTPs across the nation. The samples were analyzed for seven target pharmaceuticals, including opioids and muscle relaxants, some of which had not been previously studied in the environment. Pharmaceutical concentrations in effluents from two of the three WWTPs in New York State, both of which receive more than 20% of their discharge from PMFs, were compared to the measurements made at the third plant in New York State and at other plants across the nation not receiving discharges from PMFs. Maximum pharmaceuticals concentrations in effluent samples from the 24 WWTPs not receiving discharges from PMFs rarely (about 1%) exceeded 1 part per billion. By contrast, maximum concentrations in effluents from the two WWTPs receiving PMF discharges were as high as 3888 ppb of metaxalone (a muscle relaxant), 1700 ppb of oxycodone (an opioid prescribed for pain relief), greater than 400 ppb of methadone (an opioid prescribed for pain relief and drug withdrawal), 160 ppb of butalbital (a barbiturate), and greater than 40 ppb of both phendimetrazine (a stimulant prescribed for obesity) and carisoprodol (a muscle relaxant).

The pharmaceuticals investigated in this study were identified using a forensic approach that identified pharmaceuticals present in samples and subsequently developed methods to quantify these pharmaceuticals at a wide range of concentrations. Additional pharmaceuticals that may be formulated at these sites also were identified as present in the effluents of these two WWTPs. Ongoing studies are documenting the levels at which these additional pharmaceuticals occur in the environment (USGS, 2013).

The efficiency of removal of pharmaceuticals by WWTPs is largely unknown. To date the most extensive study of treatment efficiency, Ternes (1998) reported removal from German WWTPs of 14 drugs representing five broad physiologic categories. Removal of the parent compound (keep in mind that possible subsequent metabolites were not accounted for) ranged from 7% (carbamazepine, an antiepileptic) to 96% (propranolol, a beta blocker); most removal efficiencies averaged about 60%. Fenofibrate, acetaminophen, salicylic acid, *o*-hydroxyhippuric acid, and gentistic acid (acetylsalicylic acid metabolites) could not be detected in effluent; salicylic acid was found in the influent at concentrations up to 54 μg/L. It is important to understand that, absent the stoichiometric accounting of metabolic products, one cannot distinguish between the three major fates of a substance: (1) degradation to lower molecular weight compounds, (2) physical sequestration by solids (and subsequent removal as sludge), and (3) conjugates that can later be hydrolyzed to yield the parent compound (e.g., clofibric and fenofibric acid conjugates). Therefore, by simply following the disappearance (removal) of a substance, one cannot conclude that it was structurally altered or destroyed, as it may simply reside in another state or form. Identifying metabolic products is difficult not only because of the number of metabolites (sometimes several per parent compound) but also because standard reference materials are difficult to obtain commercially and can be costly.

Despite high removal rates in WWTPs for some drugs, upsets in the homeostasis of a treatment plant can result in higher than normal discharges. For example, Ternes (1998) found that wet-weather runoff dramatically reduces the removal rates for certain drugs, such as several nonsteroidal anti-inflammatory drugs (NSAIDs) and lipid regulators, in a facility located close to Frankfurt. During the increased period of influent flow, the removal rate dropped to below 5% from over 60% previously; several days were required for the removal rates to recover. Clearly, even for drugs efficiently removed, the operational state of the WWTP can have a dramatic effect on the removal efficiencies. Other transients that could affect removal include transitions between seasons and sporadic plug-flow influx of toxicants from various sources. Overflows from WWTP failure or overcapacity events (e.g., floods, excessive water use) lead to the direct, untreated introduction of sewage into the environment. In efforts to improve tributary conditions by increasing stream flow, some cities (e.g., Portland, Oregon) have considered increasing the percentage of annual overflow events (Learn, 1999). The highest concentration in a WWTP effluent reported by Ternes (1998) was for bezafibrate (4.6 μg/L); the highest concentration in surface water was also for bezafibrate (3.1 μg/L).

Landfills

In most instances, we have been trained to get rid of expired or unwanted medications by "disposing of them in a manner that children cannot get access to them." In practical terms, this usually involves flushing them down the toilet or putting them into the household trash. In the former approach they end up in the sewer, whereas in the latter they end up in the landfill (Jjemba, 2008). PPCPs can also be introduced to landfills via domestic industrial routes and indirectly via sewage sludge (biosolids). Holm et al. (1995) first reported leachates carrying pharmaceuticals from a landfill. Large amounts of numerous sulfonamides (antibiotics) and barbiturates from domestic waste and from a pharmaceutical manufacturer were disposed of at a Danish landfill over a 45-year period. High concentrations (ppm) of many of these drugs were found in leachates close to the landfill; these compounds even accounted for 5% of the total nonvolatile organic carbon found in the leachate. It was also found that the concentration dropped off dramatically tens of meters down gradient, presumably a result of microbial attenuation.

Drinking Water

From 1990 to 1995, few pharmaceuticals were identified in domestic drinking water, probably because of the dearth of monitoring efforts and because the required detection limits were too low for the current routine analytical technology. In Germany, however, clofibric acid concentrations up to 165 ng/L (Stan et al., 1994) and 270 ng/L (Heberer et al., 1998) have been measured in tap water; the presumed source was from recharged groundwaters that had been contaminated by sewage. Stumpf et al. (1996)

and Ternes et al. (1998) found several pharmaceuticals in German drinking water in the lower nanograms-per-liter range, with a maximum of 70 ng/L for clofibric acid. Additionally, these investigators found that diclofenac, bezafibrate, phenazone, and carbamazepine were sometimes present. In the majority of the samples analyzed, however, no drugs were observed. These investigations indicate that contamination of drinking water does not appear to be a general problem. Depending on the water source for drinking/water production, however, certain facilities can experience contamination, especially if the source is polluted groundwater and if polishing technology does not remove the PPCP (Heberer et al., 1998; Stumpf et al., 1999). A major unaddressed issue regarding human health is the long-term effects of ingesting via potable waters very low, subtherapeutic doses of numerous pharmaceuticals multiple times a day for many decades. This concern especially relates to infants, fetuses, and people suffering from certain enzyme deficiencies (which can even be food induced, such as microsomal oxidase inhibition by grapefruit juice).

Domestic Animals

Whereas the concentration of many drugs is greatly attenuated through sewage treatment plants, larger quantities of many pharmaceuticals are used in various animal husbandry operations, especially concentrated animal feeding operations (CAFOs). With aquaculture in particular, which uses many anti-infectives and anesthetics, the chance for introduction into the immediate environment is greatly enhanced, and the possibility of direct human consumption of therapeutic quantities is correspondingly heightened. Even in the United States the extremely large populations of pet dogs and cats are recipients of numerous drugs (e.g., tranquilizers, antidepressants)—some prescribed by veterinarians and others intended for their owners' use, as pet owners sometimes administer medications to their pets to test off-label uses for themselves. PPCPs (both veterinary drugs and OTC products) used with terrestrial domestic animals can be dispersed into the environment through the same routes as those PPCPs used by humans, with the added major route of runoff or leaching of on-ground fecal material.

PERSONAL CARE PRODUCTS IN THE ENVIRONMENT

For the purposes of this text, personal care products are defined as chemicals marketed for direct use by the consumer (excluding OTC medication with documented physiologic effects) and having intended end uses primarily on the human body (products not intended for ingestion, with the exception of food supplements). In general, these chemicals are directed at altering odor, appearance, touch, or taste while not displaying significant biochemical activity. Most of these chemicals are used as the active ingredients or preservatives in cosmetics, toiletries, or fragrances. They are not used for the treatment of disease, but some may be intended to prevent diseases (e.g., sunscreen agents). In contrast to drugs, almost no attention has been given to the environmental fate or effects of personal care products—the focus has traditionally been on the effects from intended use on human health. Many of these substances are used in very large quantities, often more than recommended.

Personal care products differ from pharmaceuticals in that large amounts can be directly introduced to the environment; for example, these products can be released directly into recreational waters or volatilized into the air (e.g., musks). Because of this release, they can bypass possible degradation in POTWs. Also, in contrast to pharmaceuticals, less is known about the effects of this broad and diverse class of chemicals on non-target organisms, especially aquatic organisms. Data are also limited on the unexpected effects on humans. For example, common sunscreen ingredients, 2-phenylbenzimidazole-5-sulfonic acid and 2-phenybenzimidazole, can cause DNA breakage when exposed to UV-B (Stevenson and Davies, 1999). The quantities of personal care products produced commercially can be very large. For example, in Germany alone, the combined annual output for eight separate categories was estimated (Statistisches Bundesamt, 1993) at 559,000 tons for 1993. A few examples are given blow of common personal care products that are ubiquitous pollutants and may possess substantial bioactivity.

Fragrances (Musks)

Fragrances (musks) are ubiquitous, persistent, bioaccumulative pollutants that are sometimes highly toxic; amino musk transformation products are toxicologically significant. Synthetic musks are comprised of a series of structurally similar chemicals (which emulate the odor but not the structure of the expensive, natural product from the Asian musk deer) used in a broad spectrum of fragranced consumer items, both as fragrance and as fixative. Included are the older, synthetic nitro musks (e.g., ambrette, musk ketone, musk xylene, the lesser known musks moskene and tibetene) and a variety of new, synthetic polycyclic musks that are best known by their individual trade names or acronyms. The polycyclic musks (substituted indanes and tetralins are the major musks used today, accounting for almost two thirds of worldwide production) and especially the inexpensive nitro musks (nitrated aromatics accounting for about one third of worldwide production) are used in nearly every commercial fragrance formulation (cosmetics, detergents, toiletries) and most other personal care products with fragrance; they are also used as food additives and in cigarettes and fish baits (Gatermann et al., 1998).

The nitro musks are under scrutiny in a number of countries because of their persistence and possible adverse environmental impacts and therefore are beginning to be phased out in some countries. Musk xylol has proved carcinogenic in a rodent bioassay and is significantly absorbed through human skin; from exposure to combined sources, a person could absorb 240 µg/day (Bronaugh et al., 1998). The human lipid concentration of various musks parallels that of other bioaccumulative pollutants such as PCBs (Muller et al., 1996). Worldwide production of synthetic musks in 1988 was 7000 tons (Gatermann et al., 1998); worldwide production for nitro musks in 1993 was 1000 tons, two thirds of which were musk xylene (Kafferlein et al., 1998).

Synthetic musks first began to be identified in environmental samples almost 20 years ago (Yamagishi et al., 1981, 1983). Yamagishi et al. (1981) identified musk xylene and musk ketone in goldfish (*Carassius auratus langsdorfii*) in Japanese rivers and not much later in river water, sewage, marine mussels (*Mytilus edulis*), and oysters (*Crassosterea gigas*) (Yamagishi et al., 1983). The studies by Yamagishi et al. represented the first comprehensive monitoring efforts, identifying musk xylene and musk ketone in freshwater fish, marine shellfish, river water, and WWTP waters. Musk xylene was found in all samples, and musk ketone was found in 80% of the 74 samples analyzed. Concentrations in WWTP effluents ranged from 25 to 36 ng/L for musk xylene and from 140 to 410 ng/L for musk ketone. Concentrations of musk xylene in fish muscle were in the tens of parts per billion, whereas those for musk ketone were less than 10 µg/kg, with the highest values occurring in fish downstream of sewage treatment works (STWs). In contrast, for shellfish, the concentrations were lower, between 1 and 5.3 µg/kg, presumably because of their lower lipid contents. In river water, musk xylene occurred in all samples, whether upstream or downstream of WWTPs, and ranged between 1 and 23 ng/L; those of musk ketone were generally in the same range, but in distinct contrast they were not detectable in upstream samples.

Geyer et al. (1994) published an excellent review on residues of nitro musk fragrances in fish and mussels, as well as in breast milk and human lipids, and on the current ecotoxicologic and toxicologic knowledge for these personal care products. Residues of musk xylene and musk ketone found in the fillets of freshwater fish (e.g., pike, eel, brass, Zander, rainbow trout) from rivers of North Germany were between 10 and 350 µg/kg lipid and 10 and 380 µg/kg lipid for musk xylene and musk ketone, respectively. In mussels (*Mytilus edulis*), 10 to 30 µg/kg lipid of both fragrances were detected. In human breast milk from German women, musk xylene and musk ketone were detected at between 10 and 240 mg/kg lipid (Geyer at al., 1994). The literature has a number of additional publications from Europe, especially Germany and Switzerland. Rimkus et al. (1997) gave a brief overview of the occurrence of musks in the environment, and Kafferlein et al. (1998) and Geyer et al. (1998) published thorough reviews on the occurrence (in the environment and in personal care products), transformation, and toxicology of the ubiquitous musk xylene. These reviews summarize many more occurrence studies (for musk xylene) than mentioned here.

Musks are refractory to biodegradation (other than reduction of nitro musks to amino derivatives), which explains why they have been measured in water bodies throughout the world (Gatermann et al., 1998). They also are very lipophilic—their octanol–water partition coefficients are similar to those for DDT and hexacholorocyclohexane (Winkler et al., 1998)—and therefore can bioconcentrate/bioaccumulate (Geyer et al., 1994; Rimkus et al., 1997). Concern has been expressed regarding developmental toxicity in aquatic organisms. Musk ambrette (2,6-dinitro-3-methoxy-4-*tert*-butyl toluene) may play a role in damaging the nervous system (Kirschner, 1997).

Draisci et al. (1998) examined freshwater fish in Italy and identified two of five targeted polycyclic musks in most fish samples; a hexahydro-hexamethyl-cyclopenta-benzopyran (HHCB; trade name Galaxolide) and an acetyl hexamethyl tetralin (AHTN; trade name Tonalide) were identified at levels ranging from less than 4 ng/g (ppb) to 105 ng/g in fish muscle tissue. In the Swiss river Glatt, Muller et al. (1996) identified Galaxolide, Tonalide, and 4-acetyl-6-*tert*-buryl-1,1-demethylindane (ADBI; trade name Celestolie) at concentrations of 136, 75, and 3.2 ng/L, respectively; they also found the nitro musks tibetene ambrette, moskene, ketone, and xylene at concentrations of 0.04, <0.03, 0.08, 8.3, and 0.62 ng/L, respectively. Galaxolide, Tonalide, and Celestolide were identified in the fatty tissue of bream and perch from the Ruhr River, Germany, at average concentrations between 2.5 and 4.6 mg/kg (ppm), illustrating the extreme bioaccumulation potential for these compounds (Mersch-Sundermanno et al., 1998). Heberer et al. (1999) investigated the contamination of surface waters in Berlin, Germany, and vicinity that received high percentages of treated sewage and found maximum concentrations above 10 μg/L for the polycyclic musks Galaxolide, Tonalide, and Celestolide.

Winkler et al. (1998) measured musks in 31 particulate matter and water samples from the Elbe River, Germany. In all particulate matter samples, concentrations for musk ketone were 4 to 22 ng/g; for Galazolide, 148 to 736 ng/g; and for Tonalide, 194 to 770 ng/g. Celestolide was found at concentrations of 4 to 43 ng/g in 23 of the particulate matter samples. The values for the three most prevalent musks were within the same order of magnitude as those for 15 polycyclic aromatic hydrocarbons (PAHs) and exceeded those for 14 common polychlorinated organic pollutants; only hexachlorobiphenyl (HCB) and *p,p′*-DDT were of similar concentration.

It is not surprising that musks have been detected in air. Kallenborn et al. (1999) detected three polycyclic musks and two nitro musks in Norwegian outdoor air samples. The polycyclic musks were more prevalent. Concentrations of these musks ranged from low pictograms per cubic meter to hundreds of pictograms per cubic meter. The most common was the polycyclic musk Galaxolide, but the relative ratios among the musks are a function of usage (which varies among countries) and photolability.

Although the significance of the aquatic toxicity of the nitro and polycyclic musks is debatable (genotoxicity from the polycyclic seems to not be a concern) (Kevekordes et al., 1998), the aminobenzene (reduced) versions of the nitro musks can be highly toxic; these reduced derivatives are undoubtedly created under the anaerobic conditions of sewage sludge digestion. Behechti et al. (1998) tested the acute toxicity of four reduced analogs of musk xylene on *Daphnia magna*. The *p*-aminodinitro compound exhibited the most toxicity of the four, with extremely low median effective concentration (EC_{50}) values averaging 0.25 μg/L (0.25 ppb).

In 1998, the amino transformation products of nitro musks were identified in sewage treatment effluent and in the Elbe River, German. Gatermann et al. (1998) identified musk xylene and musk ketone together with their amino derivatives 4- and 2-amino musk xylenes and 2-amino musk ketone. In sewage treatment influent, the concentrations of musk xylene and musk ketone were 150 and 550 ng/L, respectively. In the effluent, their concentrations dropped to 10 and 6 ng/L, respectively. In contrast, although the amino derivatives could not be detected in the influent, their concentrations in the effluents dramatically increased, showing extensive transformation of the parent nitro musks: 2-amino musk xylene (10 ng/L), 4-amino musk xylene (34 ng/L), and 2-amino musk ketone (250 ng/L). It was concluded that the amino derivatives could be expected in sewage effluent at concentrations more than an order of magnitude higher than the patent nitro musks. In the Elbe, 4-amino musk xylene was found at higher concentrations (1 to 9 ng/L) than the parent compound.

Given that the amino nitro musk transformation products (1) are more water soluble than the parent musks, (2) still have significant octanol–water partition coefficients (high bioconcentration potential), and (3) are more toxic than the parent nitro musks, more attention should be focused on these compounds. Because synthetic musks are ubiquitous, used in large quantities, introduced into the environment almost exclusively via treated sewage effluent, and persistent and bioconcentratable, they are prime candidates for monitoring in both water and biota as indicators for the presence of other PPCPs. Their analysis, especially in biota, has been thoroughly discussed by Gatermann et al. (1998) and by Rimkus et al. (1997).

Disinfectants and Antiseptics

Triclosan (Irgasan DP 300, a chlorinated diphenyl ether: 2,4,4′-trichloro-2′-hydroxydiphenyl ether) is an antiseptic agent that has been widely used for almost 30 years in a vast array of consumer products. Its use as a preservative and disinfectant continues to grow; for example, it is incorporated at <1% in Colgate's Total toothpaste, the first toothpaste approved by the FDA to fight gingivitis; however, there is no evidence, according to the FDA, that triclosan provides an extra benefit to health beyond its antigingivitis effect in toothpaste. Nevertheless, triclosan has many other uses. For example, triclosan is registered with the USEPA as a pesticide and is freely available OTC. The use of triclosan in commercial products includes footwear (in hosiery and insoles of shoes known as "odor-eaters"), hospital handsoap, acne creams (e.g., Clearasil), and as a slow-release product called Microban, which is incorporated into a wide variety of plastic products ranging from children's toys to kitchen utensils such as cutting boards. Many of these uses can result in direct discharge of triclosan to wastewater treatment systems, and as such this compound can find its way into receiving waters depending on its resistance to microbial degradation. Okumura and Nishikawa (1996) found traces of triclosan ranging from 0.05 to 0.15 µg/L in water. Although triclosan has long been regarded as a biocide, a toxicant having a wide-ranging, nonspecific mechanism of action (in this case, gross membrane disruption), McMurry et al. (1998) reported that triclosan is rather an antibacterial having particular enzymatic targets (lipid synthesis). As such, bacteria could develop resistance to triclosan. As with all antibiotics in the environment, this could lead to development of resistance and change in microbial community structure (diversity).

A wide array of disinfectants is used in rather large amounts not just by hospitals but also by households and livestock breeders. These compounds are often substituted phenolics as well as others such as triclosan. Biphenylol, 4-chlorocresol, chlorophene, bromophene, 4-chloroxylenol, and tetrabromo-*o*-cresol (Ternes et al., 1998) are some of the active ingredients, at percentage volumes of <1 to 20%. A survey of 49 WWTPs in Germany (Ternes et al., 1998) routinely found biphenylol and chlorophene in both influents—up to 2.6 µg/L for biphenylol and up to 0.71 µg/L for chlorophene—and effluents. The removal of chlorophene from the effluent was less sensitive than for biphenylol, with surface waters having concentrations similar to those of the effluents.

Preservatives

Parabens (alkyl-*p*-hydroxybenzoates) are one of the most widely and heavily used suites of antimicrobial preservatives by the cosmetic and pharmaceutical industries for skin creams, tanning lotions, toiletries, pharmaceuticals, and foodstuffs. Parabens are effective preservatives in many types of formulas. Although the acute toxicity of these compounds is very low, Routledge et al. (1998) reported that these compounds (methyl through butyl homologs) display weak estrogenic activity in several assays. Although the risk from dermal application in humans is unknown, the probable continual introduction of these benzoates into wastewater treatment systems and directly to recreational waters from the skin leads to the question of risk to aquatic organisms. Butylparaben showed the most competitive binding to the rat estrogen receptor at a concentration one to two orders of magnitude higher than that of nonylphenol and showed estrogenic activity in a yeast estrogen screen at 10^{-6} M.

Sunscreen Agents

The occurrence of sunscreen agents (UV filters) in the German lake Meerfelder Maar was investigated by Nagtegaal et al. (1998). The combined concentrations of six sunscreen agents (SSAs) identified in perch (*Perca fluviatilis*) in the summer of 1991 were as high as 2.0 mg/kg lipid, and in roach (*Rutilus rutilus* L.) in the summer of 1993 as high as 0.50 mg/kg lipid. Methylbenzylidene camphor (MBC) was detected in roach from three other German lakes. These lipophilic SSAs seem to occur widely in fish from small lakes used for recreational swimming. Both fish species had body burdens of SSA on par with PCBs and DDT. The bioaccumulation factor, calculated as quotient of the MBC concentration in the whole fish (21 μg/kg) vs. that in the water (0.004 μg/L), exceeded 5200, indicating high lipophilicity. The fact that SSAs, such as 2-hydroxy-4-methoxybenzophenone (oxybenzone) and 2-ethylhexyl-4-methoxycinamate, can be detected in human breast milk (16 and 417 ng/g lipid, respectively) (Hany and Nagel, 1995), shows the potential for dermal absorption and bioconcentration in aquatic species.

Nutraceuticals and Herbal Remedies

Nutraceuticals are a group of nutritional supplements of highly bioactive food supplements. The term is applied to products that include isolated nutrients, dietary supplements, herbal products, specific diets, genetically modified food, and processed foods such as cereals, soups, and beverages that are intended as supplements to the diet. Nutraceuticals and many herbal remedies can have potent physiologic effects. These are a mainstay of alternative medicine and have enjoyed explosive growth in use in the United States and other countries over the past several decades. Nutraceuticals are not classified as drugs by the FDA, primarily because a given botanical usually has not one but an array of distinct compounds whose assemblage elicits the putative effect and because these arrays cannot be easily standardized. As such they are not regulated and are available OTC (and heavily promoted via the Internet). Even in those cases in which the natural product is identical to a prescription pharmaceutical (e.g., the Chinese red-yeast product cholestin contains lovastatin, an active ingredient in the approved prescription drug Mevacor used to lower cholesterol levels), a 1999 ruling (*Pharmanex, Inc. v. Donna Shalala*) prevented the FDA from regulation.

Due to the accelerating inverted age structure of our society, coupled with the U.S. 1994 Dietary Supplement Health and Education Act, which eased regulations on the introduction and marketing of supplements, the use of nutraceuticals could greatly escalate. The significance of dietary supplements in the United States was epitomized by the creation of the Office of Dietary Supplements (ODS) via the DSHEA in 1995 under the National Institutes of Health (NIH). The ODS maintains a searchable database, the International Bibliographic Information on Dietary Supplements (IBIDS), of published scientific literature on dietary supplements. The NIH was also mandated to create the National Center for Complementary and Alternative Medicine (NCCAM) to facilitate the evaluations of alternative medical treatment modalities to determine their effectiveness.

Countless nutraceuticals, both new and ancient, are being consumed at a high rate. There several questions regarding the potential for nutraceuticals to be excreted, surviving wastewater treatment, and then eliciting effects on aquatic organisms. Nutraceuticals and herbal remedies would have the same potential fate in the environment as pharmaceuticals, with the added dimension that their usage rates could be much higher, as they are readily available and taken without the controls of prescription medication. Because these compounds are natural products, however, they would be expected to be more easily biodegraded. Although the argument can be made that naturally occurring compounds would not pose an ecologic risk, this ignores the fact that (1) the concentrations of these compounds in effluents could be higher than they are in the environment in which they occur naturally, and (2) many of these substances come only from isolated parts of the world (e.g., kava, huperzine) and their use and dispersal in other parts of the world would be anthropogenic. The use of these compounds serves to redistribute their normal occurrence in the environment, and even though they might be naturally occurring this dispersion promotes exposure to organisms that normally would never occur.

DRUG CLASSES AND ENVIRONMENTAL OCCURRENCES

Hormones and Mimics

An excellent overview of hormone systems was given by the Endocrine Disruptor Screening and Testing Advisory Committee (EDSTAC, 1998). Steroids were the first physiologic compounds to be reported in sewage effluent (Aherne and Briggs, 1989; Shore et al., 1993; Tabak and Bunch, 1970; Tabak et al., 1981) and as such were the first pharmaceuticals to capture the attention of environmental scientists. Estrogenic drugs, primarily synthetic xenoestrogens, are used extensively in estrogen-replacement therapy and in oral contraceptives, in veterinary medicine for growth enhance, and in athletic performance enhancement. A special issue of *The Science of the Total Environment* (Ternes and Wilken, 1998) was devoted to drugs (especially hormones) as pollutants in the aquatic environment.

Although the synthetic oral contraceptive 17α-ethynylestradiol occurs generally at low concentrations (<7 ng/L) in POTW effluent, it is still suspected, in combination with the steroidal estrogens 17-estradiol and estrone (Desbrow et al., 1998), of causing vitellogenin production (feminization) in male fish. Feminization is a phenomenon first observed for fish in sewage treatment lagoons in the mid-1980s (Routledge et al., 1998). An overview of pharmaceutical hormones in the environment was presented by Arcand-Hoy et al. (1998). The estrogenic activity of various waters (from sewage to drinking water) has been shown to vary dramatically, spanning six orders of magnitude. Some other widely used synthetic hormone modulators include Proscar/Propecia (finasteride, an androgen hormone inhibitor) and various thyroxine analogs (thyroid hormones); nothing is known of the environmental fates of these compounds. In general, the lipophilicity of these hormones is sufficiently great that at least a large portion of them are removed via sorptive processes in sewage treatment (Johnson et al., 1999; Routledge et al., 1999) and therefore partition to the sludge, but even the low concentrations that remain in the effluents may be capable of exerting physiologic effects in aquatic biota.

In addition to these synthetic steroids and xenoestrogens is a suite of naturally occurring estrogen hormones—for example, phytoestrogens such as the complex series of leguminous isoflavonoids, including genistein, daidzein, and glycitein in soy. Further complicating the picture are endocrine disrupting chemicals (EDCs), also referred to as hormonally active agents (HAAs) by the National Research Council (NRC, 1999), which gained attention primarily as a result of the publication of *Our Stolen Future* (Colborn et al., 1997). These inadvertent EDCs include such commonly recognized industrial pollutants and products as halogenated dioxins and furans, PCBs, organohalogen pesticides, phthalates, and bisphenol A.

The issue of screening many of the major commercial chemicals (over 87,000 total) for endocrine disruption potential has been formalized with the creation of the EDSTAC, which had been charged by the USEPA with the task of implementing a screening and testing program (EDSTAC, 1998). The Chemical Manufacturers Association (CMA) also launched an intensive health effects investigation of over 3000 high-volume chemicals (called the Health and Environmental Research Initiative) (CMA, 1999). It is significant, however, and should be noted that pharmaceuticals are not specifically targeted by the EDSTAC (or the CMA) in its tiered screening program that focuses on pesticides, commodity chemicals, naturally occurring nonsteroidal estrogens (phytoestrogens and mycotoxins), food additives, cosmetics, nutritional supplements, and representative mixtures (for possible synergistic effects). Even though the strategy gives top priority to "chemicals with widespread exposure at the national level" (CMA, 1999), PPCPs are not specially targeted. It is also significant that the screening strategy initially focused on only the three primary hormone systems—estrogen, androgen, and thyroid—hormone systems of relatively unknown importance to invertebrates (EDSTAC, 1998).

A controversial hypothesis regarding multiple toxicants (sharing a common mode of action), when each is present at a low level, is that of *synergism*. Evidence of synergism among estrogenic mimics (where the effect can be elicited at orders-of-magnitude lower concentrations than predicted by additive action) was reported by Arnold et al. (1996), but others rebutted this hypothesis. They did not find any evidence of synergism in mixtures of mild estrogenic pollutants.

Another subclass of hormonelike substances includes those that are being purposefully designed to mimic the activity of therapeutically significant hormones. A long-sought objective has been to obviate the need for hormone-replacement therapy (e.g., insulin) by designing small synthetic (non-peptidyl) molecules that mimic the hormone's effect yet can be ingested orally, taken up the gut, and remain stable for a sufficiently long period of time in the blood. The first report of a "designer" hormone mimic (Barinaga, 1998; Tian et al., 1998), a polybenimidazole that activates the receptor for a cytokine that regulates white blood cell production, perhaps portends the advent of many synthetic hormone mimics in therapeutic medicine. If the finding can be generalized, it could mean that the possible routes of hormone disruption by simple molecules could extend beyond that of the estrogen/androgen system.

With the exception of estrogenic mimics, the possibility of disrupting the activity of proteinaceous hormones by lower molecular weight anthropogenic chemicals has been held in low regard. This view has been based on the fact that a relatively large, complex proteinaceous molecule (the hormone) neatly fits within the complex three-dimensional domain of its target receptor, whereas in contrast a much smaller nonproteinaceous molecule would have little to offer in terms of recognition specificity. It has been believed that the complexity of larger proteins such as insulin was required to enable recognition by the corresponding receptors; smaller compounds simply did not convey enough three-dimensional information to have high-binding constraints for one or multiple receptors.

The report by Tian et al. (1998) demonstrates for the first time that a relatively small non-peptide molecule can bind to a receptor normally dedicated to a proteinaceous hormone. Although this has high therapeutic significance (this research might catalyze concerted attempts to develop the first protein-mimicking and therefore perhaps hormone-mimicking low-molecular-weight drugs), it also alludes to the possibility that existing anthropogenic compounds might have a greater chance of interacting with hormone receptors than was previously believed. Although the synthetic substance was three to six orders of magnitude less potent, its ability to bind to the receptor was undisputed (in the mouse *in vitro* and, more importantly, *in vivo*).

Antibiotics

A large body of literature exists on antibiotics in the environment. Veterinary and animal husbandry, especially aquaculture, usage plays a major role in their introduction into the environment. In one study of hospital effluent, fluoroquinolones werea the chemical class contributing the major portion to overall DNA toxicity (Hartmann et al., 1998); ciprofloxacin, for example, was identified at 3 to 87 μg/L. Hirsch et al. (1999) analyzed German WWTP effluents, groundwaters, and surface waters for 18 antibiotics representing macrolides, sulfonamides, penicillins, and tetracyclines. Although the penicillins (susceptible to hydrolysis) and the tetracyclines (can precipitate with calcium and similar cations) were not found, the others were detected in the microgram-per-liter range. Indeed, the rampant, widespread, and sometimes indiscriminate use of antibiotics, coupled with their subsequent release into the environment, is the leading proposed cause of the accelerated and spreading resistance found among bacterial pathogens, exacerbated by the fact that resistance is maintained even in the absence of continued selective pressure (an irreversible occurrence). Sufficiently high concentrations could also have acute effects on bacteria. Such exposures could easily lead to altered microbial community structures in nature and thereby affect the higher food chain. Their use in aquaculture results in eventual human consumption.

In 1999, a number of stream surveys documented the significant prevalence of native bacteria that display resistance to a wide array of antibiotics including vancomycin (Ash et al., 1999). Isolates from wild geese near Chicago, Illinois, were reported to be resistant to ampicillin, tetracycline, penicillin, and erythromycin (Eichorst et al., 1999). All of these reports could simply indicate that the natural occurrence of antibiotic resistance in native bacterial populations is much higher than expected or that these bacteria are being selected for by the uncontrolled release of antibiotics into the environment. If the latter is true, then, excluding the significance of antibiotics themselves in the environment, their occurrence can be viewed as indicating the possible presence of other PPCPs.

Blood Lipid Regulators

Clofibric acid was the first prescription drug (actually an SRS) reported in a sewage effluent (Garrison et al., 1976; Stan and Heberer, 1997), and it continues to be one of the most frequently reported PPCPs in monitoring studies. Clofibric acid (2-[4]-chlorophenoxy-2-methyl propanoic acid), the active metabolite from a series of widely used blood lipid regulators, and which also happens to be structurally related to the phenylalkanoic acid herbicide mecoprop (the methylphenoxy structural analog), has captured much attention from investigators in Europe. Stan et al. (1994) first reported clofibric acid in Berlin tap water at concentrations between 10 and 165 ng/L. Heberer and Stan (1997) found clofibric acid at levels up to 4 µg/L in groundwater under a sewage treatment farm; they also found clofibric acid concentrations up to 270 ng/L in drinking water samples. They concluded that it is not removed by sewage/water treatment processes.

Buser et al. (1998) reported finding clofibric acid in various Swiss waters ranging from rural to urban lakes. Concentrations ranged from 1 to 9 ng/L (ppt), whereas the parallel concentrations for mecoprop where higher at 8 to 45 ng/L; little of either compound was found in a relatively remote mountain lake, indicating no atmospheric deposition. Because this drug is not manufactured in Switzerland, its route of introduction into the environment had to be through medical use and subsequent excretion and disposal. Although these concentrations are very low, they are significant in that they are similar to the concentrations found for any of the conventional ubiquitous and persistent pollutants, sometimes referred to as persistent organic pollutants (POPs) or persistent bioaccumulative toxicants (PBTs) such as lindane. In one of the lakes studied, Buser et al. (1998) calculated steady-state amounts of clofibric acid to be roughly 19 kg (with export and import amounts balancing each other). Perhaps more significantly, they also found amounts of clofibric acid up to 7.8 ng/L in the North Sea; the parallel concentrations of mecoprop in the same North Sea samples were lower (up to only 2.7 ng/L), indicating that mecoprop was less persistent than clofibric acid.

Stumpf et al. (1996) and Ternes (1998) reported Bezafibrate, Gemfibrozil, and clofibric/fenofibric acids in river waters at the nanograms-per-liter level. Stumpf et al. (1999) reported that the removal efficiencies from Brazilian WWTPs for clofibric/fenofibric acids, Bezafibrate, and Gemfibrozil ranged from only 6 to 50%, verifying extremely limited degradation for these compounds. This chemical class is ubiquitous because the daily human dosages are generally high (grams per day). Buser et al. (1998) concluded that the concentrations seen in urban Swiss and German rivers, coupled with essentially the same concentrations in the North Sea, lead to an annual input of 50 to 100 tons of clofibric acid into the North Sea. The concentration of clofibric acid in the environment is more a function of dilution than of degradation. Clofibric acid is the most widely and routinely reported drug found in open waters. It would be expected that its occurrence in other parts of the world would parallel these studies.

Nonopioid Analgestics and Nonsteroidal Antiinflammatory Drugs

Stumpf et al. (1996) were the first to identify diclofenac, ibuprofen, acetylsalicylic acid, and ketoprofen in sewage and river water. Ternes (1998) reported levels of diclofenac, indometacine, ibuprofen, naproxen, ketoprofen, and phenazone in POTW effluent exceeding 1 µg/L; all of these except ketoprofen were also found in surface waters at concentrations several-fold lower. In another study, Ternes et al. (1998) reported average concentrations of acetylsalicylic acid generally less than 1 µg/L in most POTW effluents as well as less than 0.14 µg/L in rivers. They also reported salicylic acid concentrations of 54 µg/L in POTW influents, with two other acetylsalicylic metabolites, gentisic acid (4.6 µ/L), and *o*-hydroxyhippuric acid (6.8 µg/L). Although low levels (0.5 µg/L) of salicylic acid appeared in the effluents, no detectable amounts of the metabolites could be found. Ternes et al. (1998) also found naproxen (a nonsteroidal antiinflammatory drug) in all POTW effluents examined and in river waters (~0.05 to 0.4 µg/L); two veterinary NSAIDs, meclofenamic and tofenamic acids, were not detectable in any river sample. In their screening of waters in Berlin, Heberer et al. (1998) found that the most prevalent drugs, other than clofibric acid, were the NSAIDs diclofenac, ibuprofen, and propyphenzaone. In groundwater from a drinking water plant, they found diclofenac, ibuprofen, and *N*-methylphenacetin (from phenacetin) (Heberer et al., 1998). In the influent to Swiss WWTPs, Buser et al. (1998) found diclofenac at concentrations of 0.5 to 1.8 µg/L, whereas the concentrations in the respective effluents were only moderately reduced (at most 50%). In the receiving water (Swiss lakes and rivers), they found 11 to 310 ng/L but only 1 to 12 ng/L in exiting waters. They concluded that photolysis was the major cause of the diminished concentrations of diclofenac in surface waters. Buser et al. (1999) showed that ibuprofen, although present in influents at 1 to 3.3 µg/L, was easily degraded to yield low effluent concentrations (nanograms/liter) in contrast to the NSAIDs, which were more refractory.

Beta-Blockers/β_2-Sympathomimetics

Hirsch et al. (1996) and Ternes (1998) identified the beta-blockers metoprolol and propranolol, with lesser amounts of betaxolol, bisoprolol, and nadolol, in POTW effluent. Only metoprolol and propranolol were found in surface waters at concentrations just about the limit of detection. The β_2-sympatnomimetics (bronchodilators) terbutalin and salbutarnol (albuterol in the United States), but rarely clenbuterol and fenoterol, were detected in POTW effluent but only at low concentrations, less than 0.2 µg/L. They were rarely seen in surface waters. It may be significant to note that medications delivered by inhalers could result in portions of the dose being deposited externally because of improper dosing technique. Fenfluramine (*N*-ethyl-α-methyl-3-[trifluoromethyl] benzene ethanamine hydrochloride), known as Pondimin in addition to other brand names, is a sympathomimetic amine that was used as a popular diet (anorectic) drug but was removed from the U.S. market in 1998 by the FDA because of heart valve damage. Although no one has looked for fenfluramine in sewage, it is known to enhance the release of serotonin (3-(2-aminoethyl)indol-5-ol or 5-hydroxytryptamine creatinine sulfate [5-HT]); in the crayfish, 5-HT in turn triggers release of ovary-stimulating hormone, resulting in larger oocytes with enhanced amounts of vitellin (consequences unknown) (Kulkarni et al., 1992). Similarly, in fiddler crabs, fenfluramine at a dose of 125 nmol stimulates (through 5-HT) the production of gonad-stimulating hormone, which accelerates testicular maturation (Sarojini et al., 1993).

Antidepressants and Obsessive–Compulsive Regulators

Selective serotonin reuptake inhibitors (SSRIs) are a major class of widely prescribed antidepressants that includes Prozac, Zoloft, Luvox, and Paxil. These drugs enjoy widespread and heavy use. One of the few series of studies reported in the literature that addresses the effects of drugs on non-target organisms (albeit not the intent of the studies) was performed in a quest for more effective spawning inducers for economically important bivalves (Fong, 1998). Fong's studies and those of other physiologists studying the function of serotonin in a wide array of aquatic creatures could prove highly significant in any discussion of the importance of low levels of pharmaceuticals in the environment. Fong's work is perhaps the most significant to date for showing the potential for dramatic physiologic effects on non-target species (in this case, invertebrates) by low (ppb) concentrations of pharmaceuticals. Serotonin is a biogenic amine common in both vertebrate and invertebrate nervous systems. SSRIs increase serotonin neurotransmission by inhibiting its reuptake at the synapse by inhibiting the transporter enzymes. In addition to playing a key role in mammalian neurotransmission, serotonin is involved in a wide array of physiologic regulatory roles in mollusks, among most other creatures. For bivalves, reproductive functions including spawning, oocyte maturation, and parturition are regulated by serotonin, (Fong, 1998). Serotonin controls a wide spectrum of additional behaviors and reflexes in mollusks, including heartbeat rhythm, feeding/biting, swimming motor patterns, beating cilia, and induction of larval metamorphosis (Couper and Leise, 1996). It also stimulates the release of various neurohormones in crustaceans (hyperglycemic hormone, red pigment-dispersing hormone, neurodepressing hormone, and molt-inhibiting hormone) and ovarian maturation (Sarojini et al., 1995).

It has long been known that serotonin at concentrations of 10^{-4} to 10^{-3} *M* (~0.18 to 1.8 g/L) induces spawning in bivalves. Some commercial farmers make use of this by adding serotonin to induce spawning. Fong (1998) found that Prozac (fluoxetine) and Luvox (fluvoxamine) are the most potent inducers ever found, eliciting spawning behavior in zebra mussels at aqueous concentrations many orders of magnitude lower than serotonin. Fluoxetine elicited significant spawning in male mussels at concentrations of 10^{-7} *M* (~150 µg/L); females were an order of magnitude less sensitive at 10^{-6} *M*. Fluvoxamine was the most potent of the SSRIs, eliciting significant spawning in male mussels at 10^{-9} *M* (~0.318 µg/L); females were two orders of magnitude less sensitive, at 10^{-7} *M*. In males, spawning was complete in the first hour, while females were slower (within 2 hr). Paxil (paroxetine) was the least potent of these three SSRIs, eliciting male spawning, but to a lesser degree, at 10^{-6} *M*, and having no inducing effect on females at any concentration. It should be noted that Fong stated that the evidence was not clear as to whether these compounds were indeed acting as SSRIs or via some other mechanism. It is also unknown how these compounds are taken up by mollusks (Fong, 1998).

In another study, Fong et al. (1998) showed that fluvoxamine induces significant parturition in fingernail clams at 1 n*M*; 1 n*M* fluvoxamine also potentiated the effect of 10 µ*M* 5-HT by almost 5-fold. Paroxetine was less potent, requiring a concentration of 10 µ*M* to bring about significant parturition. In contrast, even at concentrations of 100 µ*M*, fluoxetine displayed no effect, although it was capable at 5 µ*M* of potentiating 5-HT at concentrations that were otherwise subthreshold. It is interesting that the order of potency for inducing parturition in clams differs from the order for induction of spawning in mussels (above). This points out the complexity of considering any approach involving extrapolations from one species to another or from one drug to another within a given class.

In crustaceans, Kulkarni et al. (1992) found that fluoxetine significantly potentiates the effect of 5-HT in crayfish, enhancing the release of ovary-stimulating hormone, which results in larger oocytes with enhanced amounts of vitellin; any ecologic consequences of higher vitellin protein levels are unknown. Similarly, in fiddler crabs, fluoxetine at a dose of 125 nmol stimulates (through 5-HT) the production of gonad-stimulating hormone, which accelerates testicular maturation (Sarojini et al., 1993).

It is clear that aquatic life can be exquisitely sensitive to at least some of this class of compounds. Although some SSRIs are extremely potent, others have almost no effect, which possibly makes that approach of assessing ecologic risk on a class-by-class basis infeasible. The concentration of SSRIs plays a complicated role with respect to effects. For example, Couper and Leise (1996) found that, although injected fluoxetine induced significant metamorphosis in a gastropod, 10^{-4} *M* induced less metamorphosis than 10^{-6} *M*. Simple extrapolations of effects from higher concentrations do not necessarily have any relevance to effects at lower concentrations. The potential for SSRIs to elicit subtle effects on aquatic life is further extended by serotonin reuptake mechanisms that also are a factor in snails and squids (Fong, 1998), particularly in the regulation of aggression (Huber et al., 1997). Yet another example of a subtle effect that would go unnoticed is the fighting behavior of lobsters, in which serotonin causes behavior reversal by stimulating subordinates to engage in fighting against dominants by reducing their propensity to retreat (Huber et al., 1997).

Antiepileptics

Antiepileptics (used to treat epileptic seizures) are ubiquitous and prevalent due to poor WWTP removal. Carbamazepine was the drug detected most frequently and in highest concentrations during a study by Ternes (1998). This drug was detected in all POTWs and receiving waters, with a maximum concentration of 6.3 µg/L. Ternes hypothesized that the ubiquitous occurrence resulted from the very low removal efficiency from POTWs, which was calculated to be only 7%, Sacher et al. (1998) found carbamazepine levels in the river Rhine in Germany up to 0.90 µg/L and always above 0.1 µg/L.

Antineoplastics

Antineoplastics are highly [geno]toxic compounds, primarily from hospitals, with poor removal from WWTPs. These agents, antitumor agents primarily used only within hospitals for chemotherapy, are found sporadically and in a range of concentrations, probably because only small amounts are introduced to WWTPs via domestic sewage because of their long-lived physiologic retention. These compounds act as nonspecific alkylating agents (i.e., specific receptors are not involved) and therefore have the potential to act as either acute or long-felt stressors (mutagens, carcinogens, teratogens, embryotoxins) in any organism. The fact that two oxazaphosphorines, ifosfamide and cyclophosphamide, were found in certain effluents in the low microgram-per-liter range indicates that these highly toxic compounds, which are probably refractory to microbial degradation at POTWs (Steger-Hartmann et al., 1997), can find their way into the environment. Indeed, Steger-Hartmann et al. (1997) found levels of cyclophosphamide in sewage influent from servicing hospitals ranging from undetectable to 143 ng/L; the levels in the effluent reached 17 ng/L.

Additional evidence pointing to the refractory nature of ifosfamide was presented by Kummerer et al. (1997), who found that concentrations of ifosfamide in hospital effluent matched the predicted values of up to 1.91 μg/L; also, the concentrations in the influent and effluent of POTWs that serviced chemotherapy hospitals were essentially unchanged (influent/effluent maximum, 43 ng/L; median, 6.5 to 9.3 ng/L). Kummerer et al. (1997) found ifosfamide to be totally refractory to removal by POTWs and to totally resist alteration during a 2-month bench-scale POTW simulation.

Another class of antineoplastics, the palatinates, includes carboplatin and cisplatin. Although the stability of these compounds in sewage systems is unknown, Kummerer et al. (1999) calculated that if they were present in hospital sewage effluents as the intact parent compound then they could be present at daily average concentrations of up to 600 ng/L (on the basis of total platinum). Although the majority of the dose for these compounds is excreted in the urine in the first day, a large amount (~30%) resides in the body and is slowly excreted over a period of years and therefore could be excreted to residential sewage systems. Falter and Wilken (1999) showed that while these compounds are difficult to determine analytically, their potential to remain in the aqueous phase after sewage treatment is high.

White and Rasmussen (1998), in a detailed overview on the genotoxicity of wastewaters, suggested that, although the genotoxic potency of industrial wastewaters is often the highest, the overall loading of genotoxic compounds to surface waters is far greater, up to several orders of magnitude, from municipal treatment plants. They presented a striking correlation between the occurrence of direct-acting mutagens in surface waters and the human population served by the discharging WWTPs. This correlation points to the activities and metabolism of humans, not industrial activities, as the origin for these mutagens. A number of possible sources for the mutagens are discussed, an obvious one of which is antineoplastic drugs. These data point to antineoplastics as a class of drugs of potential concern for environmental effects, not just for their acute toxicity but perhaps more for their ability to effect subtle genetic changes, the cumulative impact of which over time can lead to more profound ecologic change. Hospitals are the major source of genotoxic drugs. POTWs that service hospitals, especially multiple hospitals, are likely candidates for releasing these chemicals into surface waters.

Impotence Drugs

This class of drugs displays widespread use, new modes of action, and unknown effects on nontarget organisms. It is interesting to note that even though a number of drugs from various chemical classes have been used over the years for treating importance, the emergence of Viagra (sildenafil citrate) has focused tremendous attention on this market. The significance of this therapeutic class of drugs, with new ones awaiting FDA approval, is that they all tend to have distinct modes of action, most of which differ from those of traditional drugs. Although potential effects on wildlife are totally unknown, the fact that Viagra, for example, works by inhibiting a phosphodiesterase responsible for regulating the concentration of cyclic guanosine monophosphate, which indirectly relaxes muscles and increases blood flow (Wilson, 1998) gives cause for concern regarding the disruption of this common phosphodiesterase in unintended target species. Impotence drugs will prove to have very high usage rates, especially since they are one of the most common drugs available without prescription over the Internet, yielding high potential for environmental exposure and possibly non-target effects.

Tranquilizers

Little is known about the possible occurrence of tranquilizers; however, Ternes (1998) reported diazepam in almost half of the POTWs but only in low concentrations of less than 0.04 μg/L. It could not be detected in surface waters. Genicola (1999) reported diazepam in the groundwater from a monitoring well at a Superfund site near Atlantic City, New Jersey. Concentrations were approximately 10 to 40 μg/L and probably originated in a landfill in which pharmaceutical manufacturers disposed of chemicals.

Retinoids

Retinoids, low-molecular-weight lipophilic derivatives of vitamin A, can have profound effects on the development of various embryonic systems (Maden, 1996) especially amphibians in which retinoic acid receptors have been hypothesized to play a role in frog deformities. Although they are naturally occurring, retinoids have been used for a number of years for a wide array of medical conditions including skin disorders (e.g., Accutane [isotretinoin] for acne), antiaging treatments (e.g., Retin-A [tretinoin] for skin wrinkles), and cancer (e.g., Vesanoid [tretinoin] for leukemia). Isotretinoin (13-cisretinoic acid) is related to both retinoic acid and retinol (vitamin A). Tretinoin is among the top 200 prescribed drugs in the United States. Methoprene, an insecticidal synthetic retinoic acid mimic, is photolabile and yields numerous photoproducts, some of which also elicit strong retinoic acid activity. Although retinoic acids would also be expected to be photolabile (and therefore not persistent), their products may also still possess receptor activity.

Diagnostic Contrast Media

X-ray images of soft tissues are routinely captured by the use of contrast media. Some of the more widely used members of contrast media are highly substituted and sterically hindered amidated, iodinated aromatics such as diatrizoate and iopromide (Kalsch, 1999), which are used worldwide at annual rates exceeding 3000 tons. Kalsch (1999) found these compounds to be quite resistant to transformation in WWTPs and in river waters. When transformations were effected, they merely terminated with unidentified resistant metabolites. Ternes et al. (2000) recently reported significant amounts of iopromide in rivers.

In municipal WWTP effluents, Ternes et al. (1999) found concentrations as high as 15 μg/L (iopamidol) and 11 μg/L (iopromide). In a WWTP close to Frankfurt/Main, they found two other contrast agents, diatrizoate and iomeprol, at concentrations up to 8.7 μg/L, as well as iothalamic acid and ioxithalamic acid in the nanogram-per-liter range. In rivers and streams, five iodinated diagnostics were repeatedly detected, with median values up to 0.49 μg/L for iopamidol and up to 0.23 μg/L for diatrizoate. Isolated maximum values above 100 μg/L for diatrizoate indicted that relatively high local concentrations can occur, especially in small streams containing a high percentage of WWTP discharges. Maximum groundwater concentrations for iodinated contrast agents ranged up to 2.4 μg/L and may well represent a worst case with respect to the occurrence of pharmaceuticals in native waters. In Germany alone, individual contrast agents can experience annual usage rates of 100 tons. Such high usage, coupled with inefficient human metabolism (95% unmetabolized) and ineffective elimination of iodinated contrast agents by WWTPs, can lead to very high environmental accumulations and persistence. Despite these negative attributes, contrast agents have no bioaccumulation potential and have low toxicity (Steger-Hartmann et al., 1998); no acute toxicity was found for bacteria (*Vibrio fisheri*), algae (*Scenedesmus subspicatus*), crustaceans (*Daphnia*), or fish (*Danio rerio*, *Lueciscus idus meanotus*) exposed to no more than 10 g/L of iohexol, iotrolan, diatrizoate, or iopromide.

ILLICIT DRUGS IN WASTEWATER

In wastewater treatment, the purpose of *screening* is to remove large solids such as rags, cans, rocks, branches, leaves, roots, etc. 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. The waste stream passes through the screen and the large solids (screenings) are trapped on the bars for removal.

> ***Note:*** The screenings must be removed frequently enough to prevent accumulation that would block the screen and cause the water level in front of the screen to build up.

The bar screen may be coarse (2- to 4-inch openings) or fine (0.75- to 2.0-inch openings). The bar screen may be manually cleaned (bars or screens are placed at an angle of 30° for easier solids removal) or mechanically cleaned (bars are placed at a 45° to 60° angle to improve mechanical cleaner operation).

The screening method employed depends on the design of the plant, the amount of solids expected, and whether the screen is for constant or emergency use only. Manually cleaned screens are cleaned at least once per shift (or often enough to prevent buildup that could 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.

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 could 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 the manufacturer's recommendations or the plant's operations and maintenance manual. Screenings from mechanically operated bar screens are disposed of in the same manner as screenings from manually operated screen: landfill disposal, incineration, or being ground into smaller particles for return to the wastewater flow.

As stated earlier, bar screens are designed to remove large solids such as rags, cans, rocks, branches, leaves, roots, and so forth. The author's walk-around inspections of wastewater treatment plants, which always begin at the plant's headworks (bar screen area where raw influent enters the plant), have revealed that the "and so forth" can include not often thought about or normally mentioned items such as small guns of all makes and models; ammunition, spent and live; aborted fetuses; human tissues; adult diapers; mop heads and towels; illicit drugs and drug paraphernalia; and even $100 bills. Several plant operators over the years have shown their recent acquisition of paper money, including $100 bills, that were removed from the screenings after the bills had entered the plant with the raw sewage flow. Apparently, the money in the sewage influent is the result of police knocking on the door of an illicit drug dealer's hangout (typically a residential home) and the drugs and money being deposited down the toilet to do away with incriminating evidence.

This book is not about illicit drug money, however. The interest is in whether the disposal of illicit drugs into the environment is harming the environment. At this point and time, we do not know what we do not know about this problem; whether or not they have adverse effects is completely unknown (Daughton, 2001). Not knowing the impact of illicit drugs on the environment is not the point at this point of time; what is important today is our awareness of the potential issues related to illicit drug disposal and our need to investigate this problem.

IMPACT OF SURFACE WATER POLLUTION

Unless you notice water bodies best described as cesspools or experience water that smells foul and tastes worse (and ultimately might make you ill), you may think that water pollution is relative, and find it difficult to define. Once you come up with a definition that might have something to do with physical characteristics and negative impacts, you may also realize that freshwater pollution is not a new phenomenon. Only the issue of freshwater pollution as a major public concern is relatively new.

Natural forms of pollutants have always been present in surface waters. Many of the pollutants we have discussed in this section were being washed from the air, eroded from land surfaces, or leached from the soil and ultimately found their way into surface water bodies long before humans evolved to walk on Earth. Floods and dead animals pollute, but their effects are local and generally temporary. In prehistoric times (and even in more recent times) natural disasters have contributed to surface water pollution. Cataclysmic events—earthquakes, volcanic eruptions, meteor impact, transitions from ice age to interglacial age to ice age—have all contributed to surface water pollution. Natural purification processes, over time, were able to self-clean surface water bodies. We can accurately say that without these self-purifying processes, the water-dependent life on earth could not have developed as it did. But the natural problems, the ones the environment could eventually self-clean, are augmented by anthropogenic ones. Manmade problems piled on top of the natural pollutants present us with greater risks—and greater challenges.

GROUNDWATER

Of the approximately 3 feet of water that falls each year on every square foot of Earth (on average), approximately 6 inches of that water returns to the sea. Evaporation takes another 2 feet. The last 6 inches infiltrates through the Earth's interstices, voids, hollows, and cavities, filtering into the sponge-like soil. When it travels down into and through the soil, the course that the water follows may carry it only a few inches, a few feet, or several hundred feet before it joins the subterranean water stores that comprise the Earth's groundwater supply. This water supply (one people are often oblivious to) contains an estimated 1,700,000 cubic miles of water, hidden underground. Enough water, if you could spread it over the surface of the Earth, to blanket all of the planet's land surfaces with 1000 feet of water. U.S. groundwater sources constitute a freshwater supply greater than all the surface water in the United States—and that includes the Great Lakes.

This enormous reservoir, our groundwater supply, feeds all the natural fountains and springs of Earth. These natural exits for groundwater allow it to bubble up in cool, blue pools from springs. In more unusual circumstances, from places too deep within the Earth to imagine, groundwater heats up, forms steam, and bursts from the surface in geysers and hot springs. Although we make use of many different groundwater sources, not all groundwater supplies can be tapped for use. In some places, the water is not accessible because of pumping costs and drilling difficulties. Groundwater supplies, too, are not always pure. Contaminated groundwater supplies have become a significant pollution problem. Most of the groundwater supply, however, lies within reach of the surface, accessible by drilling a borehole or well down to the water table. Humans have obtained water this way for millennia, and as more and more people inhabit Earth more use is being made of our groundwater supplies. Currently, groundwater serves as a reliable source of potable water for millions of the planet's inhabitants, and if used with moderation groundwater should remain a viable source for years to come.

GROUNDWATER USES AND SOURCES

The water we use, by population, breaks down to roughly 50% groundwater sources and 50% surface water sources. Large cities rely primarily on surface water for their supplies, but 95% of small communities and rural areas use groundwater. A larger percent of the U.S. population is supplied by surface water than by groundwater, but only one-fourth of the total number of communities is supplied by surface water. As a water supply source, groundwater has several desirable characteristics: (1) natural storage, which eliminates the need for manmade impoundments; (2) availability at the point of demand, so transmission costs are reduced significantly; and (3) filtration through the natural geologic strata, which means that groundwater usually appears clearer to the eye than surface water does (McGhee, 1991). For these reasons, groundwater is generally preferred as a municipal and industrial water source.

For many years, we believed that groundwater was safe from contamination, naturally cleansed by traveling through the soil. Groundwater was considered safe to drink, and many water utilities delivered it to their customers with no further treatment. We know better now. We have discovered that groundwater is not automatically safe to use as a potable water supply. Discoveries of contaminated groundwater have led to the closure of thousands of potable water wells across the United States. The USEPA reported that in the mid-1980s more than 8000 drinking water wells in areas all over the nation were no longer usable because of contamination. Monitoring the complex groundwater situation nationwide is fraught with difficulty because of the vast number of potential and possible contamination sources, including contamination by toxic or hazardous materials leaking from waste treatment facilities, natural sources, or landfills that may not be evident to either the public or regulatory agencies, as well as from many other sources. Groundwater contamination's biggest problem is twofold: monitoring its condition is difficult and, when contaminated, restoring it is difficult (and expensive)—if possible at all.

Aquifers

An aquifer performs two important functions: storage and transport. Expressed simply, the subsurface is charged with the water that then becomes groundwater when the surface water seeps down from the rain-soaked surface and sinks until it reaches an impermeable layer, where it collects and fills all the pores and cracks of the permeable portions. The top of this saturated zone is called the *water table* (see Figure 8.2). In reality, the groundwater system is a bit more complicated than that shown in Figure 8.2. Groundwater occurs in two different zones in unconfined aquifers (an aquifer not overlain by an impermeable layer is unconfined). These zones are distinguished by whether or not water fills all the cracks and pores between particles of soil and rock. The unsaturated zone, which lies just beneath the land surface, is characterized by crevices that contain both air and water. While the unsaturated zone contains water (vadose water), this water is essentially unavailable for use. Water flow in a confined aquifer (a water-bearing layer sandwiched between two less permeable layers) is restricted to vertical movement only (see Figure 8.3). An unconfined aquifer allows water to flow with more freedom of movement and resembles flow in an open channel.

Groundwater Flow

To have any flow at all, a hydraulic gradient must exist, whether groundwater flow occurs in an unconfined aquifer's open-channel-like flow or a confined aquifer's vertical-only (pipe-like) flow. The hydraulic gradient is the difference in hydraulic head divided by the distance along the fluid

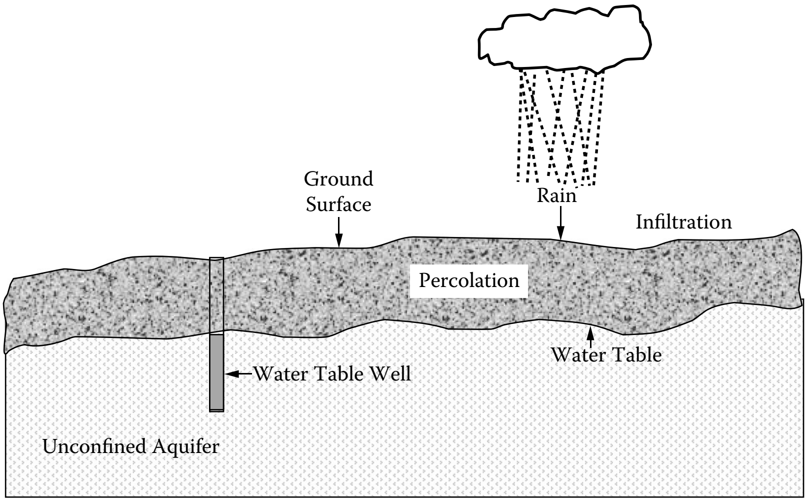

FIGURE 8.2 Unconfined aquifer.

flow path. For our applications of the concept, you should know that groundwater moves through an aquifer in the direction of the hydraulic gradient, at a rate proportional to the gradient (the direction of the slope of the water table), inversely related to the aquifer's permeability. The more permeable the substrate and the steeper the slope, the more rapidly the water flows.

Groundwater, of course, contrary to popular belief, does not flow like a river. Percolating downward, groundwater moves from high elevations to lower elevations at a variable rate that is dependent on underground conditions. Sometimes slow moving, it can also move surprisingly quickly, from less than an inch to a several feet a day.

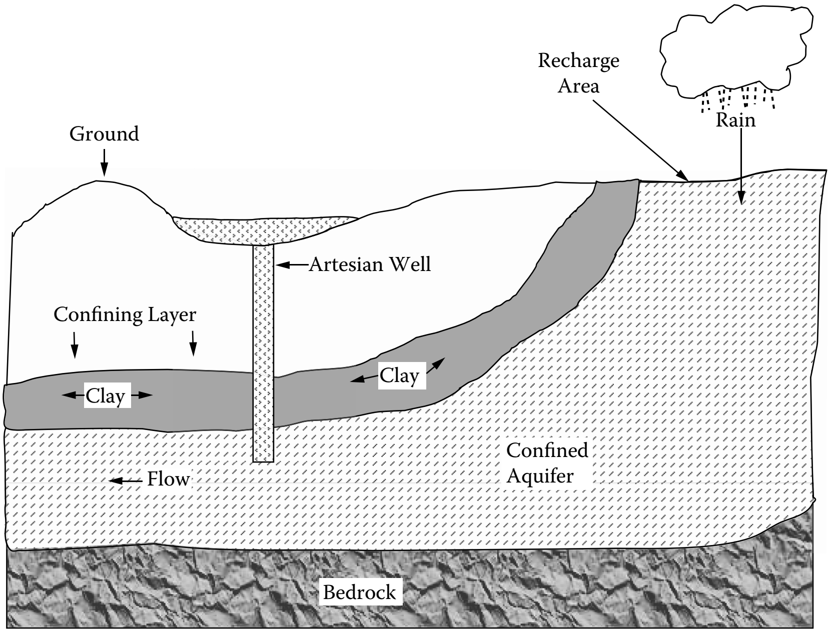

FIGURE 8.3 Confined aquifer.

Groundwater aquifers, as we said previously, supply a large portion of the U.S. population—and almost all of the rural population. They are important sources of water. Groundwater use continues to increase, which threatens both the quantity and quality of this critically important resource. Two important points should be remembered about groundwater: (1) The groundwater supply is not inexhaustible, and (2) groundwater is not exempt from surface contamination. It is not completely purified as it percolates through the ground, even though the interconnectedness of the hydrological cycle in self-purification works to our advantage. The processes integral to the water cycle can trap toxins, complicating efforts to clean them up, which is of special concern for persistent pollutants. The natural processes that clean our water as it travels through the hydrological cycle worked well for centuries, but now, in many places, humans have overloaded the capacity of the water cycle to self purify. While we are now cleaning up problems created by past environmental abuse and ignorance, inevitably we are creating problems that future generations will have to clean up. The solutions we try now will present future generations with problems we did not foresee, but recreating past mistakes is foolish and foolhardy. Our water system is too valuable for us to risk.

Groundwater Pollution

Groundwater pollution can be a very serious problem. We already know, through experience and study, that any pollutant that contacts the ground holds the possibility for contaminating groundwater. As water enters the ground, it filters naturally through the soil; in some soils that process quite effectively, many substances are removed, including suspended solids and bacteria—and pollutants. Some chemicals are removed as they bind themselves to the surface of soil particles (phosphates). In some areas, though, industrial and municipal wastes are sprayed on the ground surface to take advantage of the natural self-purification process; the wastewater filters through the soil, becomes purified in the process, and recharges the groundwater reservoir. Natural purification of water as it passes through the soil is a beneficial process but slow, because the water has no access to air and is not readily diluted.

Drainage-basin activities that pollute surface waters also cause groundwater contamination. Problems can occur from sources as diverse as septic tanks, agriculture, industrial waste lagoons, underground injection wells, underground storage tanks, and landfills. Waste disposal sites located in unsuitable soils (or even directly over fractured dolomites and limestones) can cause major problems. Disposal sites located directly on top of such rock allow polluted water to travel into wells. At least 25% of the usable groundwater (from wells) is already contaminated in some areas (Draper, 1987).

Causes of groundwater contamination vary. Increasingly, groundwater contamination from saltwater, microbiological contaminants, and toxic organic and inorganic chemicals is being observed. The major source of groundwater contamination in the United States comes from the improper disposal of toxic industrial wastes. The levels of and problems related to contamination from these wastes are increased significantly when waste disposal sites are not protected by some type of lining, when disposal sites lie in permeable materials above usable water aquifers, and when these sites are located close to water supply wells. The Conservation Foundation (1982) reported that groundwater contamination was responsible for closing hundreds of U.S. wells.

WETLANDS

Wetlands routinely replenish and purify groundwater supplies. By absorbing excess nutrients and immobilizing pesticides, heavy metals, and other toxins, wetland plants prevent them from moving up the food chain. Wetlands have been used to treat sewage in some locations; however, wetland ecosystems are relatively fragile, and their capacity to cleanse polluted water is limited. Many have been overwhelmed by pollution, although more of our natural wetland areas have been destroyed by anthropogenic activities. In the United States, for example, half of our wetlands have been lost to urban and agricultural development (Goldsmith and Hildyard, 1988).

WATER TREATMENT

In this section, the focus is on water treatment operations and the various unit processes currently used to treat raw source water before it is distributed to the user. In addition, the reasons for water treatment and the basic theories associated with individual treatment unit processes are discussed. Water treatment systems are installed to remove those materials that cause disease or create nuisances. At its simplest level, the basic goal of water treatment operations is to protect public health, with a broader goal to provide potable and palatable water. The bottom line is that the water treatment process functions to provide water that is safe to drink and is pleasant in appearance, taste, and odor.

In this text, *water treatment* is defined as any unit process that changes or alters the chemical, physical, or bacteriological quality of water with the purpose of making it safe for human consumption or appealing to the customer. Treatment also is used to protect the water distribution system components from corrosion. Many water treatment unit processes are commonly used today. The treatment processes used depend on the evaluation of the nature and quality of the particular water to be treated and the desired quality of the finished water. For water treatment unit processes employed to treat raw water, one thing is certain: As new U.S. Environmental Protection Agency (USEPA) regulations take effect, many more processes will come into use in an attempt to produce water that complies with all current regulations, despite source water conditions.

Small water systems tend to use a smaller number of the wide array of unit treatment processes available, in part because they usually rely on groundwater as the source and because their small size makes many sophisticated processes impractical (e.g., too expensive to install, too expensive to operate, too sophisticated for limited operating staff). This chapter concentrates on those individual treatment unit processes usually found in conventional water treatment systems, corrosion control methods, and fluoridation. A summary of basic water treatment processes (many of which are discussed in this chapter) is presented Table 8.2.

PURPOSE OF WATER TREATMENT

The purpose of water treatment is to condition, modify, or remove undesirable impurities and to provide water that is safe, palatable, and acceptable to users. This may seem an obvious, expected purpose of treating water, but various regulations also require water treatment. Some regulations state that if the contaminants listed under the various regulations are found in excess of maximum contaminant levels (MCLs) then the water must be treated to reduce the levels. If a well or spring source is surface influenced, treatment is required, regardless of the actual presence of contamination. Some impurities affect the aesthetic qualities (taste, odor, color, and hardness) of the water; if they exceed secondary MCLs established by the USEPA and the state, the water may have to be treated.

If we assume that the water source used to feed a typical water supply system is groundwater (usually the case in the United States), a number of common groundwater problems may require water treatment. Keep in mind that water that must be treated for any one of these problems may also exhibit several other problems:

- Bacteriological contamination
- Hydrogen sulfide odors
- Hard water
- Corrosive water
- Iron and manganese

Earlier it was stated that the focus our discussion in this text is on the conventional model of water treatment. Figure 8.4 presents the conventional model discussed throughout this text. The figure clearly illustrates that water treatment is made up of various stages, unit processes, or a train of

TABLE 8.2
Basic Water Treatment Processes

Process	Purpose
Screening	Removes large debris (leaves, sticks, fish) that can foul or damage plant equipment
Chemical pretreatment	Conditions the water for removal of algae and other aquatic nuisances
Presedimentation	Removes gravel, sand, silt, and other gritty materials
Microstraining	Removes algae, aquatic plants, and small debris
Chemical feed and rapid mix	Adds chemicals (e.g., coagulants, pH, adjusters) to water
Coagulation–flocculation	Converts nonsettleable or settable particles
Sedimentation	Removes settleable particles
Softening	Removes hardness-causing chemicals from water
Filtration	Removes particles of solid matter which can include biological contamination and turbidity
Disinfection	Kills disease-causing organisms
Adsorption using granular activated carbon	Removes radon and many organic chemicals such as pesticides, solvents, and trihalomethanes
Aeration	Removes volatile organic compounds (VOCs), radon H_2S, and other dissolved gases; oxidizes iron and manganese
Corrosion control	Prevents scaling and corrosion
Reverse osmosis, electrodialysis	Removes nearly all inorganic contaminants
Ion exchange	Removes some inorganic contaminants including hardness-causing chemicals
Activated alumina	Removes some inorganic contamination
Oxidation filtration	Removes some inorganic contaminants (e.g., iron, manganese, radium)

Source: Adapted from AWWA, *Introduction to Water Treatment*, Vol. 2, American Water Works Association, Denver, CO, 1984.

processes combined to form one treatment system. Note that a given waterworks may contain all the unit processes discussed in the following or any combination of them. One or more of these stages may be used to treat any one or more of the source water problems listed above. Also note that the model shown in Figure 8.4 does not necessarily apply to very small water systems. In some small systems, water treatment may consist of nothing more than removal of water via pumping from a groundwater source to storage to distribution. In some small water supply operations, disinfection may be added because it is required. Although it is likely that the basic model shown in Figure 8.4 does not reflect the type of treatment process used in most small systems, we use it in this handbook for illustrative and instructive purposes because higher level licensure requires operators, at a minimum, to learn these processes.

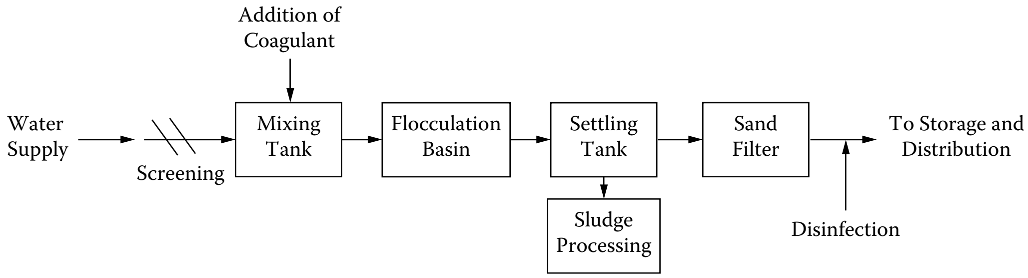

FIGURE 8.4 Conventional water treatment model.

PRETREATMENT

Simply stated, water pretreatment (also called *preliminary treatment*) is any physical, chemical, or mechanical process used before main water treatment processes. It can include screening, presedimentation, and chemical addition (see Figure 8.4). Pretreatment in water treatment operations usually consists of oxidation or other treatment for the removal of tastes and odors, iron and manganese, trihalomethane precursors, or entrapped gases (such as hydrogen sulfide). Unit processes may include chlorine, potassium permanganate or ozone oxidation, activated carbon addition, aeration, and presedimentation. Pretreatment of surface water supplies accomplishes the removal of certain constituents and materials that interfere with or place an unnecessary burden on conventional water treatment facilities.

Typical pretreatment processes include the following (TWUA, 1988):

- Removal of debris from water from rivers and reservoirs that would clog pumping equipment
- Destratification of reservoirs to prevent anaerobic decomposition that could result in reducing iron and manganese in the soil to a state that would be soluble in water which can cause subsequent removal problems in the treatment plant; the production of hydrogen sulfide and other taste- and odor-producing compounds also results from stratification
- Chemical treatment of reservoirs to control the growth of algae and other aquatic growths that could result in taste and odor problems
- Presedimentation to remove excessively heavy silt loads prior to the treatment processes
- Aeration to remove dissolved odor-causing gases such as hydrogen sulfide and other dissolved gases or volatile constituents and to aid in the oxidation of iron and manganese, although manganese or high concentrations of iron are not removed during detention provided in conventional aeration units
- Chemical oxidation of iron and manganese, sulfides, taste- and odor-producing compounds, and organic precursors that may produce trihalomethanes upon the addition of chlorine
- Adsorption for removal of tastes and odors

Note: An important point to keep in mind is that, in small systems using groundwater as a source, pretreatment may be the only treatment process used. Pretreatment may be incorporated as part of the total treatment process or may be located adjacent to the source before the water is sent to the treatment facility.

Aeration

Aeration is commonly used to treat water that contains trapped gases (such as hydrogen sulfide) that can impart an unpleasant taste and odor to the water. Just allowing the water to rest in a vented tank will (sometimes) drive off much of the gas, but usually some form of forced aeration is needed. Aeration works well (about 85% of the sulfides may be removed) whenever the pH of the water is less than 6.5. Aeration may also be useful in oxidizing iron and manganese, oxidizing humic substances that might form trihalomethanes when chlorinated, eliminating other sources of taste and odor, or imparting oxygen to oxygen-deficient water.

Note: Iron is a naturally occurring mineral found in many water supplies. When the concentration of iron exceeds 0.3 mg/L, red stains will occur on fixtures and clothing. The customer then incurs costs for cleaning and replacement of damaged fixtures and clothing. Manganese, like iron, is a naturally occurring mineral found in many water supplies. When the concentration of manganese exceeds 0.05 mg/L, black stains occur on fixtures and clothing. As with iron, this increases customer costs for cleaning and replacement of damaged fixtures and clothing. Iron and manganese are commonly found together in the same water supply. We discuss iron and manganese later.

Screening

Screening is usually the first major step in the water pretreatment process (see Figure 8.4). It is defined as the process whereby relatively large and suspended debris is removed from the water before it enters the plant. River water, for example, typically contains suspended and floating debris varying in size from small rocks to logs. Removing these solids is important, not only because these items have no place in potable water but also because this river trash may cause damage to downstream equipment (e.g., clogging and damaging pumps), increase chemical requirements, impede hydraulic flow in open channels or pipes, or hinder the treatment process. The most important criteria used in the selection of a particular screening system for water treatment technology are the screen opening size and flow rate. Other important criteria include costs related to operation and equipment, plant hydraulics, debris handling requirements, and operator qualifications and availability. Large surface water treatment plants may employ a variety of screening devices including rash screens (or trash rakes), traveling water screens, drum screens, bar screens, or passive screens.

Chemical Addition

Much of the procedural information presented in this section applies to both water and wastewater operations. Two of the major chemical pretreatment processes used in treating water for potable use are iron and manganese removal and hardness removal. Another chemical treatment process that is not necessarily part of the pretreatment process, but is also discussed in this section, is corrosion control. Corrosion prevention is effected by chemical treatment—not only in the treatment process but also in the distribution process. Before discussing each of these treatment methods in detail, however, it is important to describe chemical addition, chemical feeders, and chemical feeder calibration.

When chemicals are used in the pretreatment process, they must be the proper ones, fed in the correct concentration and introduced to the water at the proper locations. Determining the proper amount of chemical to use is accomplished by testing. The operator must test the raw water periodically to determine if the chemical dosage should be adjusted. For surface supplies, checking must be done more frequently than for groundwater (remember, surface water supplies are subject to change on short notice, while groundwaters generally remain stable). The operator must be aware of the potential for interactions between various chemicals and how to determine the optimum dosage (e.g., adding both chlorine and activated carbon at the same point will minimize the effectiveness of both processes, as the adsorptive power of the carbon will be used to remove the chlorine from the water).

Note: Sometimes using too many chemicals can be worse than not using enough.

Prechlorination (distinguished from chlorination used in disinfection at the end of treatment) is often used as an oxidant to help with the removal of iron and manganese; however, a concern for systems that prechlorinate is the potential for the formation of total trihalomethanes (TTHMs), which form as a byproduct of the reaction between chlorine and naturally occurring compounds in raw water. The USEPA TTHM standard does not apply to water systems that serve fewer than 10,000 people, but operators should be aware of the impact and causes of TTHMs. Chlorine dosage or the application point may be changed to reduce problems with TTHMs.

Note: TTHMs such as chloroform are known or suspected to be carcinogenic and are limited by water and state regulations.

All chemicals intended for use in drinking water must meet certain standards. Thus, when ordering water treatment chemicals, the operator must be confident that they meet all appropriate standards for drinking water use.

Note: To be effective, pretreatment chemicals must be thoroughly mixed with the water. Short-circuiting or plug flows of chemicals that do not come in contact with most of the water will not result in proper treatment.

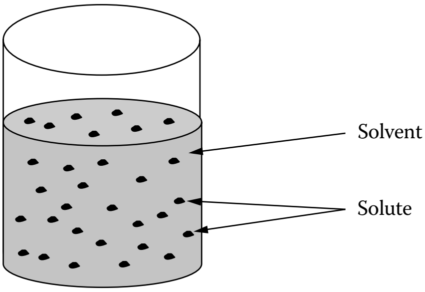

FIGURE 8.5 Solution with two components: solvent and solute.

Chemicals are normally fed with dry chemical feeders or solution (metering) pumps. Operators must be familiar with all of the adjustments required to control the rate at which the chemical is fed to the water (wastewater). Some feeders are manually controlled and must be adjusted by the operator when the raw water quality or the flow rate changes; other feeders are paced by a flow meter to adjust the chemical feed so it matches the water flow rate. Operators must also be familiar with chemical solution and feeder calibration. As mentioned, a significant part of the waterworks operator's daily functions is measuring quantities of chemicals and applying them to water at preset rates. Normally accomplished semiautomatically by use of electromechanical–chemical feed devices, waterworks operators must still know what chemicals to add, how much to add to the water (wastewater), and the purpose of the chemical addition.

Chemical Solutions

A *water solution* is a homogeneous liquid made of the *solvent* (the substance that dissolves another substance) and the *solute* (the substance that dissolves in the solvent). Water is the solvent (see Figure 8.5). The solute (whatever it may be) may dissolve up to a certain limit. This level is its *solubility*—that is, the solubility of the solute in the particular solvent (water) at a particular temperature and pressure.

> **Note:** Temperature and pressure influence the stability of solutions but not filtration, because only suspended material can be eliminated by filtration or by sedimentation.

Remember, in chemical solutions, the substance being dissolved is the solute, and the liquid present in the greatest amount in a solution (that does the dissolving) is the solvent. The operator should also be familiar with another term—*concentration*, which is the amount of solute dissolved in a given amount of solvent. Concentration is measured as

$$\%\ \text{Strength} = \frac{\text{Weight of solute}}{\text{Weight of solution}} \times 100 = \frac{\text{Weight of solute}}{\text{Weight of solute} + \text{solvent}} \times 100 \tag{8.1}$$

■ EXAMPLE 8.1

Problem: If 30 lb of chemical are added to 400 lb of water, what is the percent strength (by weight) of the solution?

Solution:

$$\%\ \text{Strength} = \frac{30\ \text{lb solute}}{\text{Weight of solution}} \times 100$$

$$= \frac{30\ \text{lb solute}}{30\ \text{lb solute} + 400\ \text{lb water}} \times 100 = \frac{30\ \text{lb}}{430\ \text{lb}} = 7.0\ \text{(rounded)}$$

Important to the process of making accurate computations of chemical strength is a complete understanding of the dimensional units involved; for example, operators should understand exactly what *milligrams per liter* (mg/L) signify:

$$\text{Milligrams per liter (mg/L)} = \frac{\text{Milligrams of solute}}{\text{Liters of solution}} \tag{8.2}$$

Another important dimensional unit commonly used when dealing with chemical solutions is *parts per million* (ppm):

$$\text{Parts per million (ppm)} = \frac{\text{Parts of solute}}{\text{Million parts of solution}} \tag{8.3}$$

Note: "Parts" is usually a weight measurement.

An example is

$$9\text{ ppm} = \frac{9\text{ lb solids}}{1{,}000{,}000\text{ lb solution}} \quad \text{or} \quad 9\text{ ppm} = \frac{9\text{ mg solids}}{1{,}000{,}000\text{ mg solution}}$$

This leads us to two important parameters that operators should commit to memory:

- 1 mg/L = 1 ppm
- 1% = 10,000 mg/L

When working with chemical solutions, it is also necessary to be familiar with two important chemical properties: *density* and *specific gravity*. Density is defined as the weight of a substance per a unit of its volume—for example, pounds per cubic foot or pounds per gallon. Specific gravity is defined as the ratio of the density of a substance to a standard density.

$$\text{Density} = \frac{\text{Mass of substance}}{\text{Volume of substance}} \tag{8.4}$$

$$\text{Specific gravity} = \frac{\text{Density of substance}}{\text{Density of water}} \tag{8.5}$$

Here are a few key facts about density:

- Density is measured in units of lb/ft^3, lb/gal, or mg/L.
- Density of water = 62.5 lb/ft^3 = 8.34 lb/gal.
- Density of concrete = 130 lb/ft^3.
- Density of alum (liquid @ 60°F) = 1.33.
- Density of hydrogen peroxide (35%) = 1.132.

Here are a few facts about specific gravity:

- Specific gravity has no units.
- Specific gravity of water = 1.0.
- Specific gravity of concrete = 2.08.
- Specific gravity of alum (liquid @ 60°F) = 1.33.
- Specific gravity of hydrogen peroxide (35%) = 1.132.

Chemical Feeders

Simply put, a chemical feeder is a mechanical device for measuring a quantity of chemical and applying it to water at a preset rate. Two types of chemical feeders are commonly used: solution (or liquid) feeders and dry feeders. Liquid feeders apply chemicals in solutions or suspensions, and dry feeders apply chemicals in granular or powdered forms. In a solution feeder, the chemical enters and leaves the feeder in a liquid state; in a dry feeder, the chemical enters and leaves the feeder in a dry state. Solution feeders are small, positive-displacement metering pumps of three types: (1) reciprocating (piston-plunger or diaphragm type), (2) vacuum type (e.g., gas chlorinator), or (3) gravity feed rotameter (e.g., drip feeder). Positive displacement pumps are used in high-pressure, low-flow applications; they deliver a specific volume of liquid for each stroke of a piston or rotation of an impeller.

Two types of dry feeders are *volumetric* and *gravimetric*, depending on whether the chemical is measured by volume (volumetric) or weight (gravimetric). Simpler and less expensive than gravimetric pumps, volumetric dry feeders are also less accurate. Gravimetric dry feeders are extremely accurate, deliver high feed rates, and are more expensive than volumetric feeders.

Chemical Feeder Calibration

Chemical feeder calibration ensures effective control of the treatment process. Obviously, chemical feed without some type of metering and accounting of the chemicals used adversely affects the water treatment process. Chemical feeder calibration also optimizes economy of operation; that is, it ensures the optimum use of expensive chemicals. Finally, operators must have accurate knowledge of the capabilities of each individual feeder at specific settings. When a certain dose must be administered, the operator must rely on the feeder to feed the correct amount of chemical. Proper calibration ensures chemical dosages can be set with confidence. At a minimum, chemical feeders must be calibrated on an annual basis. During operation, when the operator changes chemical strength or chemical purity or makes any adjustment to the feeder, or when the treated water flow changes, the chemical feeder should be calibrated. Ideally, any time maintenance is performed on chemical feed equipment, calibration should be performed.

What factors affect chemical feeder calibration (i.e., feed rate)? For solution feeders, calibration is affected any time the solution strength changes, any time a mechanical change is introduced in the pump (change in stroke length or stroke frequency), or whenever flow rate changes. In the dry chemical feeder, calibration is affected any time chemical purity changes or mechanical damage occurs (e.g., belt change), or whenever flow rate changes. In the calibration process, calibration charts are usually used or made up to fit the calibration equipment. The calibration chart is also affected by certain factors, including changes in chemicals, changes in the flow rate of the water being treated, or a mechanical change in the feeder.

■ EXAMPLE 8.2

This real-world example demonstrates that performing a chemical feed procedure is not necessarily as simple as opening a bag of chemicals and dumping the contents into the feed system.

Problem: Consider the chlorination dosage rates below.

Setting		**Dosage**
100%	111/121	0.93 mg/L
70%	78/121	0.66 mg/L
50%	54/121	0.45 mg/L
20%	20/121	0.16 mg/L

Solution: This is not a good dosage setup for a chlorination system. Maintenance of a chlorine residual at the ends of the distribution system should be within 0.5 to 1.0 ppm. At 0.9 ppm, dosage will probably result in this range—depending on the chlorine demand of the raw water and detention time in the system. However, the pump is set at its highest setting. We have room to decrease the dosage but no ability to increase the dosage without changing the solution strength in the solution tank. In this example, doubling the solution strength to 1% provides the ideal solution, resulting in the following chart changes.

Setting		Dosage
100%	222/121	1.86 mg/L
70%	154/121	1.32 mg/L
50%	108/121	0.90 mg/L
20%	40/121	0.32 mg/L

This is ideal, because the dosage we want to feed is at the 50% setting for our chlorinator. We can now easily increase or decrease the dosage, whereas the previous setup only allowed the dosage to be decreased.

Iron and Manganese Removal

Iron and manganese are frequently found in groundwater and in some surface waters. They do not cause health-related problems but are objectionable because they may cause aesthetic problems. Severe aesthetic problems may cause consumers to avoid an otherwise safe water supply in favor of one of unknown or questionable quality, or they may cause customers to incur unnecessary expenses for bottled water. Aesthetic problems associated with iron and manganese include the discoloration of water (iron, reddish water; manganese, brown or black water), staining of plumbing fixtures, a bitter taste, and the growth of microorganisms.

Although no health concerns are directly associated with iron and manganese, the growth of iron bacteria slimes may cause indirect health problems. Economic problems include damage to textiles, dye, paper, and food. Iron residue (or tuberculation) in pipes increases pumping head, decreases carrying capacity, may clog pipes, and may corrode through pipes.

> ***Note:*** Iron and manganese are secondary contaminants. Their secondary maximum contaminant levels (SMCLs) are 0.3 mg/L for iron and 0.05 mg/L for manganese.

Iron and manganese are most likely found in groundwater supplies, industrial waste, and acid mine drainage and are byproducts of pipeline corrosion. They may accumulate in lake and reservoir sediments, causing possible problems during lake/reservoir turnover. They are not usually found in running waters (e.g., streams, rivers).

Iron and Manganese Removal Techniques

Chemical precipitation treatments for iron and manganese removal are called *deferrization* and *demanganization*, respectively. The usual process is *aeration*, where dissolved oxygen in the chemical causes precipitation; chlorine or potassium permanganate may also be required.

Precipitation Precipitation (or pH adjustment) of iron or manganese from water in their solid forms can be performed in treatment plants by adjusting the pH of the water through the addition of lime or other chemicals. Some of the precipitate will settle out with time, while the rest is easily removed by sand filters. This process requires the pH of the water to be in the range of 10 to 11.

> ***Note:*** Although the precipitation or pH adjustment technique for treating water containing iron and manganese is effective, note that the pH level must be adjusted higher (10 to 11) to cause the precipitation, which means that the pH level must also then be lowered (to 8.5 or a bit lower) to use the water for consumption.

Oxidation One of the most common methods for removing iron and manganese is the process of oxidation (another chemical process), usually followed by settling and filtration. Air, chlorine, or potassium permanganate can oxidize these minerals. Each oxidant has advantages and disadvantages, as each operates slightly differently:

- *Air*—To be effective as an oxidant, the air must come in contact with as much of the water as possible. Aeration is often accomplished by bubbling diffused air through the water, by spraying the water up into the air, or by trickling the water over rocks, boards, or plastic packing materials in an aeration tower. The more finely divided the drops of water, the more oxygen comes in contact with the water and the dissolved iron and manganese.
- *Chlorine*—This is one of the most popular oxidants for iron and manganese control because it is also widely used as a disinfectant; controlling iron and manganese by prechlorination can be as simple as adding a new chlorine feed point in a facility already feeding chlorine. It also provides a predisinfecting step that can help control bacterial growth throughout the rest of the treatment system. The downside to using chlorine is that when chlorine reacts with the organic materials found in surface water and some groundwaters it forms TTHMs. This process also requires that the pH of the water be in the range of 6.5 to 7; because many groundwaters are more acidic than this, pH adjustment with lime, soda ash, or caustic soda may be necessary when oxidizing with chlorine.
- *Potassium permanganate*—This is the best oxidizing chemical to use for manganese control removal. An extremely strong oxidant, it has the additional benefit of producing manganese dioxide during the oxidation reaction. Manganese dioxide acts as an adsorbent for soluble manganese ions. This attraction for soluble manganese provides removal to extremely low levels.

The oxidized compounds form precipitates that are removed by a filter. Note that sufficient time should be allowed from the addition of the oxidant to the filtration step; otherwise, the oxidation process will be completed after filtration, creating insoluble iron and manganese precipitates in the distribution system.

Ion Exchange The ion exchange process is used primarily to soften hard waters, but it will also remove soluble iron and manganese. The water passes through a bed of resin that adsorbs undesirable ions from the water, replacing them with less troublesome ions. When the resin has given up all of its donor ions, it is regenerated with strong salt brine (sodium chloride); the sodium ions from the brine replace the adsorbed ions and restore the ion exchange capabilities.

Sequestering Sequestering or stabilization may be used when the water contains mainly low concentrations of iron and the volumes required are relatively small. This process does not actually remove the iron or manganese from the water but complexes (binds it chemically) it with other ions in a soluble form that is not likely to come out of solution (i.e., not likely oxidized).

Aeration The primary physical process uses air to oxidize the iron and manganese. The water is either pumped up into the air or allowed to fall over an aeration device. The air oxidizes the iron and manganese, which are then removed by use of a filter. To raise the pH, lime is often added to the process. Although this is referred to as a physical process, removal is accomplished by chemical oxidation.

Potassium Permanganate Oxidation and Manganese Greensand The continuous regeneration potassium greensand filter process is another commonly used filtration technique for iron and manganese control. Manganese greensand is a mineral (gluconite) that has been treated with alternating solutions of manganous chloride and potassium permanganate. The result is a sand-like (zeolite) material coated with a layer of manganese dioxide—an adsorbent for soluble iron and manganese. Manganese greensand has the ability to capture (adsorb) soluble iron and manganese that may have escaped oxidation, as well as the capability of physically filtering out the particles of oxidized iron and manganese. Manganese greensand filters are generally set up as pressure filters, totally enclosed tanks containing the greensand. The process of adsorbing soluble iron and manganese uses up the greensand by converting the manganese dioxide coating to manganic oxide, which does not have the adsorption property. The greensand can be regenerated in much the same way as ion exchange resins by washing the sand with potassium permanganate.

HARDNESS TREATMENT

Hardness in water is caused by the presence of certain positively charged metallic ions in solution in the water. The most common of these hardness-causing ions are calcium and magnesium; others include iron, strontium, and barium. As a general rule, groundwaters are harder than surface waters, so hardness is frequently of concern to the small water system operator. This hardness is derived from contact with soil and rock formations such as limestone. Although rainwater itself will not dissolve many solids, the natural carbon dioxide in the soil enters the water and forms carbonic acid (HCO), which is capable of dissolving minerals. Where soil is thick (contributing more carbon dioxide to the water) and limestone is present, hardness is likely to be a problem. The total amount of hardness in water is expressed as the sum of its calcium carbonate ($CaCO_3$) and its magnesium hardness; however, for practical purposes, hardness is expressed as calcium carbonate. This means that, regardless of the amount of the various components that make up hardness, they can be related to a specific amount of calcium carbonate (e.g., hardness is expressed as "mg/L as $CaCO_3$," or milligrams per liter as calcium carbonate).

> ***Note:*** The two types of water hardness are *temporary hardness* and *permanent hardness*. Temporary hardness is also known as *carbonate hardness* (hardness that can be removed by boiling), and permanent hardness is also known as *noncarbonate hardness* (hardness that cannot be removed by boiling).

Hardness is of concern in domestic water consumption because hard water increases soap consumption, leaves a soapy scum in the sink or tub, can cause water heater electrodes to burn out quickly, can cause discoloration of plumbing fixtures and utensils, and is perceived as being less desirable water. In industrial water use, hardness is a concern because it can cause boiler scale and damage to industrial equipment.

The objection of customers to hardness is often dependent on the amount of hardness they are used to. People familiar with water with a hardness of 20 mg/L might think that a hardness of 100 mg/L is too much. On the other hand, a person who has been using water with a hardness of 200 mg/L might think that 100 mg/L is very soft. Table 8.3 lists the classifications of hardness.

Hardness Calculation

Recall that hardness is expressed as mg/L as $CaCO_3$. The mg/L of calcium and manganese must be converted to mg/L as $CaCO_3$ before they can be added. The hardness (in mg/L as $CaCO_3$) for any given metallic ion is calculated using the following formula:

$$\text{Hardness (mg/L as CaCO}_3\text{)} = M\text{(mg/L)} \times \frac{50}{\text{EW of } M} \tag{8.6}$$

TABLE 8.3
Classifications of Hardness

Classification	mg/L as Calcium Carbonate ($CaCO_3$)
Soft	0–75
Moderately hard	75–150
Hard	150–300
Very hard	Over 300

where

M = Metal ion concentration (mg/L).

EW = Equivalent weight = gram molecular weight ÷ valence.

Treatment Methods

Two common methods are used to reduce hardness:

- *Ion exchange*—The ion exchange process is the process most frequently used for softening water. As a result of charging a resin with sodium ions, the resin exchanges the sodium ions for calcium or magnesium ions. Naturally occurring and synthetic cation exchange resins are available. Natural exchange resins include such substances as aluminum silicate, zeolite clays (zeolites are hydrous silicates found naturally in the cavities of lavas [greensand], glauconite zeolites, or synthetic, porous zeolites), humus, and certain types of sediments. These resins are placed in a pressure vessel. Salt brine is flushed through the resins. The sodium ions in the salt brine attach to the resin. The resin is now said to be charged. Once charged, water is passed through the resin, and the resin exchanges the sodium ions attached to the resin for calcium and magnesium ions, thus removing them from the water. The zeolite clays are most common because they are quite durable, can tolerate extreme ranges in pH, and are chemically stable. They have relatively limited exchange capacities, however, so they should only be used for water with a moderate total hardness. One of the results is that the water may be more corrosive than before. Another concern is that addition of sodium ions to the water may increase the health risk of those with high blood pressure.
- *Cation exchange*—The cation exchange process takes place with little or no intervention from the treatment plant operator. Water containing hardness-causing cations (Ca^{2+}, Mg^{2+}, Fe^{3+}) is passed through a bed of cation exchange resin. The water coming through the bed contains hardness near zero, although it will have elevated sodium content. (The sodium content is not likely to be high enough to be noticeable, but it could be high enough to pose problems to people on highly restricted salt-free diets.) The total lack of hardness in the finished water is likely to make it very corrosive, so normal practice bypasses a portion of the water around the softening process. The treated and untreated waters are blended to produce an effluent with a total hardness around 50 to 75 mg/L as $CaCO_3$.

CORROSION

Water operators add chemicals (e.g., lime or sodium hydroxide) to water at the source or at the waterworks to control corrosion. Using chemicals to achieve a slightly alkaline chemical balance prevents the water from corroding distribution pipes and consumers' plumbing and keeps substances such as lead from leaching out of plumbing and into the drinking water. For our purposes, we define *corrosion* as the conversion of a metal to a salt or oxide with a loss of desirable properties such as mechanical strength. Corrosion may occur over an entire exposed surface or may be localized at micro- or macroscopic discontinuities in metal. In all types of corrosion, a gradual decomposition of the material occurs, often due to an electrochemical reaction. Corrosion may be caused by (1) stray current electrolysis, (2) dissimilar metals (i.e., galvanic corrosion), or (3) differential concentration cells. Corrosion begins at the surface of a material and moves inward.

The adverse effects of corrosion can be categorized according to health, aesthetics, and economic effects, among others. The corrosion of toxic metal pipe made from lead creates a serious *health hazard*. Lead tends to accumulate in the bones of humans and animals. Signs of lead intoxication include gastrointestinal disturbances, fatigue, anemia, and muscular paralysis. Lead is not a natural contaminant in either surface waters or groundwaters, and the MCL of 0.005 mg/L in source waters is rarely exceeded. It is a corrosion byproduct from high lead solder joints in copper and lead piping. Small dosages of lead can lead to developmental problems in children. The USEPA's Lead and Copper Rule addresses the matter of lead in drinking water exceeding specified action levels.

> ***Note:*** The USEPA's Lead and Copper Rule requires that a treatment facility achieve optimum corrosion control. Because lead and copper contamination generally occurs after water has left the public water system, the best way for the water system operator to find out if customer water is contaminated is to test water that has come from a household faucet.

It is important to note that the USEPA made minor changes in 1999 to the original Lead and Copper Rule. These minor revisions (also known as the Lead and Copper Rule Minor Revisions, or LCRMRs) streamline requirements, promote consistent national implementation, and in many cases reduce the burden for water systems. The LCRMRs do not change the action levels of 0.015 mg/L for lead and 1.3 mg/L for copper or the maximum contaminant level goals (MCLGs) established by the original Lead and Copper Rule, which are 0 mg/L for lead and 1.3 mg/L for copper. The LCRMRs also do not affect the basic requirements of the rule to optimize corrosion control and, if appropriate, treat source water, provide public education, and replace lead service lines (USEPA 1990d).

Cadmium is the only other toxic metal found in samples from plumbing systems. Cadmium is a contaminant found in zinc. Its adverse health effects are best known for being associated with severe bone and kidney syndrome in Japan. The proposed maximum contaminant level (PMCL) for cadmium is 0.01 mg/L.

> ***Note:*** Water systems should try to supply water free of lead and that has no more than 1.3 mg of copper per liter. This is a nonenforceable health goal.

Aesthetic effects that are a result of corrosion of iron include pitting and are a consequence of the deposition of ferric hydroxide and other products and the solution of iron—*tuberculation.* Tuberculation reduces the hydraulic capacity of the pipe. Corrosion of iron can cause customer complaints of reddish or reddish-brown staining of plumbing fixtures and laundry. Corrosion of copper lines can cause customer complaints of bluish or blue–green stains on plumbing fixtures. Sulfide corrosion of copper and iron lines can cause a blackish color in the water. The byproducts of microbial activity (especially iron bacteria) can cause foul tastes or odors in the water.

The *economic effects* of corrosion may include water main replacement, especially when tuberculation reduces the flow capacity of the main. Tuberculation increases pipe roughness, causing an increase in pumping costs and a reduction in distribution system pressure. Tuberculation and corrosion can cause leaks in distribution mains and household plumbing. Corrosion of household plumping may require extensive treatment, public education, and other actions under the Lead and Copper Rule.

Other effects of corrosion include short service life of household plumbing caused by pitting. A build-up of mineral deposits in a hot water system may eventually restrict hot-water flow. Also, the structural integrity of steel water storage tanks may deteriorate, causing structural failures. Steel ladders in clearwells or water storage tanks may corrode, introducing iron into the finished water. Steel parts in flocculation tanks, sedimentation basins, clarifiers, and filters may also corrode.

Types of Corrosion

Three types of corrosion occur in water mains:

- *Galvanic* occurs when two dissimilar metals come into contact and are exposed to a conductive environment; a potential exists between them, and current flows. This type of corrosion is the result of an electrochemical reaction when the flow of electric current itself is an essential part of the reaction.

- *Tuberculation* refers to the formation of localized corrosion products scattered over the surface in the form of knob-like mounds. These mounds increase the roughness of the inside of the pipe, increasing resistance to water flow and decreasing the *C* factor of the pipe.
- *Pitting* is localized corrosion that is classified as pitting when the diameter of the cavity at the metal surface is the same or less than the depth of the cavity.

Factors Affecting Corrosion

The primary factors affecting corrosion are pH, alkalinity, hardness (calcium), dissolved oxygen, and total dissolved solids. Secondary factors include temperature, velocity of water in pipes, and carbon dioxide (CO_2).

Determination of Corrosion Problems

To determine if corrosion is taking place in water mains, materials removed from the distribution system should be examined for signs of corrosion damage. A primary indicator of corrosion damage is pitting. (Measure the depth of pits to gauge the extent of damage.) Another common method used to determine if corrosion or scaling is taking place in distribution lines is to insert special steel specimens of known weight (called *coupons*) in the pipe and examine them for corrosion after a period of time. Detecting evidence of leaks, conducting flow tests and chemical tests for dissolved oxygen and toxic metals, and receiving customer complaints (e.g., red or black water, laundry and fixture stains) can also reveal corrosion problems.

Formulas can also be used to determine corrosion (to an extent). The *Langelier Saturation Index* (LSI) and the *Aggressive Index* (AI) are two of the most commonly used indices. The LSI determines whether water is corrosive. The AI is used for waters that have low natural pH, are high in dissolved oxygen, are low in total dissolved solids, and have low alkalinity and low hardness. These waters are very aggressive and can be corrosive. Both of these indices are typically used as starting points in determining the adjustments required to produce a protective film:

- LSI approximately 0.5
- AI value of 12 or higher

Note: The LSI and AI are based on the dissolving of and precipitation of calcium carbonate; therefore, the respective indices may not actually reflect the corrosive nature of the particular water for a specific pipe material. They can be useful tools, however, in selecting materials or treatment options for corrosion control.

Corrosion Control

As mentioned, one method used to reduce the corrosive nature of water is *chemical addition*. Selection of the chemicals depends on the characteristics of the water, where the chemicals can be applied, how they can be applied and mixed with water, and the cost of the chemicals.

If the product of the calcium hardness times the alkalinity of the water is less than 100, treatments may be required. Both lime and CO_2 may be required for proper treatment of the water. If the calcium hardness and alkalinity levels are between 100 and 500, either lime or soda ash (Na_2CO_3) will be satisfactory. The decision regarding which chemical to use depends on the cost of the equipment and chemicals. If the product of the calcium hardness times the alkalinity is greater than 500, either lime or caustic soda (NaOH) may be used. Soda ash will be ruled out because of the expense.

The chemicals chosen for treatment of public drinking water supplies modify the water characteristics, making the water less corrosive to the pipe. Modification of water quality can increase the pH of the water, thus reducing the hydrogen ions available for galvanic corrosion, as well as reducing the solubility of copper, zinc, iron, lead, and calcium and increasing the possibility of forming carbonate protective films.

Calcium carbonate stability is the most effective means of controlling corrosion. Lime, caustic soda, or soda ash is added until the pH and the alkalinity indicate that the water is saturated with calcium carbonate. Saturation does *not* always ensure noncorrosiveness. Utilities should exercise caution when applying sodium compounds, because a high sodium content in water can be a health concern for some customers. By increasing the alkalinity of the water, the bicarbonate and carbonate available to form a protective carbonate film also increase. By decreasing the dissolved oxygen of the water, the rate of galvanic corrosion is reduced, along with the possibility of iron tuberculation.

Inorganic phosphates used include the following:

- Zinc phosphates, which can cause algal blooms on open reservoirs
- Sodium silicate, which is used by individual customers, such as apartments, houses, and office buildings
- Sodium polyphosphates (tetrasodium pyrophosphate or sodium hexametaphosphate), which control scale formation in supersaturated waters and are known as *sequestering agents*
- Silicates (SiO_2), which form a film; an initial dosage of 12 to 16 mg/L for about 30 days will adequately coat the pipes, and a 1.0-mg/L concentration should be maintained thereafter

Note: Great care and caution must be exercised any time feeding corrosion control chemicals into a public drinking water system!

Another corrosion control method is *aeration.* Aeration works to remove carbon dioxide (CO_2), which can be reduced to about 5 mg/L. *Cathodic protection*, often employed to control corrosion, involves applying an outside electric current to the metal to reverse the electromechanical corrosion process. The application of DC current prevents normal electron flow. Cathodic protection uses a sacrificial metal electrode (a magnesium anode) that corrodes instead of the pipe or tank. *Linings*, *coatings*, and *paints* can also be used in corrosion control. Slip-line with a plastic liner, cement mortar, zinc or magnesium, polyethylene, epoxy, and coal tar enamels are some of the materials that can be used.

Note: Before using any protective coatings, consult the district engineer first!

Several *corrosive-resistant pipe materials* are used to prevent corrosion:

- PVC plastic pipe
- Aluminum
- Nickel
- Silicon
- Brass
- Bronze
- Stainless steel
- Reinforced concrete

In addition to internal corrosion problems, waterworks operators must also be concerned with external corrosion problems. The primary culprit involved with external corrosion of distribution system pipe is soil. The measure of corrosivity of the soil is the *soil resistivity.* If the soil resistivity is greater than 5000 ohm/cm, serious corrosion is unlikely. Steel pipe may be used under these conditions. If soil resistivity is less than 500 ohm/cm, plastic PVC pipe should be used. For intermediate ranges of soil resistivity (500 to 5000 ohm/cm), ductile iron pipe, linings, and coatings should be used.

Several operating problems are commonly associated with corrosion control:

- $CaCO_3$ not depositing a film is usually a result of poor pH control (out of the normal range of 6.5 to 8.5). This may also cause excessive film deposition.
- Persistence of red water problems are most probably a result of poor flow patterns, insufficient velocity, tuberculation of pipe surface, and the presence of iron bacteria:

1. *Velocity*—Chemicals must make contact with the pipe surface. Dead ends and low-flow areas should have a flushing program; dead ends should be looped.
2. *Tuberculation*—The best approach is to clean with *pig*. In extreme cases, clean pipe with metal scrapers and install cement-mortar lining.
3. *Iron bacteria*—Slime prevents film contact with the pipe surface. Slime will grow and the coating will be lost. Pipe cleaning and disinfection programs are necessary.

COAGULATION

The primary purpose in surface-water treatment is chemical clarification by coagulation and mixing, flocculation, sedimentation, and filtration. These unit processes, along with disinfection, work to remove particles; natural organic matter (NOM), such as bacteria, algae, zooplankton, and organic compounds; and microbes from water to produce water that is noncorrosive. Specifically, coagulation and flocculation work to destabilize particles and to agglomerate dissolved and particulate matter. Sedimentation removes solids and provides 1/2-log *Giardia* and 1-log virus removal. Filtration removes solids and provides 2-log *Giardia* and 1-log virus removal. Finally, disinfection provides microbial inactivation and 1/2-log *Giardia* and 2-log virus removal.

From Figure 8.4, it can be seen that following screening and the other pretreatment processes the next unit process in a conventional water treatment system is a mixer where chemicals are added in what is known as coagulation. The exception to this unit process configuration occurs in small systems using groundwater, when chlorine or other taste and odor control measures are introduced at the intake and are the extent of treatment.

Materials present in raw water may vary in size, concentration, and type. Dispersed substances in the water may be classified as *suspended*, *colloidal*, or *solution*. Suspended particles may vary in mass and size and are dependent on the flow of water. High flows and velocities can carry larger material. As velocities decrease, the suspended particles settle according to size and mass. Other material may be in solution; for example, salt dissolves in water. Matter in the colloidal state does not dissolve, but the particles are so small they will not settle out of the water. Color (as in tea-colored swamp water) is mainly due to colloids or extremely fine particles of matter in suspension. Colloidal and solute particles in water are electrically charged. Because most of the charges are alike (negative) and repel each other, the particles stay dispersed and remain in the colloidal or soluble state.

Suspended matter will settle without treatment, if the water is still enough to allow it to settle. The rate of settling of particles can be determined, as this settling follows certain laws of physics; however, much of the suspended matter may be so slow in settling that the normal settling processes become impractical, and if colloidal particles are present then settling will not occur. Moreover, water drawn from a raw water source often contains many small unstable (unsticky) particles; therefore, sedimentation alone is usually an impractical way to obtain clear water in most locations, and another method of increasing the settling rate must be used: coagulation, which is designed to convert stable (unsticky) particles to unstable (sticky) particles.

Coagulation is a series of chemical and mechanical operations by which coagulants are applied and made effective. These operations are comprised of two distinct phases: (1) rapid mixing to disperse coagulant chemicals by violent agitation into the water being treated, and (2) flocculation to agglomerate small particles into well-defined floc by gentle agitation for a much longer time.

Coagulation results from adding salts of iron or aluminum to the water. The coagulant must be added to the raw water and perfectly distributed into the liquid; such uniformity of chemical treatment is reached through rapid agitation or mixing. Common coagulants (salts) include the following:

- Alum (aluminum sulfate)
- Sodium aluminate
- Ferric sulfate

- Ferrous sulfate
- Ferric chloride
- Polymers

Coagulation is the reaction between one of these salts and water. The simplest coagulation process occurs between alum and water. Alum, or aluminum sulfate, is produced by a chemical reaction between bauxite ore and sulfuric acid. The normal strength of liquid alum is adjusted to 8.3%, while the strength of dry alum is 17%.

When alum is placed in water, a chemical reaction occurs that produces positively charged aluminum ions. The overall result is the reduction of electrical charges and the formation of a sticky substance—the formation of *floc*, which when properly formed will settle. These two destabilizing factors are the major contributions of coagulation toward the removal of turbidity, color, and microorganisms.

Liquid alum is preferred in water treatment because it has several advantages over other coagulants:

- Ease of handling
- Lower costs
- Less labor required to unload, store, and convey
- Elimination of dissolving operations
- Less storage space required
- Greater accuracy in measurement and control
- Elimination of the nuisance and unpleasantness of handling dry alum
- Easier maintenance

The formation of floc is the first step of coagulation; for greatest efficiency, rapid, intimate mixing of the raw water and the coagulant must occur. After mixing, the water should be slowly stirred so the very small, newly formed particles can attract and enmesh colloidal particles, holding them together to form larger floc. This slow mixing is the second stage of the process (flocculation), covered later.

A number of factors influence the coagulation process—pH, turbidity, temperature, alkalinity, and the use of polymers. The degree to which these factors influence coagulation depends on the coagulant use. The raw water conditions, optimum pH for coagulation, and other factors must be considered before deciding which chemical is to be fed and at what levels.

To determine the correct chemical dosage, a *jar test* or *coagulation test* is performed. Jar tests (widely used for many years by the water treatment industry) simulate full-scale coagulation and flocculation processes to determine optimum chemical dosages. It is important to note that jar testing is only an attempt to achieve a ballpark approximation of correct chemical dosage for the treatment process. The test conditions are intended to reflect the normal operation of a chemical treatment facility. The test can be used to

- Select the most effective chemical.
- Select the optimum dosage.
- Determine the value of a flocculant aid and the proper dose.

The testing procedure requires a series of samples to be placed in testing jars (see Figure 8.6) and mixed at 100 ppm. Varying amounts of the process chemical or specified amounts of several flocculants are added (one volume/sample container). The mix is continued for 1 minute. Next, the mixing is slowed to 30 rpm to provide gentle agitation, and then the floc is allowed to settle. The flocculation period and settling process are observed carefully to determine the floc strength, settleability,

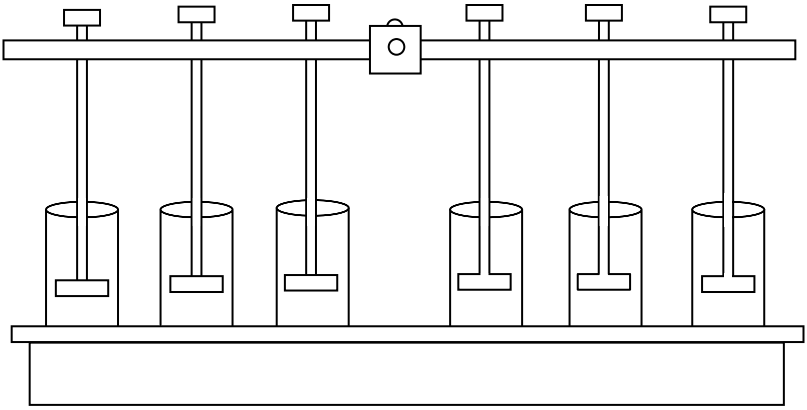

FIGURE 8.6 Variable-speed paddle mixer used in jar testing procedure.

and clarity of the *supernatant liquor* (the water that remains above the settled floc). Additionally, the supernatant can be tested to determine the efficiency of the chemical addition for removal of total suspended solids (TSS), biochemical oxygen demand (BOD_5), and phosphorus.

The equipment required for the jar test includes a six-position, variable-speed paddle mixer (see Figure 8.6); six 2-quart wide-mouthed jars; an interval timer; and assorted glassware, pipets, graduates, and so forth. The jar test procedure follows:

1. Place an appropriate volume of water sample in each of the jars (250- to 1000-mL samples may be used, depending on the size of the equipment being use). Start mixers and set for 100 rpm.
2. Add previously selected amounts of the chemical being evaluated. (Initial tests may use wide variations in chemical volumes to determine the approximate range; this is then narrowed in subsequent tests).
3. Continue mixing for 1 minute.
4. Reduce the mixer speed to a gentle agitation (30 rpm), and continue mixing for 20 minutes. Again, time and mixer speed may be varied to reflect the particular facility.

Note: During this time, observe the floc formation—that is, how well the floc holds together during the agitation (floc strength).

5. Turn off the mixer and allow solids to settle for 20 to 30 minutes. Observe the settling characteristics, the clarity of the supernatant, the settleability of the solids, the flocculation of the solids, and the compactability of the solids.
6. Perform phosphate tests to determine removals.
7. Select the dose that provided the best treatment based on observations made during the analysis.

After initial ranges and chemical selections are determined, repeat the test using a smaller range of dosages to optimize performance.

FLOCCULATION

As we see in Figure 8.4, flocculation follows coagulation in the conventional water treatment process. Flocculation is the physical process of slowly mixing the coagulated water to increase the probability of particle collision; unstable particles collide and stick together to form fewer larger flocs. Through experience, we have found that effective mixing reduces the required amount of chemicals and greatly improves the sedimentation process, resulting in longer filter runs and higher quality finished water. The goal of flocculation is to form a uniform, feather-like material similar to snowflakes—a dense, tenacious floc that entraps the fine, suspended, and colloidal particles and carries them down rapidly into the settling basin. Proper flocculation requires from 15 to 45 minutes. The time is based on water chemistry, water temperature, and mixing intensity. Temperature is the key component in determining the amount of time required for floc formation. To increase the speed of floc formation and the strength and weight of the floc, polymers are often added.

SEDIMENTATION

After raw water and chemicals have been mixed and the floc formed, the water containing the floc (because it has a higher specific gravity than water) flows to the sedimentation or settling basin (see Figure 8.4). Sedimentation is also called *clarification*. Sedimentation removes settleable solids by gravity. Water moves slowly though the sedimentation tank/basin with a minimum of turbulence at entry and exit points with minimum short-circuiting. Sludge accumulates at the bottom of the tank or basin. Typical tanks or basins used in sedimentation include conventional rectangular basins, conventional center-feed basins, peripheral-feed basins, and spiral-flow basins.

In conventional treatment plants, the amount of detention time required for settling can vary from 2 to 6 hours. Detention time should be based on the total filter capacity when the filters are passing 2 gpm per square foot of superficial sand area. For plants with higher filter rates, the detention time is based on a filter rate of 3 to 4 gpm per square foot of sand area. The time requirement is dependent on the weight of the floc, the temperature of the water, and how quiescent the basin is.

A number of conditions affect sedimentation: (1) uniformity of flow of water through the basin; (2) stratification of water due to difference in temperature between water entering and water already in the basin; (3) release of gases that may collect in small bubbles on suspended solids, causing them to rise and float as scum rather than settle as sludge; (4) disintegration of previously formed floc; and (5) size and density of the floc.

FILTRATION

In the conventional water treatment process, filtration usually follows coagulation, flocculation, and sedimentation (see Figure 8.4). At present, filtration is not always used in small water systems; however, regulatory requirements under the USEPA Interim Enhanced Surface Water Treatment rules may make water filtering necessary at most water supply systems. Water filtration is a physical process of separating suspended and colloidal particles from water by passing water through a granular material. The process of filtration involves straining, settling, and adsorption. As floc passes into the filter, the spaces between the filter grains become clogged, reducing this opening and increasing removal. Some material is removed merely because it settles on a media grain. One of the most important processes is adsorption of the floc onto the surface of individual filter grains. This helps collect the floc and reduces the size of the openings between the filter media grains. In addition to removing silt and sediment, floc, algae, insect larvae, and any other large elements, filtration also contributes to the removal of bacteria and protozoa such as *Giardia lamblia* and *Cryptosporidium*. Some filtration processes are also used for iron and manganese removal.

Types of Filtration Technologies

The Surface Water Treatment Rule (SWTR) specifies four filtration technologies, although it also allows the use of alternative filtration technologies (e.g., cartridge filters). The specified technologies are (1) slow sand and rapid sand filtration, (2) pressure filtration, (3) diatomaceous earth filtration, and (4) direct filtration. Of these, all but rapid sand filtration are commonly employed in small water systems that use filtration. Each type of filtration system has advantages and disadvantages. Regardless of the type of filter, however, filtration involves the processes of *straining* (where particles are captured in the small spaces between filter media grains), *sedimentation* (where the particles land on top of the grains and stay there), and *adsorption* (where a chemical attraction occurs between the particles and the surface of the media grains).

Slow Sand Filters

The first slow sand filter was installed in London in 1829, and the technique was used widely throughout Europe, although not in the United States. By 1900, rapid sand filtration began taking over as the dominant filtration technology, although a few slow sand filters are still in operation today. With the advent of the Safe Drinking Water Act (SDWA) and its regulations (especially the Surface Water Treatment Rule) and recognition of the problems associated with *Giardia lamblia* and *Cryptosporidium* in surface water, the water industry is reexamining the use of slow sand filters. The low technology requirements may prevent many state water systems from using this type of equipment. On the plus side, slow sand filtration is well suited for small water systems. It is a proven, effective filtration process with relatively low construction costs and low operating costs (it does not require constant operator attention). It is quite effective for water systems as large as 5000 people; beyond that, the surface area requirements and manual labor required to recondition the filters make rapid sand filters the more effective choice. The filtration rate is generally in the range of 45 to 150 gallons per day per square foot. Components of a slow sand filter include the following:

- A covered structure to hold the filter media
- An underdrain system
- Graded rock that is placed around and just above the underdrain
- The filter media, consisting of 30 to 55 inches of sand with a grain size of 0.25 to 0.35 mm
- Inlet and outlet piping to convey the water to and from the filter and the means to drain filtered water to waste

The area above the top of the sand layer is flooded with water to a depth of 3 to 5 feet, and the water is allowed to trickle down through the sand. An overflow device prevents excessive water depth. The filter must have provisions for filling it from the bottom up, and it must be equipped with a loss-of-head gauge, a rate-of-flow control device (such as an orifice or butterfly valve), a weir or effluent pipe that ensures that the water level cannot drop below the sand surface, and filtered waste sample taps. When the filter is first placed in service, the head loss through the media caused by the resistance of the sand is about 0.2 feet (i.e., a layer of water 0.2 feet deep on top of the filter will provide enough pressure to push the water downward through the filter). As the filter operates, the media become clogged with the material being filtered out of the water, and the head loss increases. When it reaches about 4 to 5 feet, the filter must be cleaned. For efficient operation of a slow sand filter, the water being filtered should have a turbidity averaging less than 5 TU, with a maximum of 30 TU. Slow sand filters are not backwashed the way conventional filtration units are. One to 2 inches of material must be removed on a periodic basis to keep the filter operating.

Rapid Sand Filters

The rapid sand filter, which is similar in some ways to the slow sand filter, is one of the most widely used filtration units. The major difference is in the principle of operation—that is, in the speed or rate at which water passes through the media. In operation, water passes downward through a sand bed that removes the suspended particles. The suspended particles consist of the coagulated matter remaining in the water after sedimentation, as well as a small amount of uncoagulated suspended matter. Some significant differences exist in construction, control, and operation between slow sand filters and rapid sand filters. Because of the design and construction of the rapid sand filtration, the land area required to filter the same quantity of water is reduced. Components of a rapid sand filter include the following:

- Structure to house media
- Filter media
- Gravel media support layer
- Underdrain system
- Valves and piping system
- Filter backwash system
- Waste disposal system

Usually 2 to 3 feet deep, the filter media are supported by approximately 1 foot of gravel. The media may be fine sand or a combination of sand, anthracite coal, and coal (dual- or multimedia filter). Water is applied to a rapid sand filter at a rate of 1.5 gallons per minute per square foot (gpm/ft^2) of filter media surface. When the rate is between 4 and 6 gpm/ft^2, the filter is referred to as a *high-rate filter*; at a rate over 6 gpm/ft^2, the filter is referred to as a *ultra-high-rate filter*. These rates compare to the slow sand filtration rate of 45 to 150 gallons per day per square foot. High-rate and ultra-high-rate filters must meet additional conditions to ensure proper operation.

Generally, raw water turbidity is not that high; however, even if raw water turbidity values exceed 1000 TU, properly operated rapid sand filters can produce filtered water with a turbidity or well under 0.5 TU. The time the filter is in operation between cleanings (filter runs) usually ranges from 12 to 72 hours, depending on the quality of the raw water; the end of the run is indicated by the head loss approaching 6 to 8 feet. Filter *breakthrough* (when filtered material is pulled through the filter into the effluent) can occur if the head loss becomes too great. Operation with head loss too high can also cause *air binding* (which blocks part of the filter with air bubbles), increasing the flow rate through the remaining filter area.

Rapid sand filters have the advantage of a lower land requirement, and they have other advantages, as well; for example, rapid sand filters cost less, are less labor intensive to clean, and offer higher efficiency with highly turbid waters. On the downside, the operation and maintenance costs of rapid sand filters are much higher in comparison because of the increased complexity of the filter controls and backwashing system. When backwashing a rapid sand filter, the filter is cleaned by passing treated water backward (upward) through the filter media and agitating the top of the media. The need for backwashing is determined by a combination of filter run time (i.e., the length of time since the last backwashing), effluent turbidity, and head loss through the filter. Depending on the raw water quality, the run time varies from one filtration plant to another (and may even vary from one filter to another in the same plant).

Note: Backwashing usually requires 3 to 7% of the water produced by the plant.

Pressure Filter Systems

When raw water is pumped or piped from the source to a gravity filter, the head (pressure) is lost as the water enters the floc basin. When this occurs, pumping the water from the plant clearwell to the reservoir is usually necessary. One way to reduce pumping is to place the plant components into pressure vessels, thus maintaining the head. This type of arrangement is known as a pressure filter system. Pressure filters are also quite popular for iron and manganese removal and for filtration of water from wells. They may be placed directly in the pipeline from the well or pump with little head loss. Most pressure filters operate at a rate of about 3 gpm/ft^2. Although pressure filtration is operationally the same as rapid sand filtration and consists of components similar to those of a rapid sand filter, the main difference between a rapid sand filtration system and a pressure filtration system is that the entire pressure filter is contained within a pressure vessel. These units are often highly automated and are usually purchased as self-contained units with all necessary piping, controls, and equipment contained in a single unit. They are backwashed in much the same manner as the rapid sand filter. The major advantage of the pressure filter is its low initial cost. They are usually prefabricated, with standardized designs. A major disadvantage is that the operator is unable to observe the filter in the pressure filter and so is unable to determine the condition of the media. Unless the unit has an automatic shutdown feature for high effluent turbidity, driving filtered material through the filter is possible.

Diatomaceous Earth Filters

Diatomaceous earth is a white material made from the skeletal remains of diatoms. The skeletons are microscopic and in most cases porous. Diatomaceous earth is available in various grades, and the grade is selected based on filtration requirements. These diatoms are mixed in water slurry and fed onto a fine screen called a *septum*, usually made of stainless steel, nylon, or plastic. The slurry is fed at a rate of 0.2 lb/ft^2 of filter area. The diatoms collect in a precoat over the septum, forming an extremely fine screen. Diatoms are fed continuously with the raw water, causing the buildup of a filter cake approximately 1/8 to 1/5 inch thick. The openings are so small that the fine particles that cause turbidity are trapped on the screen. Coating the septum with diatoms gives it the ability to filter out very small microscopic material. The fine screen and the buildup of filtered particles cause a high head loss through the filter. When the head loss reaches a maximum level (30 psi on a pressure-type filter or 15 inches of mercury on a vacuum-type filter), the filter cake must be removed by backwashing. The slurry of diatoms is fed with raw water during filtration in a process called *body feed*. The body feed prevents premature clogging of the septum cake. These diatoms are caught on the septum, increasing the head loss and preventing the cake from clogging too rapidly by the particles being filtered. Although the body feed increases head loss, head loss increases are more gradual than if body feed were not used. Diatomaceous earth filters are relatively low in cost to construct, but they have high operating costs and can cause frequent operating problems if not properly operated and maintained. They can be used to filter raw surface waters or surface-influenced groundwaters with low turbidity (<5 NTU) and low coliform concentrations (no more than 50 coliforms per 100 mL) and may also be used for iron and manganese removal following oxidation. Filtration rates are between 1.0 and 1.5 gpm/ft^2.

Direct Filtration

Direct filtration is a treatment scheme that omits the flocculation and sedimentation steps prior to filtration. Coagulant chemicals are added, and the water is passed directly onto the filter. All solids removal takes place on the filter, which can lead to much shorter filter runs, more frequent backwashing, and a greater percentage of finished water used for backwashing. The lack of a flocculation process and sedimentation basin reduces construction cost but increases the requirement for skilled operators and high-quality instrumentation. Direct filtration must be used only where the water flow rate and raw water quality are fairly consistent and where the incoming turbidity is low.

Alternative Filters

A *cartridge filter system* can be employed as an alternative filtering system to reduce turbidity and remove *Giardia*. A cartridge filter is made of a synthetic media contained in a plastic or metal housing. These systems are normally installed in a series of three or four filters. Each filter contains media successively smaller than the previous filter. The media sizes typically range from 50 to 5 μm or less. The filter arrangement is dependent on the quality of the water, the capability of the filter, and the quantity of water needed. The USEPA and state agencies have established criteria for the selection and use of cartridge filters. Generally, cartridge filter systems are regulated in the same manner as other filtration systems. Because of new regulatory requirements and the need to provide more efficient removal of pathogenic protozoans (e.g., *Giardia* and *Cryptosporidium*) from water supplies, *membrane filtration systems* are finding increased application in water treatment systems. A *membrane* is a thin film separating two different phases of a material acting as a selective barrier to the transport of matter operated by some driving force. Simply, a membrane can be regarded as a sieve with very small pores. Membrane filtration processes are typically pressure, electrically, vacuum, or thermally driven. The types of drinking water membrane filtration systems include microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. A typical membrane filtration process has one input and two outputs. Membrane performance is largely a function of the properties of the materials to be separated and can vary throughout operation.

Filtration and Compliance with Turbidity Requirements

Under the 1996 Safe Drinking Water Act Amendments, the USEPA was directed to supplement the existing Surface Water Treatment Rule (SWTR) with the Interim Enhanced Surface Water Treatment Rule (IESWTR) (USEPA, 1999a) to improve protection against waterborne pathogens. Key provisions established in the IESWTR include (USEPA, 1998):

- A maximum contaminant level goal (MCLG) of 0 for *Cryptosporidium*, with a 2-log (99%) *Cryptosporidium* removal requirement for systems that filter
- Strengthened combined filter effluent turbidity performance standards
- Individual filter turbidity monitoring provisions
- Disinfection benchmark provisions to ensure continued levels of microbial protection while facilities take the necessary steps to comply with new disinfection byproduct standards
- Inclusion of *Cryptosporidium* in the definition of groundwater under the direct influence (GWUDI) of surface water and in the watershed control requirements for unfiltered public water systems
- Requirements for covers on new finished water reservoirs
- Sanitary surveys for all surface water systems regardless of size

Additional Compliance Issues

The following section outlines additional compliance issues associated with the IESWTR.

Schedule The IESWTR was published on December 16, 1998, and became effective on February 16, 1999. The SDWA requires, within 24 months following the promulgation of a rule, that the primacy agencies adopt any state regulations necessary to implement the rule. Under §14.13, these rules must be at least as stringent as those required by USEPA. Thus, primacy agencies had to promulgate regulations at least as stringent as the IESWTR by December 17, 2000. Beginning December 17, 2001, systems serving at least 10,000 people have to meet the turbidity requirements in §141.173.

Individual Filter Follow-up Action Based on the monitoring results obtained through continuous filter monitoring, a system may have to conduct one of the following follow-up actions due to persistently high turbidity levels at an individual filter:

- Filter profile
- Individual filter self assessment
- Comprehensive performance evaluation

These specific requirements are found in §141.175(b)(1)–(4).

Abnormal Filter Operations and Filter Profile A filter profile must be produced if no obvious reason for abnormal filter performance can be identified. A filter profile is a graphical representation of individual filter performance based on continuous turbidity measurements or total particle counts vs. time for an entire filter run, from startup to backwash inclusively, that includes assessment of filter performance while another filter is being backwashed. The run length during this assessment should be representative of typical plant filter runs. The profile should include an explanation of the cause of any filter performance spikes during the run. Examples of possible abnormal filter operations that may be obvious to operators include the following:

- Outages or maintenance activities at processes within the treatment train
- Coagulant feed pump or equipment failure
- Filters being run at significantly higher loading rates than approved

It is important to note that, although the reasons for abnormal filter operation may appear obvious, they could be masking other reasons that are more difficult to identify. These may include such situations as

- Disruption in filter media
- Excessive or insufficient coagulant dosage
- Hydraulic surges due to pump changes or other filters being brought on/offline.

Systems must use their best professional judgment and discretion when determining when to develop a filter profile. Attention at this stage will help systems avoid the other forms of follow-up action described below.

Individual Filter Self-Assessment A system must conduct an individual filter self-assessment for any individual filter that has a measured turbidity level of greater than 1.0 NTU in two consecutive measurements taken 15 minutes apart in each of 3 consecutive months. The system must report the filter number, the turbidity measurement, and the date(s) on which the exceedance occurred.

Comprehensive Performance Evaluation A system must conduct a comprehensive performance evaluation (CPE) if any individual filter has a measured turbidity level of greater than 2.0 NTU in two consecutive measurements taken 15 minutes apart in 2 consecutive months. The system must report the filter number, the turbidity measurement, and the date(s) on which the exceedance occurred. The system must contact the state or a third party approved by the state to conduct a comprehensive performance evaluation.

> ***Note:*** The USEPA has developed a guidance document called *Handbook: Optimizing Water Treatment Plant Performance Using the Composite Correction Program*, EPA/625/6-91/027 (1998).

Notification The IESWTR contains two distinct types of notification: state and public. It is important to understand the differences between each and the requirements of each.

- *State notification*—Systems are required to notify states under §141.31. Systems must report to the state within 48 hours the failure to comply with any national primary drinking water regulation. The system within 10 days of completion of each public notification required pursuant to §141.32 must submit to the state a representative copy of each type of notice distributed, published, posted, or made available to persons served by the system or the media. The water supply system must also submit to the state (within the time stated in the request made by the state) copies of any records required to be maintained under §141.33 or copies of any documents then in existence which the state or the Administrator is entitled to inspect pursuant to the authority of §1445 of the Safe Drinking Water Act or the equivalent provisions of the state law.
- *Public notification*—The IESWTR specifies that the public notification requirements of the Safe Drinking Water Act and the implementation regulations of §141.32 must be followed. These regulations divide public notification requirements into two tiers:
  Tier 1
  - Failure to comply with MCL
  - Failure to comply with prescribed treatment technique
  - Failure to comply with a variance or exemption schedule

Tier 2

- Failure to comply with monitoring requirements
- Failure to comply with a testing procedure prescribed by a National Primary Drinking Water Regulation (NPDWR)
- Operating under a variance/exemption (this is not considered a violation but public notification is required)

Certain general requirements must be met by all public notices. All notices must provide a clear and readily understandable explanation of the violation, any potential adverse health effects, the population at risk, the steps the system is taking to correct the violation, the necessity of seeking alternative water supplies (if any), and any preventative measures the consumer should take. The notice must be conspicuous and not contain any unduly technical language, unduly small print, or similar obstacles. The notice must include the telephone number of the owner or operator or designee of the public water system as a source of additional information concerning the violation where appropriate. The notice must be bi- or multilingual if appropriate.

Tier 1 Violations In addition, the public notification rule requires that when providing notification on potential adverse health effects in Tier 1 public notices and in notices on the granting and continued existence of a variance or exemption, the owner/operator of a public water system must include certain mandatory health effects language. For violations of treatment technique requirements for filtration and disinfection, the mandatory health effects language is

> The USEPA sets drinking water standards and has determined that the presence of microbiological contaminants is a health concern at certain levels of exposure. If water is inadequately treated, microbiological contaminants in that water cause disease. Disease symptoms may include diarrhea, cramps, nausea, and possibly jaundice, and any associated headaches and fatigue. These symptoms, however, are not just associated with disease-causing organisms in drinking water but also may be caused by a number of factors other than your drinking water. USEPA has set enforceable requirements for treating drinking water to reduce the risk of these adverse health effects. Treatment such as filtering and disinfection of the water removes or destroys microbiological contaminants. Drinking water which is treated to meet UEPA requirements is associated with little to none of this risk and should be considered safe.

Further, the owner or operator of a community water system must give a copy of the most recent notice for any Tier 1 violations to all new billing units or hookups prior to or at the time service begins. The type of media for performing public notification and the time period in which notification must be sent vary with the type of violation and are specified in §141.32. For Tier 1 violations, the owner or operator of a public water system must give notice:

> By publication in a local daily newspaper as soon as possible but in no case later than 14 days after the violation or failure. If the area does not have a daily newspaper, then notice shall be given by publication in a weekly newspaper of general circulation in the area, and
>
> By either direct mail delivery or hand delivery of the notice, either by itself or with the water bill no later than 45 days after the violation or failure. The primacy agency may waive the requirement if it determines that the owner or operator has corrected the violation with 45 days.

Although the IESWTR does not specify any acute violations, the primacy agency may specify some Tier 1 violations as posing an acute risk to human health; examples might include the following:

- A waterborne outbreak in an unfiltered supply
- Turbidity of a filtered water exceeds 1.0 NTU at any time
- Failure to maintain a disinfectant residual of at least 0.2 mg/L in the water being delivered to the distribution system.

For these violations or any others defined by the primacy agency as "acute" violations, the system must furnish a copy of the notice to the radio and television stations serving the area as soon as possible but in no case later than 72 hours after the violation. Depending on the circumstances particular to the system, as determined by the primacy agency, the notice may instruct that all water be boiled prior to consumption. There are two variations on these requirements. First, the owner or operator of a community water system in an area not served by a daily or weekly newspaper must give notice within 14 days after the violation by hand delivery or continuous posting of a notice of the violation. The notice must continue for as long as the violation exists. Notice by hand delivery must be repeated at least every 3 months for the duration of the violation. Second, the owner or operator of a non-community water system (i.e., one serving a transitory population) may give notice by hand delivery or continuous posting of the notice in conspicuous places in the area served by the system. Notice must be given within 14 days after the violation. If notice is given by posting, then it must continue as long as the violations exist. Notice given by hand delivery must be repeated at least every 3 months for as long as the violation exists.

Tier 2 Violations For Tier 2 violations (i.e., violations of §141.74 and §141.174), notice must be given within 3 months after the violation by publication in a daily newspaper of general circulation, or if there is no daily newspaper then in a weekly newspaper. In addition, the owner or operator shall give notice by mail (either by itself or with the water bill) or by hand delivery at least once every 3 months for as long as the violation exists. Notice of a variance or exemption must be given every 3 months from the date it is granted for as long as it remains in effect. If a daily or weekly newspaper does not serve the area, the owner or operator of a community water system must give notice by continuous posting in conspicuous places in the area served by the system. This must continue as long as the violation exists or the variance or exemption remains in effect. Notice by hand delivery must be repeated at least every 3 months for the duration of the violation or the variance or exemption. For noncommunity water systems, the owner or operator may give notice by hand delivery or continuous posting in conspicuous places, beginning within 3 months of the violation or the variance or exemption. Posting must continue for the duration of the violation or variance or exemption, and notice by hand delivery must be repeated at least every 3 months during this period. The primacy agency may allow for the owner or operator to provide less frequent notice for minor monitoring violations (as defined, by the primacy agency if the USEPA has approved the primacy agency's substitute requirements contained in a program revision application).

Variances and Exemptions

As with the SWTR, no variances from the requirements in §141 are permitted for subpart H systems. Under §1416(a), the USEPA or a state may exempt a public water system from any requirements related to an MCL or treatment technique of a National Primary Drinking Water Regulation (NPDWR) if it finds that: (1) due to compelling factors (which may include economic factors such as the public water system serving a disadvantaged community), the public water system (PWS) is unable to comply with the requirement or implement measures to develop an alternative source of water supply; (2) the exemption will not result in an unreasonable risk to health; (3) the PWS was in operation on the effective date of the NPDWR, or, for a system that was not in operation by that date, only if no reasonable alternative source of drinking water is available to the new systems; and (4) management or restructuring changes (or both) cannot reasonably result in compliance with the Act or improve the quality of drinking water.

DISINFECTION

Disinfection is a unit process used in both water and wastewater treatment. Many of the terms, practices, and applications discussed in this section apply to both water and wastewater treatment; however, there are also some differences between the use of disinfection in water and wastewater treatment—mainly in the types of disinfectants used and applications. Thus, in this section we discuss disinfection as it applies to water treatment. Later, we will cover disinfection as it applies to wastewater treatment. Much of the information presented in this section is based on personal experience and on USEPA (1999b).

To comply with SDWA regulations, the majority of public water systems use some form of water treatment. The 1995 USEPA Community Water System Survey reported that, in the United States, 99% of surface water systems provided some treatment to their water, and 99% of these treatment systems utilized disinfection/oxidation as part of their treatment processes. Although 45% of groundwater systems in the survey provided no treatment, 92% of those groundwater plants providing some form of treatment included disinfection/oxidation as part of the treatment process (USEPA, 1997).

Why such a public health concern regarding groundwater supplies? According to the USEPA's Bruce Macler (1996):

> There are legitimate concerns for public health from microbial contamination of groundwater systems. Microorganisms and other evidence of fecal contamination have been detected in a large number of wells tested, even those wells that had been previously judged not vulnerable to such contamination. The scientific community believes that microbial contamination of groundwater is real and widespread. Public health impact from this contamination while not well quantified, appear to be large. Disease outbreaks have occurred in many groundwater systems. Risk estimates suggest several million illnesses each year. Additional research is underway to better characterize the nature and magnitude of the public health problem.

The most commonly used disinfectants/oxidants (in no particular order) are chlorine, chlorine dioxide, chloramines, ozone, and potassium permanganate.

As mentioned, the process used to control waterborne pathogenic organisms and prevent waterborne disease is disinfection. The goal of proper disinfection in a water system is to destroy all disease-causing organisms. Disinfection should not be confused with sterilization. *Sterilization* is the complete killing of all living organisms. Waterworks operators disinfect by destroying organisms that might be dangerous; they do not attempt to sterilize water.

Disinfectants are also used to achieve other specific objectives in drinking water treatment. These other objectives include nuisance control (e.g., for zebra mussels and Asiatic clams), oxidation of specific compounds (i.e., taste- and odor-causing compounds, iron, and manganese), and use as a coagulant and filtration aid. The goals of this section are to

- Provide a brief overview of the need for disinfection in water treatment.
- Provide basic information that is common to all disinfectants.
- Discuss other uses for disinfectant chemicals (e.g., as oxidants).
- Describe trends in disinfection byproduct (DBP) formation and the health effects of DBPs found in water treatment.
- Discuss microorganisms of concern in water systems, their associated health impact, and the inactivation mechanisms and efficiencies of various disinfectants.
- Summarize current disinfection practices in the Unites States, including the use of chlorine as a disinfectant and an oxidant.

In water treatment, disinfection is almost always accomplished by adding chlorine or chlorine compounds after all other treatment steps, although in the United States ultraviolet (UV) light, potassium permanganate, and ozone processes may be encountered.

The effectiveness of disinfection in a drinking water system is measured by testing for the presence or absence of coliform bacteria. Coliform bacteria found in water are generally not pathogenic, although they are good indicators of contamination. Their presence indicates the possibility of contamination, and their absence indicates the possibility that the water is potable—if the source is adequate, the waterworks history is good, and acceptable chlorine residual is present.

Desired characteristics of a disinfectant include the following:

- It must be able to deactivate or destroy any type or number of disease-causing microorganisms that may be in a water supply, in reasonable time, within expected temperature ranges, and despite changes in the character of the water (pH, for example).
- It must be nontoxic.
- It must not add unpleasant taste or odor to the water.
- It must be readily available at a reasonable cost and be safe and easy to handle, transport, store, and apply.
- It must be quick and easy to determine the concentration of the disinfectant in the treated water.
- It should persist within the disinfected water at a high enough concentration to provide residual protection through the distribution.

Need for Disinfection in Water Treatment

Although the epidemiological relation between water and disease had been suggested as early as the 1850s, it was not until the establishment of the germ theory of disease by Pasteur in the mid-1880s that water as a carrier of disease-producing organisms was understood. In the 1850s, while London was experiencing the Broad Street well cholera epidemic, Dr. John Snow conducted his now-famous epidemiological study and concluded that the well had become contaminated by a visitor who had the disease. Cholera was one of the first diseases to be recognized as capable of being waterborne. Also, this incident was probably the first reported disease epidemic attributed to direct recycling of non-disinfected water. Now, over 100 years later, the list of potential waterborne disease due to pathogens is considerably larger and includes bacterial, viral, and parasitic microorganisms (see Tables 8.4 to 8.6).

TABLE 8.4
Waterborne Diseases from Bacteria

Causative Agent	Disease
Salmonella	
S. typhosa	Typhoid fever
S. paratyphi	Paratyphoid fever
S. schottinulleri	
S. hirschfeldi C.	
Shigella	
S. flexneri	Bacillary dysentery
S. dysenteriae	
S. sonnel	
S. paradysinteriae	
Vibrio	
V. comma	
V. cholerae	Cholera
Pasteurella tularensis	Tularemia
Brucella melitensis	Brucellosis
Leptospira icterchaemorrihagiae	Leptospirosis
Enteropathogenic *Escherichia coli*	Gastroenteritis

TABLE 8.5
Waterborne Human Enteric Viruses

Group	Subgroup
Enterovirus	Poliovirus
	Echovirus
	Coxsackievirus A and B
Reovirus	
Rotavirus	
Adenovirus	
Hepatitis	

TABLE 8.6
Waterborne Diseases from Parasites

Causative Agent	Disease
Ascario lumbricoides (round worm)	Ascariasis
Cryptosporidium muris and *C. parvum*	Cryptosporidiosis
Entamoeba histolytica	Amebiasis
Giardia lamblia	Giardiasis
Naegleria gruberi	Amoebic meningoecephalitis
Schistosoma mansoni	Schistosomiasis
Taenis saginata (beef tapeworm)	Taeniasis

A major cause for the number of disease outbreaks in potable water is contamination of the distribution system from cross-connections and backsiphonage with nonpotable water; however, outbreaks resulting from distribution system contamination are usually quickly contained and result in relatively few illnesses compared to contamination of the source water or breakdowns in the treatment system, which typically produce many cases of illnesses per incident. When considering the number of cases, the major causes of disease outbreaks are source water contamination and treatment deficiencies (White, 1992). Historically, about 46% of the outbreaks in public water systems have been found to be related to deficiencies in source water and treatment systems, with 92% of the causes of illness being due to these two particular problems.

All natural waters support biological communities. Because some microorganisms can be responsible for public health problems, biological characteristics of the source water are one of the most important parameters in water treatment. In addition to public health problems, microbiology can also affect the physical and chemical water quality and treatment plant operation.

Pathogens of Primary Concern

The three groups of pathogens of concern in water treatment are bacteria, viruses, and protozoa:

- *Bacteria*—Bacteria are single-celled organisms typically ranging in size from 0.1 to 10 μm. Shape, components, size, and the manner in which they grow can characterize the physical structure of the bacterial cell. Most bacteria can be grouped by shape into four general categories: spheroid, rod, curved rod or spiral, and filamentous. Cocci, or spherical bacteria, are approximately 1 to 3 μm in diameter. Bacilli (rod-shaped bacteria) are variable in size and range from 0.3 to 1.5 μm in width (or diameter) and from 1.0 to 10.0 μm in length. *Vibrios*, or curved rod-shaped bacteria, typically vary in size from 0.6 to 1.0 μm in width (or diameter) and from 2 to 6 μm in length. *Spirilla* (spiral bacteria) can be found in lengths up to 50 μm, whereas filamentous bacteria can occur in length in excess of 100 μm.
- *Viruses*—Viruses are microorganisms composed of the genetic material deoxyribonucleic acid (DNA) or ribonucleic acid (RNA) and a protective protein coat (single-, double-, or partially double-stranded). All viruses are obligate parasites, unable to carry out any form of metabolism, and are completely dependent on host cells for replication. Viruses are typically 0.01 to 0.1 μm in size and are very species specific with respect to infection, typically attacking only one type of host. Although the principal modes of transmission for the hepatitis B virus and poliovirus are through food, personal contact, or exchange of body fluids, these viruses can be transmitted through potable water. Some viruses, such as the retroviruses (including the HIV group), appear to be too fragile for water transmission to be a significant danger to public health (Spellman, 2007).

- *Protozoa*—Protozoa are single-cell eukaryotic microorganisms without cell walls that utilize bacteria and other organisms for food. Most protozoa are free living in nature and can be encountered in water; however, several species are parasitic and live on or in host organisms. Host organisms can vary from primitive organisms such as algae to highly complex organisms such as human beings. Several species of protozoa are known to utilize human beings as hosts.

Recent Waterborne Disease Outbreaks

Within the past 40 years, several pathogenic agents never before associated with documented waterborne outbreaks have appeared in the United States. Enteropathogenic *Escherichia coli* and *Giardia lamblia* were first identified as the etiological agent responsible for waterborne outbreaks in the 1960s. The first recorded *Cryptosporidium* infection in humans occurred in the mid-1970s. Also occurring during that time was the first recorded outbreak of pneumonia caused by *Legionella pneumophila*. Numerous documented waterborne disease outbreaks have been caused by *E. coli*, *G. lamblia*, *Cryptosporidium*, and *L. pneumophila*.

Escherichia coli

The first documented case of waterborne disease outbreaks in the United States associated with enteropathogenic *Escherichia coli* occurred in the 1960s. Various serotypes of *E. coli* have been implicated as the etiological agent responsible for disease in newborn infants, usually as the result of cross-contamination in nurseries; also, several well-documented waterborne outbreaks of *E. coli* have occurred in adults. In 1975, the etiologic agent of a large outbreak at Crater Lake National Park was *E. coli* serotype 06:H16 (Craun, 1981).

Giardia lamblia

Similar to *Escherichia coli*, *Giardia lamblia* was first identified in the 1960s as being associated with waterborne outbreaks in the United States. Recall that *G. lamblia* is a flagellated protozoan that is responsible for giardiasis, a disease that can range from being mildly to extremely debilitating. *Giardia* is currently one of the most commonly identified pathogens responsible for waterborne disease outbreaks. The life cycle of *Giardia* includes a cyst stage when the organism remains dormant and is extremely resilient (i.e., the cyst can survive some extreme environmental conditions). Once ingested by a warm-blooded animal, the life cycle of *Giardia* continues with excystation. The cysts are relatively large (8 to 14 µm) and can be removed effectively by filtration using diatomaceous earth, granular media, or membranes. Giardiasis can be acquired by ingesting viable cysts from food or water or by direct contact with fecal material. In addition to humans, wild and domestic animals have been implicated as hosts. Between 1972 and 1981, 50 waterborne outbreaks of giardiasis were reported involving about 20,000 cases (Craun and Jakubowski, 1996). Currently, no simple and reliable method exists to assay *Giardia* cysts in water samples. Microscopic methods for detection and enumeration are tedious and require examiner skill and patience. *Giardia* cysts are relatively resistant to chlorine, especially at higher pH and low temperatures.

Cryptosporidium

Cryptosporidium is a protozoan similar to *Giardia*. It forms resilient oocysts as part of its life cycle. The oocysts are smaller than *Giardia* cysts, typically about 4 to 6 µm in diameter. These oocysts can survive under adverse conditions until ingested by a warm-blooded animal and then continue with excystation. Due to the increase in the number of outbreaks of cryptosporidiosis, a tremendous amount of research has focused on *Cryptosporidium* within the last 10 years. Medical interest has increased because of its occurrence as a life-threatening infection to individuals with depressed immune systems. In 1993, the largest documented waterborne disease outbreak in the United States occurred in Milwaukee and was determined to be caused by *Cryptosporidium*. An estimated 403,000 people became ill, 4400 people were hospitalized, and 100 people died. The outbreak was associated with a deterioration in raw water quality and a simultaneous decrease in effectiveness of the coagulation–filtration process, which led to an increase in the turbidity of treated water and inadequate removal of *Cryptosporidium* oocysts.

Legionella pneumophila

An outbreak of pneumonia occurred in 1976 at the annual convention of the Pennsylvania American Legion. A total of 221 people were affected by the outbreak, and 35 of those afflicted died. The cause of the pneumonia was not determined immediately, despite an intense investigation by the CDC. Six months after the incident, microbiologists were able to isolate a bacterium from the autopsy lung tissue of one of the Legionnaires. The bacterium responsible for the outbreak was found to be distinct from other known bacterium and was named *Legionella pneumophila* (Witherell et al., 1988). Following the discovery of this organism, other *Legionella*-like organisms were discovered. Legionnaires' disease does not appear to be transferred person to person. Epidemiological studies have shown that the disease enters the body through the respiratory system. *Legionella* can be inhaled in water particles less than 5 μm in size from facilities such as cooling towers, hospital hot water systems, and recreational whirlpools.

Mechanism of Pathogen Inactivation

The three primary mechanisms of pathogen inactivation are

- Destroy or impair cellular structural organization by attacking major cell constituents, such as destroying the cell wall or impairing the functions of semipermeable membranes.
- Interfere with energy-yielding metabolism through enzyme substrates in combination with prosthetic groups of enzymes, thus rendering them nonfunctional.
- Interfere with biosynthesis and growth by preventing synthesis of normal proteins, nucleic acids, coenzymes, or the cell wall.

Depending on the disinfectant and microorganism type, combinations of these mechanisms can also be responsible for pathogen inactivation. In water treatment, it is believed that the primary factors controlling disinfection efficiency are (1) the ability of the disinfectant to oxidize or rupture the cell wall, and (2) the ability of the disinfectant to diffuse into the cell and interfere with cellular activity (Montgomery, 1985). In addition, it is important to point out that disinfection is effective in reducing waterborne diseases because most pathogenic organisms are more sensitive to disinfection than are nonpathogens; however, disinfection is only as effective as the care used in controlling the process and ensuring that all of the water supply is continually treated with the amount of disinfectant required to produce safe water.

Other Uses of Disinfectants in Water Treatment

Disinfectants are used for more than just disinfection in drinking water treatment. Although inactivation of pathogenic organisms is their primary function, disinfectants are also used as oxidants in drinking water treatment for several other functions:

- Minimization of disinfection byproduct formation
- Control of nuisance Asiatic clams and zebra mussels
- Oxidation of iron and manganese
- Prevention of regrowth in the distribution system and maintenance of biological stability

- Removal of taste and odors through chemical oxidation
- Improvement of coagulation and filtration efficiency
- Prevention of algal growth in sedimentation basins and filters
- Removal of color

A brief discussion of these additional oxidant uses follows.

Minimization of DBP Formation

Strong oxidants may play a role in disinfection and DBP control strategies in water treatment. Several strong oxidants, including potassium permanganate and ozone, may be used to control DBP precursors.

> ***Note:*** Potassium permanganate can be used to oxidize organic precursors at the head of the treatment plant, thus minimizing the formation of byproducts at the downstream disinfection stage of the plant. The use of ozone for oxidation of DBP precursors is currently being studied. Early work has shown that the effects of ozonation, prior to chlorination, were highly site specific and unpredictable. The key variables that seem to determine the effect of ozone are dose, pH, alkalinity, and the nature of the organic material. Ozone has been shown to be effective for DBP precursor reduction at low pHs; however, at higher pH levels (i.e., above 7.5), ozone may actually increase the amount of chlorination byproduct precursors.

Control of Nuisance Asiatic Clams and Zebra Mussels

The Asiatic clam (*Corbicula fluminea*) was introduced to the United States from Southeast Asia in 1938 and now inhabits almost every major river system south of the 40° latitude. Asiatic clams have been found in the Trinity River in Texas; the Ohio River at Evansville, Indiana; the New River at Glen Lyn, Virginia; and the Catawba River in Rock Hill, South Carolina. This animal has invaded many water utilities, clogging source water transmission systems and valves, screens, and meters; damaging centrifugal pumps; and causing taste and odor problems (Belanger et al., 1991; Britton and Morton, 1982; Cameron et al., 1989; Sinclair, 1964).

Cameron et al. (1989) investigated the effectiveness of several oxidants in controlling the Asiatic clam in both the juvenile and adult phases. As expected, the adult clam was found to be much more resistant to oxidants than the juvenile form. In many cases, the traditional method of control, free chlorination, cannot be used because of the formation of excessive amounts of THMs. Cameron et al. (1989) compared the effectiveness of four oxidants for controlling the juvenile Asiatic clam in terms of the LT_{50} (time required for 50% mortality) (Table 8.7). Monochloramine was found to be the best for controlling the juvenile clams without forming THMs. The effectiveness of monochloramine increased greatly as the temperature increased. Clams can tolerate temperatures between 2 and 35°C.

TABLE 8.7
The Effects of Various Oxidants on Mortality of the Asiatic Clam

Chemical	Residual (mg/L)	Temperature (°C)	pH	Life Stage	LT_{50} (Days)
Free chlorine	0.5	23	8.0	Adult	8.7
	4.8	21	7.9	Adult	5.9
	4.7	16	7.8	Juvenile	4.8
Potassium	1.1	17	7.6	Juvenile	7.9
Permanganate	4.8	17	7.6	Juvenile	8.6
Chlorine dioxide	1.2	24	6.9	Juvenile	0.7
	4.7	22	6.6	Juvenile	0.6

Source: Adapted from Cameron, G.N. et al., *J. AWWA*, 81(10), 53–62, 1989.

The zebra mussel (*Dreissena polymorpha*) is a recent addition to the fauna of the Great Lakes. It was first found in Lake St. Clair in 1988, although it is believed that this native of the Black and Caspian seas was brought over from Europe in ballast water around 1985. The zebra mussel population in the Great Lakes has expanded very rapidly, both in size and geographical distribution (Herbert, 1989; Roberts, 1990). Lang (1994) reported that zebra mussels have been found in the Ohio River, Cumberland River, Arkansas River, Tennessee River, and Mississippi River south to New Orleans.

Klerks and Fraleigh (1991) evaluated hypochlorite, permanganate, and hydrogen peroxide with iron for their effectiveness in controlling adult zebra mussels. Both continuous and intermittent 28-day static renewal tests were conducted to determine the impact of intermittent dosing. Intermittent treatment proved to be much less effective than continuous dosing. The hydrogen peroxide–iron combination (1 to 5 mg/L with 25% iron) was less effective in controlling the zebra mussel than either permanganate or hypochlorite. Permanganate (0.5 to 2.5 mg $KMnO_4$ per L) was usually less effective than hypochlorite (0.5 to 10 mg Cl_2 per L).

Van Benschoten et al. (1995) developed a kinetic model to predict the rate of mortality of the zebra mussel in response to chlorine. The model shows the relationship between chlorine residual and temperature on the exposure time required to achieve 50 and 95% mortality. Data were collected for chlorine residuals between 0.5 and 3.0 mg Cl_2 per L and temperatures from 0.3 to 24°C. The results show a strong dependence on temperature and required contact times ranging from 2 days to more than a month, depending on environmental factors and mortality required.

Brady et al. (1996) evaluated the ability of chlorine to control the growth of zebra mussel and quagga mussel (*Dreissenda bugensis*). The quagga mussel is a newly identified mollusk within the Great Lakes that is similar in appearance to the zebra mussel. Full-scale chlorination treatment produced a significantly higher mortality for the quagga mussel. The required contact times for 100% mortality for quagga and zebra mussels were 23 days and 37 days, respectively, suggesting that chlorination programs designed to control zebra mussels should also be effective for controlling populations of quagga mussels.

Mastisoff et al. (1996) evaluated chlorine dioxide (ClO_2) to control adult zebra mussels using simple, intermittent, and continuous exposures. A single 30-minute exposure to 20 mg/L chlorine dioxide or higher concentration induced at least 50% mortality, while sodium hypochlorite produced only 26% mortality, and permanganate and hydrogen peroxide were totally ineffective when dosed at 30 mg/L for 30 minutes under the same conditions. These high dosages, even though used only for a short period of time, may not allow application directly in water for certain applications due to byproducts that remain in the water. Continuous exposure to chlorine dioxide for 4 days was effective at concentrations above 0.5 mg/L (LC_{50} = 0.35 mg/L), and 100% mortality was achieved at chlorine dioxide concentrations above 1 mg/L.

These studies all show that the dose required to induce mortality in these nuisance organisms is extremely high, both in terms of chemical dose and contact time. The potential impact on DBPs is significant, especially when the water is high in organic content with a high propensity to form THMs and other DBPs.

Oxidation of Iron and Manganese

Iron and manganese occur frequently in groundwaters but they are less problematic in surface waters. Although not harmful to human health at the low concentrations typically found in water, these compounds can cause staining and taste problems. These compounds are readily treated by oxidation to produce a precipitant that is removed in subsequent sedimentation and filtration processes. Almost all of the common oxidants except chloramines will convert ferrous (2+) iron to the ferric (3+) state and manganese (2+) to the (4+) state, which will precipitate as ferric hydroxide and manganese dioxide, respectively (AWWA, 1990). The precise chemical composition of the precipitate will depend on the nature of the water, temperature, and pH. Table 8.8 shows that oxidant doses for iron and manganese control are relatively low. In addition, the reactions are relatively

TABLE 8.8
Oxidant Doses Required for Oxidation of Iron and Manganese

Oxidant	Iron (II) (mg/mg Fe)	Manganese (II) (mg/mg Mn)
Chlorine	0.62	0.77
Chlorine dioxide	1.21	2.45
Ozone	0.43	0.85
Oxygen	0.14	0.29
Potassium permanganate	0.94	1.92

Source: Adapted from Culp, G.L. and Culp, R.L., *New Concepts in Water Purification*, Van Nostrand Reinhold, New York, 1974.

rapid, on the order of seconds, whereas DBP formation occurs over hours. Thus, with proper dosing, residual chlorine during iron and manganese oxidation is therefore relatively low and short lived. These factors reduce the potential for DBP formation as a result of oxidation for iron and manganese removal.

Prevention of Regrowth in the Distribution System and Maintenance of Biological Stability

Biodegradable organic compounds and ammonia in treated water can cause microbial growth in the distribution system. *Biological stability* refers to a condition wherein the water quality does not enhance biological growth in the distribution system. Biological stability can be accomplished in several ways:

- Remove nutrients from the water prior to distribution.
- Maintain a disinfectant residual in the treated water.
- Combine nutrient removal and disinfectant residual maintenance.

To maintain biological stability in the distribution system, the Total Coliform Rule (TCR) requires that treated water must have a residual disinfectant of 0.2 mg/L when entering the distribution system. A measurable disinfectant residual must be maintained in the distribution system, or the utility must show through monitoring that the heterotrophic plate count (HPC) remains less than less than 500/100 mL. A system remains in compliance as long as 95% of samples meet these criteria. Chlorine, monochloramine, and chlorine dioxide are typically used to maintain a disinfectant residual in the distribution system. Filtration can also be used to enhance biological stability by reducing the nutrients in the treated water.

The level of secondary disinfectant residual maintained is low, typically in the range of 0.1 to 0.3 mg/L, depending on the distribution system and water quality; however, because the contact times in the system are quite long, it is possible to generate significant amounts of DBPs in the distribution system, even at low disinfectant does. Distribution system problems associated with the use of combined chlorine residual (chloramines) or no residual have been documented. The use of combined chlorine is characterized by an initial satisfactory phase in which chloramine residuals are easily maintained throughout the system and bacterial counts are very low; however, problems may develop over a period of years, including increased bacterial counts, reduced combined chlorine residual, increased taste and odor complaints, and reduced transmission main carrying capacity. Conversion of the system to free chlorine residual produces an initial increase in consumer complaints of taste and odors resulting from oxidation of accumulated organic material. Also, it is difficult to maintain a free chlorine concentration at the ends of the distribution system (AWWA, 1990).

Removal of Taste and Odors through Chemical Oxidation

Taste and odors in drinking water are caused by several sources, including microorganisms, decaying vegetation, hydrogen sulfide, and specific compounds of municipal, industrial, or agricultural origin. Disinfectants themselves can also create taste and odor problems. In addition to specific taste- and odor-causing compounds, the sanitary impact is often accentuated by combinations of compounds. Oxidation is commonly used to remove taste- and odor-causing compounds. Because many of these compounds are very resistant to oxidation, advanced oxidation processes (e.g., ozone/hydrogen peroxide, ozone/ultraviolet) and ozone by itself are often used to address taste and odor problems. The ability of various chemicals to control taste and odors can be site specific. Suffet et al. (1986) found that ozone is generally the most effective oxidant for use in taste and odor treatment. They found ozone doses of 2.5 to 2.7 mg/L and 10 minutes of contact time (residual 0.2 mg/L) significantly reduced levels of taste and odors. Lalezary et al. (1986) used chlorine, chlorine dioxide, ozone, and permanganate to treat earthy–musty smelling compounds. In that study, chlorine dioxide was found most effective, although none of the oxidants was able to remove geosmin and 2-methylisoborneol (MIB) by more than 40 to 60%. Potassium permanganate has been used in doses of 0.25 to 20 mg/L.

Prior experiences with taste and odor treatment indicate that oxidant doses are dependent on the source of the water and causative compounds. In general, small doses can be effective for many taste and odor compounds, but some of the difficult-to-treat compounds require strong oxidants such as ozone or advanced oxidation processes or alternative technologies such as granular activated carbon (GAC) adsorption.

Improvement of Coagulation and Filtration Efficiency

Oxidants, specifically ozone, have been reported to improve coagulation and filtration efficiency. Others, however, have found no improvement in effluent turbidity from oxidation. Prendiville (1986) collected data from a large treatment plant showing that preozonation was more effective than prechlorination in reducing filter effluent turbidities. The cause of the improved coagulation is not clear, but several possibilities have been offered, including (Gurol and Pidatella, 1983; Reckhow et al., 1986):

- Oxidation of organics into more polar forms
- Oxidation of metal ions to yield insoluble complexes such as ferric iron complexes
- Change in the structure and size of suspended particles

Prevention of Algal Growth in Sedimentation Basins and Filters

Prechlorination is often used to minimize operational problems associated with biological growth in water treatment plants (AWWA, 1990). Prechlorination will prevent slime formation on filters, pipes, and tanks and reduce potential taste and odor problems associated with such slimes. Many sedimentation and filtration facilities operate with a small chlorine residual to prevent growth of algae and bacteria in the launders and on the filter surfaces. This practice has increased in recent years as utilities take advantage of additional contact time in the treatment units to meet disinfection requirements under the SWTR.

Removal of Color

Free chlorine is used for color removal. A low pH is favored. Humic compounds that have a high potential for DBP formation cause color. The chlorine dosage and kinetics for color removal are best determined through bench studies.

TABLE 8.9
Disinfection Residuals and Byproducts

Disinfectant Residuals

- Free chlorine
  - Hypochlorous acid
  - Hypochlorite ion
- Chloramines
  - Monochloramine
- Chlorine dioxide

Inorganic Byproducts

- Chlorate ion
- Chlorite ion
- Bromate ion
- Iodate ion
- Hydrogen peroxide
- Ammonia

Organic Oxidation Byproducts

- Aldehydes
- Formaldehyde
- Acetaldehyde
- Glyoxal
- Hexanal
- Heptanal
- Carboxylic acids
  - Hexanoic acid
  - Heptanoic acid
  - Oxalic acid
- Assimilable organic carbon

Halogenated Organic Byproducts

- Trihalomethanes
  - Chloroform
  - Bromodichloromethane
  - Dibromochloromethane
  - Bromoform
- Haloacetic acids
  - Monochloroacetic acid
  - Dichloroacetic acid
  - Trichloroacetic acid
  - Monobromoacetic acid
  - Dibromoacetic acid
- Haloacetonitriles
  - Dichloroacetronitrile
  - Bromochloroacetonitrile
  - Dibromoacetonitrile
  - Trichloroacetonitrile
- Haloketones
  - 1,1-Dichloropropanone
  - 1,1,1-Trichloropropanone
- Chlorophenols
  - 2-Chlorophenol
  - 2,4-Dichlorophenol
  - 2,4,6-Trichlorophenol
  - Chloropicrin
  - Chloral hydrate
  - Cyanogen chloride
  - *N*-organochloramines

Types of Disinfection Byproducts and Disinfection Residuals

Table 8.9 provides a list compiled by the USEPA of DBPs and disinfection residuals that may be of health concern. The table includes both the disinfectant residuals and the specific byproducts produced by the disinfectants of interest in drinking water treatment. These contaminants of concern are grouped into four distinct categories: *disinfectant residuals*, *inorganic byproducts*, *organic oxidation byproducts*, and *halogenated organic byproducts*. The production of DBPs depends on the type of disinfectant, the presence of organic material (e.g., TOC), bromide ion concentration, and other environmental factors as discussed in this section. By removing DBP precursors, the formation of DBPs can be reduced. The health effects of DBPs and disinfectants are generally evaluated with epidemiological studies and toxicological studies using laboratory animals. Table 8.10 shows the cancer classifications of both disinfectants and DBPs. The USEPA classification scheme for carcinogenicity weighs both animal studies and epidemiologic studies but places greater weight on evidence of carcinogenicity in humans.

Disinfection Byproduct Formation

Halogenated organic byproducts are formed when natural organic matter (NOM) reacts with free chlorine or free bromine. Free chlorine can be introduced to water directly as a primary or secondary disinfectant, with chlorine dioxide, or with chloramines. Free bromine results from oxidation of

TABLE 8.10
Health Information for Disinfectants and DBPs

Contaminant	Cancer Classification
Chloroform	Probable human carcinogen
Bromodichloromethane	Probable human carcinogen
Dibromochloromethane	Possible human carcinogen
Bromoform	Probable human carcinogen
Monochloroacetic acid	—
Dichloroacetic acid	Probable human carcinogen
Trichloroacetic acid	Possible human carcinogen
Dichloroacetonitrile	Possible human carcinogen
Bromochloroacetonitrile	—
Dibromoacetonitrile	Possible human carcinogen
Trichloroacetonitrile	—
1,1-Dichloropropanone	—
1,1,1-Trichloropropanone	—
2-Chlorophenol	Not classifiable
2,4-Dichlorphenol	Not classifiable
2,4,6-Trichlorophenol	Probable human carcinogen
Chloropicrin	—-
Chloral hydrate	Possible human carcinogen
Cyanogen chloride	—
Formaldehyde	Probable human carcinogen
Chlorate	—
Chlorite	Not classifiable
Bromate	Probable human carcinogen
Ammonia	Not classifiable
Hypochlorous acid	—
Hypochlorite	—
Monochloramine	—
Chlorine dioxide	Not classifiable

Source: USEPA, *Drinking Water Regulations and Health Advisories*, EPA 822-B-96-002, U.S. Environmental Protection Agency, Washington, DC, 1996.

the bromide ion in the source water. Factors affecting formation of halogenated DBPs include type and concentration of natural organic matter, oxidant type and dose, time, bromide ion concentration, pH, organic nitrogen concentration, and temperature. Organic nitrogen significantly influences the formation of nitrogen-containing DBPs such as the haloacetonitriles, halopicrins, and cyanogen halides. The parameter TOX represents the concentration of total organic halides in a water sample (calculated as chloride). In general, less than 50% of the TOX content has been identified, despite evidence that several of these unknown halogenated byproducts of water chlorination may be harmful to humans (Reckhow et al., 1990; Singer and Chang, 1989).

Nonhalogenated DBPs are also formed when strong oxidants react with organic compounds found in water. Ozone and peroxone oxidation of organics leads to the production of aldehydes, aldo- and keto-acids, organic acids, and, when bromide ion is present, brominated organics. Many of the oxidation byproducts are biodegradable and appear as biodegradable dissolved organic carbon (BDOC) and assimilable organic carbon (AOC) in treated water.

Bromide ion plays a key role in DBP formation. Ozone or free chlorine oxidizes bromide ion to hypobromate ion/hypobromous acid, which subsequently forms brominated DBPs. Brominated organic byproducts include compounds such as bromoform, brominated acetic acids and acetonitriles, bromopicrin, and cyanogen bromide. Only about a third of the bromide ions incorporated into byproducts have been identified.

Disinfection Byproduct Precursors

Numerous researchers have documented that NOM is the principal precursor of organic DBP formation. Chlorine reacts with NOM to produce a variety of DBPs, including THMs and haloacetic acids (HAAs). Ozone reacts with NOM to produce aldehydes, organic acids, and aldo- and keto-acids; many of these are produced by chlorine as well (Singer et al., 1993; Stevens, 1976). Natural waters contain mixtures of both humic and non-humic organic substances. NOM can be subdivided into a hydrophobic fraction composed of primarily humic material and a hydrophilic fraction composed of primarily fulvic material. The type and concentration of NOM are often assessed using surrogate measures. Although surrogate parameters have limitations, they are used because they may be measured more easily, rapidly, and inexpensively than the parameter of interest, often allowing online monitoring of the operation and performance of water treatment plants. Several surrogates are used to assess NOM:

- Total and dissolved organic carbon (TOC and DOC)
- Specific ultraviolet absorbance (SUVA), which is the absorbence at a 254-nm wavelength (UV-254) divided by the DOC; SUVA = (UV-254 ÷ DOC) × 100 (L/mg-m)
- THM formation potential (THMFP), a test that measures the quantity of THMs formed with a high dosage of free chlorine and a long reaction time
- TTHM stimulated distribution system (SDS), a test that predicts the total trihalomethane concentration at some selected point in a given distribution system where the conditions of the chlorination test simulate the distribution system at the point desired

On average, about 90% of the TOC is dissolved. DOC is defined as the TOC able to pass through a 0.45-μm filter. UV absorbance is a good technique for assessing the presence of DOC because DOC primarily consists of humic substances, which contain aromatic structures that absorb light in the UV spectrum. Oxidation of DOC reduces the UV absorbance of the water due to oxidation of some of the organic bonds that absorb UV absorbance. Complete mineralization of organic compounds to carbon dioxide usually does not occur under water treatment conditions; therefore, the overall TOC concentration usually is constant.

Concentrations of DBPs vary seasonally and are typically greatest in the summer and early fall for several reasons:

- The rate of DBP formation increases with increasing temperature.
- The nature of organic DBP precursors varies with season.
- Due to warmer temperatures, chlorine demand may be greater during summer months, requiring higher dosages to maintain disinfection.

If the bromide ion is present in source waters, it can be oxidized to hypobromous acid that can react with NOM to form brominated DBPs, such as bromoform. Furthermore, under certain conditions, ozone may react with the hypobromite ion to form bromate ion (Singer, 1982).

The ratio of bromide ion to the chlorine dose affects THM formation and bromine substitution of chlorine. Increasing the bromide ion to chlorine dose ratio shifts the speciation of THMs to produce more brominated forms. In the Krasener et al. (1989) study, the chlorine dose was roughly proportional to TOC concentration. As TOC was removed through the treatment train, the chlorine dose decreased and TTHM formation declined; however, at the same time, the ratio of bromide ion to chlorine dose increased, thereby shifting TTHM concentrations to the more brominated THMs. Thus, improving the removal of NOM prior to chlorination can shift the speciation of halogenated byproducts toward more brominated forms.

Chloropicrin is produced by the chlorination of humic materials in the presence of nitrate ion. Thibaud et al. (1988) chlorinated humic compounds in the presence of bromide ion to demonstrate the formation of brominated analogs to chloropicrin.

Impacts of pH on DBP Formation

The pH of water being chlorinated has an impact on the formation of halogenated byproducts. THM formation increases with increasing pH. Trichloroacetic acid, dichloroacetonitile, and trichloropropanone formation decreases with increased pH. Overall TOX formation decreases with increasing pH. Based on chlorination studies of humic material in model systems, high pH tends to favor chloroform formation over the formation of trichloroacetic acid and other organic halides. Accordingly, water treatment plants practicing precipitative softening at pH values greater than 9.5 to 10 are likely to have a higher fraction of TOX attributable to THMs than plants treating surface waters by conventional treatment in pH ranges of 6 to 8 (Reckhow and Singer, 1989). Because the application of chlorine dioxide and chloramines may introduce free chlorine into water, chlorination byproducts that may be formed would be influenced by pH as discussed above. Ozone application to waters containing bromide ion at high pH favors the formation of bromate ion, whereas application at low pH favors the formation of brominated organic byproducts. The pH also impacts enhanced coagulation (e.g., for ESWTR compliance) and compliance with the Lead and Copper Rule. These issues are addressed in *Microbial and Disinfection Byproduct Rules Simultaneous Compliance Guidance Manual* (USEPA, 1999c).

Organic Oxidation Byproducts

Organic oxidation byproducts are formed by reactions between NOM and all oxidizing agents added during drinking water treatment. Some of these byproducts are halogenated, as discussed in the previous section; others are not. The types and concentrations of organic oxidation byproducts produced depend on the type and dosage of the oxidant being used, chemical characteristics and concentration of the NOM being oxidized, and other factors such as the pH and temperature.

Inorganic Byproducts and Disinfectants

Table 8.11 summarizes some of the inorganic DBPs that are produced or remain as residual during disinfection. As discussed earlier, bromide ion reacts with strong oxidants to form bromate ion and other organic DBPs. Chlorine dioxide and chloramines leave residuals that are of concern for health considerations, as well as for taste and odor.

DBP Control Strategies

In 1983, the USEPA identified technologies, treatment techniques, and plant modifications that community water systems could use to comply with the maximum contaminant level for TTHMs. The principal treatment modifications involved moving the point of chlorination downstream in the water treatment plant, improving the coagulation process to enhance the removal of DBP precursors,

TABLE 8.11
Inorganic DBPs Produced During Disinfection

Disinfectant	Inorganic Byproduct or Disinfectant Residual Discussed
Chlorine dioxide	Chlorine dioxide, chlorite ion, chlorate ion, bromate ion
Ozone	Bromate ion, hydrogen peroxide
Chloramination	Monochloramine, dichloramine, trichloramine, ammonia

and using chloramines to supplement or replace the use of free chlorine (Singer and Harrington, 1993). Moving the point of chlorination downstream in the treatment train often is very effective in reducing DBP formation, because it allows the NOM precursor concentration to be reduced during treatment prior to chlorine addition. Replacing prechlorination by preoxidation with an alternate disinfectant that produces less DBPs is another option for reducing the formation of chlorinated byproducts. Other options to control the formation of DBPs include source water quality control, DBP precursor removal, and disinfection strategy selection. An overview of each is provided below.

Source Water Quality Control

Source water control strategies involve managing the source water to lower the concentrations of NOM and bromide ion in the source water. Research has shown that algal growth leads to the production of DBP precursors (Oliver and Shindler, 1980); therefore, nutrient and algal management is one method of controlling the DBP formation potential of source waters. Control of bromide ion in source waters may be accomplished by preventing brine or saltwater intrusion into the water source.

DBP Precursor Removal

Raw water can include DBP precursors in both dissolved and particulate forms. For the dissolved precursors to be removed in conventional treatment, they must be converted to a particulate form for subsequent removal during settling and filtering. The THM formation potential generally decreases by about 50% through conventional coagulation and settling, indicating the importance of moving the point of chlorine application after coagulation and settling (and even filtration) to control TOX as well as TTHM formation (Singer and Harrington, 1989). Conventional systems can lower the DBP formation potential of water prior to disinfection by further removing precursors with enhanced coagulation, granular activated carbon (GAC) adsorption, or membrane filtration prior to disinfection. Precursor removal efficiencies are site specific and vary with different source waters and treatment techniques.

Aluminum (alum) and iron (ferric) salts can remove variable amounts of NOM. For alum, the optimal pH for NOM removal is in the range of 5.5 to 6.0. The addition of alum decreases pH and may allow the optimal pH range to be reached without acid addition; however, waters with very low or very high alkalinities may require the addition of base or acid to reach the optimal NOM coagulation pH (Singer, 1992). Granular activated carbon adsorption can be used following filtration to remove additional NOM. For most applications, empty bed contact times in excess of 20 minutes are required, with regeneration frequencies on the order of 2 to 3 months. These long control times and frequent regeneration requirements make GAC an expensive treatment option. In cases where prechlorination is practiced, the chlorine rapidly degrades GAC. Addition of a disinfectant to the GAC bed can result in specific reactions where previously absorbed compounds leach into the treated water.

Membrane filtration has been shown effective in removing DBP precursors in some instances. In pilot studies, ultrafiltration (UF) with a molecular weight cutoff (MWCO) of 100,000 Da was ineffective for controlling DBP formation; however, when little or no bromide ion was present in source water, nanofiltration (NF) membranes with MWCOs of 400 to 800 Da effectively controlled DBP formation (Laine et al., 1993). In waters containing bromide ion, higher bromoform concentrations were observed after chlorination of membrane permeate (compared with raw water). This occurs as a result of filtration removing NOM while concentrating bromide ions in the permeate, thus providing a higher ratio of bromide ions to NOM than in raw water. This reduction in chlorine demand increases the ratio of bromide to chlorine, resulting in higher bromoform concentrations after chlorination of NF membrane permeate (compared with the raw water). TTHMs were lower in chlorinated permeate than chlorinated raw water; however, due to the shift in speciation of THMs toward more brominated forms, bromoform concentrations were actually greater in chlorinated treated water than in chlorinated raw water. Use of spiral-wound NF membranes (200 to 300 Da) more effectively controlled the formation of brominated THMs, but pretreatment of the water was necessary. Significant limitations in the use of membranes are disposal of the waste brine generated, membrane fouling, cost of membrane replacement, and increasing energy cost.

TABLE 8.12
Required Removal of TOC by Enhanced Coagulation for Surface Water Systems Using Conventional Treatment (Percent Reduction)

	Source Water Alkalinity (mg/L as $CaCO_3$)		
Source Water TOC (mg/L)	**0–60**	**>60–120**	**>120**
>2.0 to 4.0	35.0%	25.0%	15.0%
>4.0 to 8.0	45.0%	35.0%	25.0%
>8.0	50.0%	40.0%	30.0%

Disinfection byproduct regulations require enhanced coagulation as an initial step for removal of DBP precursors. In addition to meeting maximum contaminant levels (MCLs) and maximum residual disinfectant levels (MRDLs), some water suppliers also must meet treatment requirements to control the organic material (DBP precursors) in the raw water that combines with disinfectant residuals to form DBPs. Systems using conventional treatment are required to control precursors (measured as TOC) by using enhanced coagulation or enhanced softening. A system must remove a specified percentage of TOC (based on raw water quality) prior to the point of continuous disinfection (Table 8.12).

Systems using ozone followed by biologically active filtration or chlorine dioxide that meet specific criteria would be required to meet the TOC removal requirements prior to addition of a residual disinfectant. Systems able to reduce TOC by a specified percentage level have met the DBPR treatment technique requirements. If the system does not meet the percent reduction, it must determine its alternative minimum TOC removal level. The primacy agency approves the alternative minimum TOC removal possible for the system on the basis of the relationship between coagulant dose and TOC in the system based on results of bench or pilot-scale testing. Enhanced coagulation is determined in part as the coagulant dose where an incremental addition of 10 mg/L of alum (or an equivalent amount of ferric salt) results in a TOC removal below 0.3 mg/L.

Disinfection Strategy Selection

In addition to improving the raw or predisinfectant water quality, alternative disinfection strategies can be used to control DBPs:

- Use an alternative or supplemental disinfectant or oxidant such as chloramines or chlorine dioxide that will produce fewer DBPs.
- Move the point of chlorination to reduce TTHM formation and, where necessary, substitute chloramines, chlorine dioxide, or potassium permanganate for chlorine as a preoxidant.
- Use two different disinfectants or oxidants at various points in the treatment plant to avoid DBP formation at locations where precursors are still present in high quantities.
- Use powdered activated carbon for THM precursor or TTHM reduction seasonally or intermittently.
- Maximize precursor removal.

CT Factor

One of the most important factors for determining or predicting the germicidal efficiency of any disinfectant is the CT factor, a version of the Chick–Watson law (1908). The CT factor is defined as the product of the residual disinfectant concentration (C), in mg/L, and the contact time (T), in minutes, that residual disinfectant is in contact with the water. The USEPA developed CT values for the inactivation of *Giardia* and viruses under the SWTR. Table 8.13 compares the CT values for virus

TABLE 8.13
CT Values for Inactivation of Viruses

Disinfectant (at 10°C)	Units	Inactivation 2-Log	Inactivation 3-Log
Chlorine	mg · min/L	4	4
Chloramine	mg · min/L	643	1067
Chlorine dioxide	mg · min/L	4.2	12.8
Ozone	mg · min/L	0.5	0.8
Ultraviolet	mW · s/cm^2	21	36

Source: Data from AWWA, *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Works Systems Using Surface Water Sources*, American Water Works Association, Denver, CO, 1991.

TABLE 8.14
CT Values for Inactivation of *Giardia* Cysts

Disinfectant (at 10°C)	Inactivation (mg ·min/L) 1-Log	2-Log	3-Log
Chlorine	35	69	104
Chloramine	615	1240	1850
Chlorine dioxide	7.7	15	23
Ozone	0.48	0.95	1.43

Source: Data from AWWA, *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Works Systems Using Surface Water Sources*, American Water Works Association, Denver, CO, 1991.

inactivation using chlorine, chlorine dioxide, ozone, chloramine, and ultraviolet light disinfection under specified conditions. Table 8.14 shows the CT values for inactivation of *Giardia* cyst using chlorine, chloramine, chlorine dioxide, and ozone under specified conditions. The CT values shown in Table 8.13 and Table 8.14 are based on water temperatures of 10°C and pH values in the range of 6 to 9. CT values for chlorine disinfection are based on a free chlorine residual. Note that chlorine is less effective as pH increases from 6 to 9. In addition, for a given CT value, a low C and a high T are more effective than the reverse (i.e., a high C and a low T). For all disinfectants, as temperature increases, effectiveness increases.

Disinfectant Residual Regulatory Requirements

One of the most important factors for evaluating the merits of alternative disinfectants is their ability to maintain the microbial quality in the water distribution system. Disinfectant residuals may serve to protect the distribution system against regrowth. The Surface Water Treatment Rule requires that filtration and disinfection must be provided to ensure that the total treatment of the system achieves at least 3-log removal/inactivation of *Giardia* cysts and 4-log removal/inactivation of viruses. In addition, the disinfection process must demonstrate by continuous monitoring and recording that the disinfection residual in the water entering the distribution system is never less than 0.2 mg/L for more than 4 hours (Snead, 1980). Several of the alternative disinfectants examined in this handbook cannot be used to meet the residual requirements stated in the SWTR; for example, if either ozone or ultraviolet light disinfection is used as the primary disinfectant, a secondary disinfectant such as chlorine or chloramines should be utilized to obtain a residual in the distribution system.

Disinfection byproduct formation continues in the distribution system due to reactions between the residual disinfectant and organics in the water. Koch et al. (1991) found that with a chlorine dose of 3 to 4 mg/L, THM and haloacetic acid (HAA) concentrations increase rapidly during the first 24 hours in the distribution system. After the initial 48 hours, the subsequent increase in THMs was found to be very small. Chloral hydrate concentrations continued to increase after the initial 24 hours, but at a reduced rate. Haloketones actually decreased in the distribution system.

Nieminski et al. (1993) evaluated DBP formation in the simulated distribution systems of treatment plants in Utah. Finished water chlorine residuals ranged from 0.4 to 2.8 mg/L. Generally, THM values in the distribution system studies increased by 50 to 100% (range of 30 to 200%) of the plant effluent value after a 24-hour contact time. The 24-hour THM concentration was essentially the same as the 7-day THM formation potential. HAA concentrations in the simulated distribution system were about 100% (range of 30 to 200%) of the HAA in the plant effluent. The 7-day HAA formation potential was sometimes higher, or below the distribution system values. If chlorine is used as a secondary disinfectant, one should therefore anticipate a 100% increase in the plant effluent THMs or plan to reach the 7-day THM formation level in the distribution system.

Summary of Current National Disinfection Practices

Most water treatment plants disinfect water prior to distribution. The 1995 USEPA Community Water Systems Survey reported that 81% of all community water systems provide some form of treatment on all or a portion of their water sources. The survey also found that virtually all surface water systems provide some treatment of their water. Of those systems reporting no treatment, 80% rely on groundwater as their only water source.

The most commonly used disinfectants/oxidants are chlorine, chlorine dioxide, chloramines, ozone, and potassium permanganate. Chlorine is predominately used in surface and groundwater disinfection treatment systems; more than 60% of the treatment systems use chlorine as a disinfectant/oxidant. Potassium permanganate on the other hand, is used by many systems, but its application is primarily for oxidation, rather than for disinfection. Permanganate will have some beneficial impact on disinfection because it is a strong oxidant that will reduce the chemical demand for the ultimate disinfection chemical. Chloramine is used by some systems and is more frequently used as a post-treatment disinfectant.

The International Ozone Association (IOA, 1997) conducted a survey of ozone facilities in the United States. The survey documented the types of ozone facilities, size, objective of ozone application, and year of operation; the findings are summarized in Table 8.15. The most common use of ozone was for oxidation of iron and manganese and for taste and odor control. Of the 158 ozone facilities, 24 used GAC following ozonation. In addition to the 158 operating ozone facilities, the survey identified 19 facilities under construction and another 30 under design. The capacity of the

TABLE 8.15
Ozone Application in U.S. Water Treatment Plants

Ozone Objective	Number of Plants	Percent
THM control	50	32
Disinfection	63	40
Iron/manganese, taste and odor control	92	58
Total	158	—

systems ranged from less than 25 gpm to exceeding 500 mg. Nearly half of the operating facilities had a capacity exceeding 1 mg. Rice et al. (1998) found that, as of May 1998, 264 drinking water plants in the United States were using ozone.

Methods of disinfection include the following:

- *Heat*—Possibly the first method of disinfection, which is accomplished by boiling water for 5 to 10 minutes; good, obviously, only for household quantities of water when bacteriological quality is questionable
- *Ultraviolet (UV) light*—A practical method of treating large quantities, but absorption of UV light is very rapid so this method is limited to nonturbid waters close to the light source
- *Metal ions*—Silver, copper, mercury
- *Alkalis and acids*
- *pH adjustment*—To under 3.0 or over 11.0
- *Oxidizing agents*—Bromine, ozone, potassium permanganate, and chlorine

The vast majority of drinking water systems in the United States use chlorine for disinfection (Spellman, 2007). Along with meeting the desired characteristics listed above, chlorine has the added advantage of a long history of use and is fairly well understood. Although some small water systems may use other disinfectants, we focus on chlorine in this handbook and provide only a brief overview of other disinfection alternatives.

> ***Note:*** One of the recent developments in chlorine disinfection is the use of multiple and interactive disinfectants. In these applications, chlorine is combined with a second disinfectant to achieve improved disinfection efficiency and effective DBP control.

Chlorination

The addition of chlorine or chlorine compounds to water is called *chlorination*. Chlorination is considered to be the single most important process for preventing the spread of waterborne disease. Chlorine has many attractive features that contribute to its wide use in industry. Five key attributes of chlorine are

1. It damages the cell wall.
2. It alters the permeability of the cell (the ability to pass water in and out through the cell wall).
3. It alters the cell protoplasm.
4. It inhibits the enzyme activity of the cell so it is unable to use its food to produce energy.
5. It inhibits cell reproduction.

Some concerns regarding the use of chlorine that may restrict its use include

- Chlorine reacts with many naturally occurring organic and inorganic compounds in water to produce undesirable DBPs.
- Hazards associated with using chlorine, specifically chlorine gas, require special treatment and response programs.
- High chlorine doses can cause taste and odor problems.

Chlorine is used in water treatment facilities primarily for disinfection. Because of the oxidizing powers of chlorine, it has been found to serve other useful purposes, as well (White, 1992):

- Taste and odor control
- Prevention of algal growth
- Maintenance of clear filter media

- Removal of iron and manganese
- Destruction of hydrogen sulfide
- Bleaching of certain organic colors
- Maintenance of distribution system water quality by controlling slime growth
- Restoration and preservation of pipeline capacity
- Restoration of well capacity, water main sterilization
- Improvement in coagulation

Chlorine is available in a number of different forms:

- As pure elemental gaseous chlorine, a greenish-yellow gas possessing a pungent and irritating odor that is heavier than air, nonflammable, and nonexplosive; when released to the atmosphere, this form is toxic and corrosive
- As solid calcium hypochlorite (in tablets or granules)
- As a liquid sodium hypochlorite solution (in various strengths)

The selection of one form of chlorine over the others for a given water system depends on the amount of water to be treated, configuration of the water system, local availability of the chemicals, and skill of the operator.

One of the major advantages of using chlorine is the effective residual that it produces. A residual indicates that disinfection is completed, and the system has an acceptable bacteriological quality. Maintaining a residual in the distribution system provides another line of defense against pathogenic organisms that could enter the distribution system and helps to prevent regrowth of those microorganisms that were injured but not killed during the initial disinfection stage.

Chlorine Terminology

Often it is difficult for new waterworks operators to understand the terminology used to describe the various reactions and processes used in chlorination. Common chlorination terms include the following:

- *Chlorine reaction*—Regardless of the form of chlorine used for disinfection, the reaction in water is basically the same. The same amount of disinfection can be expected, provided the same amount of available chlorine is added to the water. The standard units used to express the concentration of chlorine in water are milligrams per liter (mg/L) and parts per million (ppm); these terms indicate the same quantity.
- *Chlorine dose*—The amount of chlorine added to the system. It can be determined by adding the desired residual for the finished water to the chlorine demand of the untreated water. Dosage can be either milligrams per liter (mg/L) or pounds per day. The most common is mg/L.
- *Chlorine demand*—The amount of chlorine used by iron, manganese, turbidity, algae, and microorganisms in the water. Because the reaction between chlorine and microorganisms is not instantaneous, demand is relative to time. For instance, the demand 5 minutes after applying chlorine will be less than the demand after 20 minutes. Demand, like dosage, is expressed in mg/L. The chlorine demand is determined as follows:

$$\text{Cl}_2 \text{ demand} = \text{Cl}_2 \text{ dose} - \text{Cl}_2 \text{ residual} \tag{8.7}$$

- *Chlorine residual*—The amount of chlorine (determined by testing) that remains after the demand is satisfied. Residual, like demand, is based on time. The longer the time after dosage, the lower the residual will be, until all of the demand has been satisfied. Residual, like dosage and demand, is expressed in mg/L. The presence of a *free residual* of at least

0.2 to 0.4 ppm usually provides a high degree of assurance that the disinfection of the water is complete. *Combined residual* is the result of combining free chlorine with nitrogen compounds. Combined residuals are also called *chloramines*. The *total chlorine residual* is the mathematical combination of free and combined residuals. Total residual can be determined directly with standard chlorine residual test kits.

- *Chlorine contact time*—A key item in predicting the effectiveness of chlorine on microorganisms. It is the interval (usually only a few minutes) between the time when chlorine is added to the water and the time the water passes by the sampling point. Contact time is the "T" in CT. CT is calculated based on the free chlorine residual prior to the first consumer multiplied by the contact time in minutes:

$$\text{CT} = \text{Concentration} \times \text{Contact time} = \text{mg/L} \times \text{minutes} \tag{8.8}$$

A certain minimum time period is required for the disinfecting action to be completed. The contact time is usually a fixed condition determined by the rate of flow of the water and the distance from the chlorination point to the first consumer connection. Ideally, the contact time should not be less than 30 minutes, but even more time is needed at lower chlorine doses, in cold weather, or under other conditions.

Pilot studies have shown that specific CT values are necessary for the inactivation of viruses and *Giardia*. The required CT value will vary depending on pH, temperature, and the organisms to be killed. Charts and formulas are available to make this determination. The USEPA has set a CT value of 3-log ($\text{CT}_{99.9}$) inactivation to ensure that the water is free of *Giardia*. State drinking water regulations provide charts containing CT values for various pH and temperature combinations. Filtration, in combination with disinfection, must provide 3-log removal or inactivation of *Giardia*. Charts in the USEPA Surface Water Treatment Rule guidance manual list the required CT values for various filter systems. Under the 1996 Interim Enhanced Surface Water Treatment Rule, the USEPA requires systems that filter to remove 99% (2 log) of *Cryptosporidium* oocysts. To be sure that the water is free of viruses, a combination of filtration and disinfection that provides 4-log (99.99%) removal of viruses has been judged the best for drinking water safety. Viruses are inactivated more easily than cysts or oocysts.

Chlorine Chemistry

The reactions of chlorine with water and the impurities that might be in the water are quite complex, but a basic understanding of these reactions can aid the operator in keeping the disinfection process operating at its highest efficiency. When dissolved in pure water, chlorine reacts with H^+ ions and OH^- radicals in the water. Two of the products of this reaction (the actual disinfecting agents) are *hypochlorous acid* (HOCl) and the *hypochlorite radical* (OCl^-). If microorganisms are present in the water, the HOCl and the OCl^- penetrate the microbe cells and react with certain enzymes. This reaction disrupts the metabolism of the organisms and kills them. The chemical equation for hypochlorous acid is as follows:

$$\underset{\text{(chlorine)}}{Cl_2} + \underset{\text{(water)}}{H_2O} \leftrightarrow \underset{\substack{\text{(hypochlorous}\\\text{acid)}}}{HOCl} + \underset{\substack{\text{(hydrochloric}\\\text{acid)}}}{HCl} \tag{8.9}$$

Note: The symbol ↔ indicates that the reactions are reversible.

Hypochlorous acid (HOCl) is a weak acid, meaning that it dissociates slightly into hydrogen and hypochlorite ions, but it is a strong oxidizing and germicidal agent. Hydrochloric acid (HCl) in the above equation is a strong acid and retains more of the properties of chlorine. HCl tends to lower the pH of the water, especially in swimming pools where the water is recirculated and continually chlorinated. The total hypochlorous acid and hypochlorite ions in water constitute the *free available chlorine*. Hypochlorites act in a manner similar to HCl when added to water, because hypochloric acid is formed.

When chlorine is first added to water containing some impurities, the chlorine immediately reacts with the dissolved inorganic or organic substances and is then unavailable for disinfection. The amount of chlorine used in this initial reaction is the *chlorine demand* of the water. If dissolved ammonia (NH_3) is present in the water, the chlorine will react with it to form compounds called *chloramines*. Only after the chlorine demand is satisfied and the reaction with all the dissolved ammonia is complete is the chlorine actually available in the form of HOCl and OCl^-. The equation for the reaction of hypochlorous acid (HOCl) and ammonia (NH_3) is as follows:

$$\begin{array}{ccccccc} \text{HOCl} & + & \text{NH}_3 & \leftrightarrow & \text{NH}_2\text{Cl} & + & \text{H}_2\text{O} \\ \text{(hypochlorous} & & \text{(ammonia)} & & \text{(mono-} & & \text{(water)} \\ \text{acid)} & & & & \text{chloramine)} & & \end{array} \tag{8.10}$$

Note: The chlorine as hypochlorous acid and hypochlorite ions remaining in the water after the above reactions are complete is known as *free available chlorine*, and it is a very active disinfectant.

Breakpoint Chlorination

To produce a free chlorine residual, enough chlorine must be added to the water to produce what is referred to as *breakpoint chlorination*, which is the point at which near complete oxidation of nitrogen compounds is reached; any residual beyond breakpoint is mostly free chlorine (see Figure 8.7). When chlorine is added to natural waters, the chlorine begins combining with and oxidizing the chemicals in the water before it begins disinfecting. Although residual chlorine will be detectable in the water, the chlorine will be in the combined form with a weak disinfecting power. As we see in Figure 8.7, adding more chlorine to the water at this point actually decreases the chlorine residual as the additional chlorine destroys the combined chlorine compounds. At this stage, water may have a strong swimming pool or medicinal taste and odor. To avoid such taste and odor issues, add still more chlorine to produce a free residual chlorine. Free chlorine has the highest disinfecting power. The point at which most of the combined chlorine compounds have been destroyed and the free chlorine starts to form is the *breakpoint*.

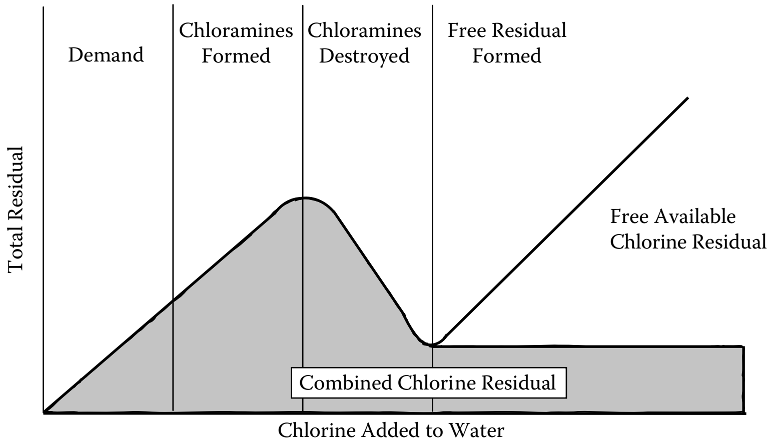

FIGURE 8.7 Breakpoint chlorination curve.

The chlorine breakpoint of water can only be determined by experimentation. This simple experiment requires 20 1000-mL breakers and a solution of chlorine. Place the raw water in the beakers and dose with progressively larger amounts of chlorine; for example, we might start with 0 in the first beaker, then 0.5 mg/L, then 1.0 mg/L, and so on. After a period of time, say 20 minutes, test each beaker for total chlorine residual and plot the results.

Breakpoint Chlorination Curve

Refer to Figure 8.7. When the curve starts, no residual exists, even though a dosage was applied. This is the *initial demand*, when microorganisms and interfering agents are using the result of the chlorine. After the initial demand, the curve slopes upward. Chlorine combining to form chloramines produces this part of the curve. All of the residual measured on this part of the curve is combined residual. At some point, the curve begins to drop back toward zero. This portion of the curve results from a reduction in combined residual, which occurs because enough chlorine has been added to destroy (oxidize) the nitrogen compounds used to form combined residuals. The breakpoint is the point where the downward slope of the curve breaks upward. At this point, all of the nitrogen compounds that could be destroyed have been destroyed. After breakpoint, the curve begins to move upward again, usually at a 45° angle. Only on this part of the curve can free residuals be found. Notice that the breakpoint is not zero. The distance that the breakpoint is above zero is a measure of the remaining combined residual in the water. This combined residual exists because some of the nitrogen compound will not have been oxidized by chlorine. If irreducible combined residual is more than 15% of the total residual, chlorine odor and taste complaints will be high.

Gas Chlorination

Gas chlorine is provided in 100-lb to 1-ton containers. Chlorine is placed in the container as a liquid. The liquid boils at room temperature and is reduced to a gas that builds pressure in the cylinder. At room temperature (70°F), a chlorine cylinder will have a pressure of 85 psi; 100- to 150-lb cylinders should be maintained in an upright position and chained to the wall. To prevent a chlorine cylinder from rupturing in a fire, the cylinder valves are equipped with special fusible plugs that melt between 158 and 164°F. Chlorine gas is 99.9% chlorine. A gas chlorinator meters the gas flow and mixes it with water, which is then injected as a water solution of pure chlorine. As the compressed liquid chlorine is withdrawn from the cylinder, it expands as a gas, withdrawing heat from the cylinder. Care must be taken not to withdraw the chlorine at too fast a rate; if the operator attempts to withdraw more than about 40 lb of chlorine per day from a 150-lb cylinder, it will freeze up.

> ***Note:*** All chlorine gas feed equipment sold today is vacuum operated. This safety feature ensures that, if a break occurs in one of the components in the chlorinator, the vacuum will be lost, and the chlorinator will shut down without allowing gas to escape.

Chlorine gas is a highly toxic lung irritant, and special facilities are required for storing and housing it. Chlorine gas will expand to 500 times its original compressed liquid volume at room temperature (1 gallon of liquid chlorine will expand to about 67 ft^3). Its advantage as a drinking water disinfectant is the convenience afforded by having a relatively large quantity of chlorine available for continuous operation for several days or weeks without the need for mixing chemicals. Where water flow rates are highly variable, the chlorination rate can be synchronized with the flow.

Chlorine gas has a very strong, characteristic odor that can be detected by most people at concentrations as low as 3.5 ppm. Highly corrosive in moist air, it is extremely toxic and irritating in concentrated form. Its toxicity ranges from being a throat irritant at 15 ppm to causing rapid death at 1000 ppm. Although chlorine does not burn, it supports combustion, so open flames should never be used around chlorination equipment.

When changing chlorine cylinders, an accidental release of chlorine may occasionally occur. To handle this type of release, a NIOSH-approved, self-contained breathing apparatus (SCBA) must be worn. Special emergency repair kits are available from the Chlorine Institute for use by emergency response teams to deal with chlorine leaks. Because chlorine gas is 2.5 times heavier than air, exhaust and inlet air ducts should be installed at floor level. A leak of chlorine gas can be found with a strong ammonia mist solution, as a white cloud develops when ammonia mist and chlorine combine.

Hypochlorination

Combining chlorine with calcium or sodium produces hypochlorites. Calcium hypochlorites are sold in powder or tablet forms and can contain chlorine concentrations up to 67%. Sodium hypochlorite is a liquid (bleach, for example) and is found in concentrations up to 16%. Chlorine concentrations of household bleach range from 4.75 to 5.25%. Most small system operators find using these liquid or dry chlorine compounds more convenient and safer than chlorine gas.

The compounds are mixed with water and fed into the water with inexpensive solution feed pumps. These pumps are designed to operate against high system pressures but can also be used to inject chlorine solutions into tanks, although injecting chlorine into the suction side of a pump is not recommended as the chlorine may corrode the pump impeller.

Calcium hypochlorite can be purchased as tablets or granules, with approximately 65% available chlorine (10 lb of calcium hypochlorite granules contain only 6.5 lb of chlorine). Normally, 6.5 lb of calcium hypochlorite will produce a concentration of 50 mg/L chlorine in 10,000 gal of water. Calcium hypochlorite can burn (at 350°F) if combined with oil or grease. When mixing calcium hypochlorite, operators must wear chemical safety goggles, a cartridge breathing apparatus, and rubberized gloves. Always place the powder in the water. Placing the water into the dry powder could cause an explosion.

Sodium hypochlorite is supplied as a clear, greenish-yellow liquid in strengths from 5.25 to 16% available chlorine. Often referred to as "bleach," it is, in fact, used for bleaching. As we stated earlier, common household bleach is a solution of sodium hypochlorite containing 4.75 to 5.25% available chlorine. The amount of sodium hypochlorite required to produce a 50-mg/L chlorine concentration in 10,000 gal of water can be calculated using the solutions equation, as shown below:

$$C_1 \times V_1 = C_2 \times V_2 \tag{8.11}$$

where

C = Solution concentration (mg/L or %).
V = Solution volume (liters, gallons, quarts, etc.).
1.0% = 10,000 mg/L.

In this example, C_1 and V_1 are associated with the sodium hypochlorite, and C_2 and V_2 are associated with the 10,000 gallons of water with a 50-mg/L chlorine concentration. Therefore:

$$C_1 = 5.25\% = \frac{5.25\% \times 10,000 \text{ mg/L}}{1.0\%} = 52,500 \text{ mg/L}$$

$$V_1 = \text{Unknown volume of sodium hypochlorite}$$

$$C_2 = 50 \text{ mg/L}$$

$$V_2 = 10,000 \text{ gal}$$

$$C_1 \times V_1 = C_2 \times V_2$$

$$52,500 \text{ mg/L} \times V_1 = 50 \text{ mg/L} \times 10,000 \text{ gal}$$

$$V_1 = \frac{50 \text{ mg/L} \times 10,000 \text{ gal}}{52,500 \text{ mg/L}} = 9.52 \text{ gal}$$

Sodium hypochlorite solutions are introduced to the water in the same manner as calcium hypochlorite solutions. The purchased stock bleach is usually diluted with water to produce a feed solution that is pumped into the water system.

Hypochlorites must be stored properly to maintain their strengths. Calcium hypochlorite must be stored in airtight containers in cool, dry, dark locations. Sodium hypochlorite degrades relatively quickly even when properly stored; it can lose more than half of its strength in 3 to 6 months. Operators should purchase hypochlorites in small quantities to be sure they are used while still strong. Old chemicals should be discarded safely.

The pumping rate of a chemical metering pump is usually manually adjusted by varying the length of the piston or diaphragm stroke. Once the stroke is set, the hypochlorinator feeds accurately at that rate; however, chlorine measurements must be made occasionally at the beginning and end of the well pump cycle to ensure correct dosage. A metering device may be used to vary the hypochlorinator feed rate, synchronized with the water flow rate. Where a well pump is used, the hypochlorinator is connected electrically with the on/off controls of the pump so the chlorine solution is not fed into the pipe when the well is not pumping.

Determining Chlorine Dosage

Proper disinfection requires calculation of the amount of chlorine that must be added to the water to produce the required dosage. The type of calculation used depends on the form of chlorine being used. The basic chlorination calculation used is the same one used for all chemical addition calculations—the *pounds formula*:

$$\text{Pounds} = \text{mg/L} \times 8.34 \times \text{MG} \tag{8.12}$$

where

Pounds = Pounds of available chlorine required.
mg/L = Desired concentration in milligrams per liter.
8.34 = Conversion factor.
MG = Millions of gallons of water to be treated.

■ EXAMPLE 8.3

Problem: Calculate the number of pounds of gaseous chlorine needed to treat 250,000 gal of water with 1.2 mg/L of chlorine.

Solution:

$$\text{Pounds} = 1.2 \text{ mg/L} \times 8.34 \times 0.25 \text{ MG} = 2.5 \text{ lb}$$

Note: Hypochlorites contain less than 100% available chlorine; thus, we must use more hypochlorite to get the same number of pounds of chlorine into the water.

If we substitute calcium hypochlorite with 65% available chlorine in our example, 2.5 lb of available chlorine is still needed, but more than 2.5 lb of calcium hypochlorite is required to provide that much chlorine. Determine how much of the chemical is needed by dividing the pounds of chlorine required by the decimal form of the percent available chlorine. Because 65% is the same as 0.65, we need to add

$$\frac{2.5 \text{ lb}}{0.65 \text{ available chlorine}} = 3.85 \text{ lb } Ca(OCl)_2$$

to get that much chlorine.

In practice, because most hypochlorites are fed as solutions, we often need to know how much chlorine solution we should feed. In addition, the practical problems faced in day-to-day operation are never so clearly stated as the practice problems we are working here; for example, small water systems do not usually deal with water flows in million gallons per day. Real-world problems usually require a lot of intermediate calculations to get everything ready to plug into the pounds formula.

■ EXAMPLE 8.4

Problem: We have raw water with a chlorine demand of 2.2 mg/L. We need a final residual of 1.0 mg/L at the entrance to the distribution system. We can use sodium hypochlorite or calcium hypochlorite granules as the source of chlorine. Well output is 65 gallons per minute (gpm), and the chemical feed pump can inject 100 milliliters per minute (mL/min) at the 50% setting. What is the required strength of the chlorine solution we will feed? What volume of 5.20% sodium hypochlorite will be needed to produce 1 gal of the chlorine feed solution? How many pounds of 65% calcium hypochlorite will be needed to mix each gallon of solution?

Solution:

1. Determine the amount of chlorine to be added to the water (the chlorine dose). The dose is defined as the chlorine demand of the water, plus the desired residual, or, in this case:

   $$\text{Dose} = \text{Demand} + \text{Residual} = 2.2\text{ mg/L} + 1.0\text{ mg/L} = 3.2\text{ mg/L}$$

   To obtain a 1.0-mg/L residual when the water enters the distribution system, we must add 3.2 mg/L of chlorine to the water.
2. Determine the strength of the chlorine feed solution that would add 3.2 mg/L of chlorine to 65 gpm of water when fed at a rate of 100 mL/min. The well pump is producing water at a flow rate (Q_1) of 65 gpm, with a chlorine concentration (C_1) of 0.0 mg/L. The metering pump will add 100 mL/min (Q_2) of chlorine solution, but we do not know its concentration (C_2) yet. The finished water will have been dosed with a chlorine concentration of 3.2 mg/L (C_1) and will enter the distribution system at a rate (Q_t) of 65 gal + 100 mL per minute, with a free residual chlorine concentration of 1.0 mg/L after the chlorine contact time.
3. Convert the metering pump flow (100 mL/min) to gpm so we can calculate Q_1. To do this, we use standard conversion factors:

   $$\frac{100\text{ mL}}{\text{min}} \times \frac{1\text{ L}}{1000\text{ mL}} \times \frac{1\text{ gal}}{3.785\text{ L}} = 0.026\text{ gal/min}$$

   So, now we know that Q_2 is 0.026 gpm and that Qt is 65 gpm + 0.026 gpm = 65,026 gpm.
4. Apply the mass balance equation. The mass balance equation says that the flow rate times the concentration of the output is equal to the flow rate times the concentration of each of the inputs added together:

   $$(Q_1 \times C_1) + (Q_2 \times C_2) = (Q_1 \times C_1) \tag{8.13}$$

   Substituting the numbers given and those we have calculated so far gives us:

$$(65 \text{ gpm} \times 0.0 \text{ mg/L}) + (0.026 \text{ gpm} \times x \text{ mg/L}) = (65 + 0.026 \text{ gpm}) \times 3.2 \text{ mg/L}$$

$$0 + 0.026x = 65.026 \times 3.2$$

$$0.026x = 208.1$$

$$x = \frac{208.1}{0.026} = 8004 \text{ mg/L}$$

This is the answer to the first part of the question, the required strength of the chlorine feed solution. Because a 1% solution is equal to 10,000 mg/L, a solution strength of 8004 mg/L is an approximately 0.80% solution.

To determine the required volume of bleach per gallon to produce this 0.80% solution, we go back to the pounds formula:

$$\text{Pounds} = \text{mg/L} \times 8.34 \times \text{MG}$$

$$8004 \text{ mg/L} \times 8.34 \times 0.000001 \text{ MG} = 0.067 \text{ lb Cl}$$

Note: Remember to convert gallons to MG

Recalling that the bleach, like water, weighs 8.34 lb/gal and contains approximately 5.20% (0.0520) available chlorine,

$$1 \text{ gal bleach} = 8.34 \text{ lb/gal} \times 0.0520 = 0.43 \text{ lb available chlorine per gal bleach}$$

If 1 gal of bleach contains 0.43 lb of available chlorine, how many gallons of bleach do we need to provide the 0.067 lb of chlorine we need for each gallon of chlorine feed solution? To determine the gallons of bleach needed, we use the simple ratio equation:

$$\frac{1 \text{ gal}}{0.43 \text{ lb } Cl_2} = \frac{x \text{ gal}}{0.067 \text{ lb } Cl_2}$$

$$x = \frac{1 \text{ gal} \times 0.067 \text{ lb}}{0.43 \text{ lb}}$$

$$= 0.16 \text{ gal bleach per gal solution}$$

Or, to determine the required volume of bleach per gallon to produce the 0.80% solution, we can use the solutions equation and calculate it this way:

$$C_1 \times V_1 = C_2 \times V_2$$

$$C_1 = 0.80\%$$

$$V_1 = 1.0 \text{ gal}$$

$$C_2 = 5.20\%$$

$$V_2 = \text{unknown}$$

$$0.80\% \text{ solution} \times 1.0 \text{ gal} = 5.20\% \text{ solution} \times x \text{ gal}$$

$$x = \frac{0.80\% \times 1.0 \text{ gal}}{5.20\%} = 0.15 \text{ gal bleach per gal solution}$$

To summarize, 1 gallon of household bleach:

- Contains 0.85 gal water
- Contains 5.20%, or 52,000 mg/L, available chlorine
- Contains 0.15 gal available chlorine
- Contains 0.43 lb available chlorine
- Weighs 8.34 lb

The third part of the problem requires that we determine the pounds of calcium hypochlorite required for each gallon of feed solution. We know that we need 0.066 lb of chlorine for each gallon of solution and that hypochlorite contains 65% available chlorine; that is, 1.0 lb of hypochlorite contains 0.65 lb of available chlorine. Using the ratio equation,

$$\frac{1 \text{ lb hypochlorite}}{0.65 \text{ lb Cl}_2} = \frac{x \text{ lb hypochlorite}}{0.067 \text{ lb Cl}_2}$$

$$x = \frac{1 \text{ lb} \times 0.067 \text{ lb}}{0.65 \text{ lb}}$$

$$x = \frac{0.067}{0.65} = 0.1 \text{ lb hypochlorite per gal solution}$$

Chlorine Generation

Onsite generation of chlorine has recently become practical. These generation systems, using only salt and electric power, can be designed to meet disinfection and residual standards and to operate unattended at remote sites. Considerations for chlorine generation include cost, concentration of the brine produced, and availability of the process (AWWA, 1997).

Chlorine Gas Chlorine gas can be generated by a number of processes including the electrolysis of alkaline brine or hydrochloric acid, the reaction between sodium chloride and nitric acid, or the oxidation of hydrochloric acid. About 70% of the chlorine produced in the United States is manufactured from the electrolysis of salt brine and caustic solutions in a diaphragm cell (White, 1992). Because chlorine is a stable compound, it is typically produced offsite by a chemical manufacturer. Once produced, chlorine is packaged as a liquefied gas under pressure for delivery to the site in railcars, tanker trucks, or cylinders.

Sodium Hypochlorite Dilute sodium hypochlorite solutions (less than 1%) can be generated electrochemically onsite from salt brine solution. Typically, sodium hypochlorite solutions are referred to as *liquid bleach* or *Javelle water*. Generally, the commercial- or industrial-grade solutions produced have hypochlorite strengths of 10 to 16%. The stability of sodium hypochlorite solution depends on the hypochlorite concentration, the storage temperature, the length of storage (time), the impurities of the solution, and exposure to light. Decomposition of hypochlorite over time can affect the feed rate and dosage, as well as produce undesirable byproducts such as chlorite ions or chlorate (Gordon et al., 1995). Because of the storage problems, many systems are investigating onsite generation of hypochlorite in lieu of its purchase from a manufacturer or vendor.

Calcium Hypochlorite To produce calcium hypochlorite, hypochlorous acid is made by adding chlorine monoxide to water and then neutralizing it with lime slurry to create a solution of calcium hypochlorite. Generally, the final product contains up to 70% available chlorine and 4 to 6% lime. Storage of calcium hypochlorite is a major safety consideration. It should never be stored where it is subject to heat or allowed to contact any organic material of an easily oxidized nature (Spellman, 2007).

TABLE 8.16
Chlorine Uses and Doses

Application	Typical Dose	Optimal pH	Reaction Time	Effectiveness	Other Considerations
Iron	0.62 mg/mg Fe	7.0	Less than 1 hour	Good	—
Manganese	0.77 mg/mg Mn	7–8	1 to 3 hours	Slow kinetics	Reaction time increases at lower pH
		9.5	Minutes		
Biological growth	1–2 mg/L	6–8	NA	Good	DBP formation
Taste/odor	Varies	6–8	Varies	Varies	Effectiveness depends on compound
Color removal	Varies	4.0–6.8	Minutes	Good	DBP formation
Zebra mussels	2–5 mg/L	—	Shock level	Good	DBP formation
	0.2–0.5 mg/L	—	Maintenance level		
Asiatic clams	0.3–0.5 mg/L	—	Continuous	Good	DBP formation

Source: Data from White (1992), Connell (1996), and Culp et al. (1986).

Primary Uses and Points of Application of Chlorine

Uses The main usage of chlorine in drinking water treatment is for disinfection; however, chlorine has also found application for a variety of other water treatment objectives, such as the control of nuisance organisms, oxidation of taste and odor compounds, oxidation of iron and manganese, color removal, and as a general treatment aid to filtration and sedimentation processes (White, 1992). Table 8.16 presents a summary of chlorine uses and doses.

Points of Application At conventional surface water treatment plants, chlorine is typically added for prechlorination at either the raw water intake or flash mixer, for intermediate chlorination ahead of the filters, for postchlorination at the filter clearwell, or for rechlorination of the distribution system (Connell, 1996). Table 8.17 summarizes typical points of application.

Typical Doses Table 8.18 shows the typical dosages for the various forms of chlorine. The wide range of chlorine gas dosages most likely represents its use as both an oxidant and a disinfectant. Sodium hypochlorite and calcium hypochlorite can also serve as both an oxidant and a disinfectant, but their higher cost may limit their use.

Factors Affecting Chlorination

Disinfection by chlorination is a rather straightforward process, but several factors (interferences) can affect the ability of chlorine to perform its main function: disinfection. *Turbidity* is one such interference. Turbidity is a general term that describes particles suspended in the water. Water with a high turbidity appears cloudy. Turbidity interferes with disinfection when microorganisms are

TABLE 8.17
Typical Chlorine Points of Application

Raw water intake
Flash mixer (prior to sedimentation)
Filter influent
Filter clearwell
Distribution system

Sources: Data from Connell (1996), White (1992), and AWWA (1990).

TABLE 8.18
Typical Chlorine Dosages at Water Treatment Plants

Chlorine Compound	Range of Dosages (mg/L)
Calcium hypochlorite	0.6–5
Sodium hypochlorite	0.2–2
Chlorine gas	1–16

Source: Data were obtained from a USEPA review of public water systems' initial sampling plans, which were required by the USEPA Information Collection Rule (ICR).

able to hide from chlorine among the particles causing the turbidity. This problem is magnified when turbidity comes from organic particles, such as from sewage effluent. To overcome this, the length of time the water is exposed to the chlorine or the chlorine dose must be increased, although highly turbid waters may still shield some microorganisms from the disinfectant. The USEPA considered this problem in its Surface Water Treatment Rule and the Interim Enhanced Surface Water Treatment Rule, which tightened controls on DBPs and turbidity and regulated *Cryptosporidium*. The IESWTR requires continuous turbidity monitoring of individual filters and tightened allowable turbidity limits for combined filter effluent, cutting the maximum from 5 NTU to 1 NTU and the average monthly limit from 0.5 NTU to 0.3 NTU.

Note: Recall that the IESWTR applies to large public water systems (those serving more than 10,000 people) that use surface water or groundwater directly influenced by surface water and was the first regulation to directly address *Cryptosporidium*.

Temperature affects the solubility of chlorine, the rate at which disinfecting ions are produced, and the proportion of highly effective forms of chlorine that will be present in the water. More importantly, however, temperature affects the rate at which the chlorine reacts with the microorganisms themselves. As water temperature decreases, the rate at which the chlorine can pass through the microorganisms' cell wall decreases, making the chlorine less effective as a disinfectant. Along with the presence of turbidity-causing agents such as suspended solids and organic matter, chemical compounds in the water may influence chlorination: high alkalinity, nitrates, manganese, iron, and hydrogen sulfide.

Measuring Chlorine Residual

During normal operations, waterworks operators perform many operating checks and tests on unit processes throughout the plant. One of the most important and frequent operating checks is the *chlorine residual test*. This test must be performed whenever a distribution sample is collected for microbiological analysis and should be done frequently where the treatment facility discharges to the water distribution system to ensure that the disinfection system is working properly.

To test for chlorine residual, several methods are available. The most common and most convenient is the *DPD color comparator method*. This method uses a small portable test kit with prepared chemicals that produce a color reaction indicating the presence of chlorine. By comparing the color produced by the reaction with a standard, we can determine the approximate chlorine residual concentration of the sample. DPD color comparator chlorine residual test kits are available from the manufacturers of chlorination equipment.

Note: The color comparator method is acceptable for most groundwater systems and for chlorine residual measurements in the distribution system; however, keep in mind that the methods used to take chlorine residual measurements for controlling the disinfection process in surface water systems and some groundwater systems where adequate disinfection is essential must be approved by standard methods.

Pathogen Inactivation and Disinfection Efficacy

Inactivation Mechanisms Research has shown that chlorine is capable of producing lethal events at or near the cell membrane as well as affecting DNA. In bacteria, chlorine was found to adversely affect cell respiration, transport, and possibly DNA activity. Chlorination was found to cause an immediate decrease in oxygen utilization in both *Escherichia coli* and *Candida parapsilosis* studies. Chlorine damages the cell wall membrane, promotes leakage through the cell membrane, and produces lower levels of DNA synthesis for *Escherichia coli*, *Candida parapsilosis*, and *Mycobacterium fortuitum* bacteria. One study also showed that chlorine inactivation is rapid and does not require bacteria reproduction (Hass and Englebrecht, 1980). These observations rule out mutations or lesions as the principal inactivation mechanisms, as these mechanisms require at least one generation of replication for inactivation to occur.

Environmental Effects Several environmental factors influence the inactivation efficiency of chlorine, including water temperature, pH, contact time, mixing, turbidity, interfering substances, and the concentration of available chlorine. In general, the highest levels of pathogen inactivation are achieved with high chlorine residuals, long contact times, high water temperature, and good mixing, combined with a low pH, low turbidity, and the absence of interfering substances. Of the environmental factors, pH and temperature have the most impact on pathogen inactivation by chlorine.

The germicidal efficiency of hypochlorous acid (HOCl) is much higher than that of the hypochlorite ion (OCl^-). The distribution of chlorine species between HOCl and OCl^- is determined by pH, as discussed earlier. Because HOCl dominates at low pH, chlorination provides more effective disinfection at low pH. At high pH, OCl^- dominates, which causes a decrease in disinfection efficiency. The inactivation efficiency of gaseous chlorine and hypochlorite is the same at the same pH after chlorine addition. Note, however, that the addition of gaseous chlorine will decrease the pH while the addition of hypochlorite will increase the pH of the water. Without pH adjustment to maintain the same treated water pH, gaseous chlorine will have greater disinfection efficiency than hypochlorite. The impact of pH on chlorine disinfection has been demonstrated in the field; for example, virus inactivation studies have shown that 50% more contact time is required at pH 7.0 than at pH 6.0 to achieve comparable levels of inactivation. These studies also demonstrated that a rise in pH from 7.0 to 8.8 or 9.0 requires six times the contact time to achieve the same level of virus inactivation (Culp and Culp, 1974). Although these studies found a decrease in inactivation with increasing pH, some studies have shown the opposite effect. An earlier study reported that viruses were more sensitive to free chlorine at high pH than at low pH (Scarpino, 1972).

For typical drinking water treatment temperatures, pathogen inactivation increases with temperature. Virus studies suggest that the contact time should be increased by two to three times to achieve comparable inactivation levels when the water temperature is lowered by 10°C (Clarke et al., 1962).

Numerous investigations have been made to determine the germicidal efficiency of chlorine. Although there are widespread differences in the susceptibility of various pathogens, the general order of increasing chlorine disinfection difficulty are bacteria, viruses, and then protozoa. Chlorine is an extremely effective disinfectant for inactivating bacteria. A study conducted during the 1940s investigated the inactivation levels as a function of time for *Escherichia coli*, *Pseudomonas aeruginosa*, *Salmonella typhi*, and *Shigella dysenteriae* (Butterfield et al., 1943). Study results indicated that HOCl is more effective than OCl^- for inactivation of these bacteria. These results have been confirmed by several researchers who have concluded that HOCl is 70 to 80 times more effective than OCl^- for inactivating bacteria (Culp et al., 1986).

Chlorine has also been shown to be a highly effective viricide. One of the most comprehensive virus studies was conducted in 1971 using treated Potomac estuary water (Liu et al., 1971). The tests were performed to determine the resistance of 20 different enteric viruses to free chlorine under constant conditions of 0.5 mg/L free chlorine and a pH and temperature of 7.8 and 2°C, respectively. In this study, the least resistant virus was found to be reovirus, which required 2.7 minutes to achieve

99.99% inactivation (4-log removal). The most resistant virus was found to be a poliovirus, which required more than 60 minutes for 99.99% inactivation. The corresponding CT range required to achieve 99.99% inactivation for all 20 viruses was between 1.4 to over 30 mg · min/L. Virus survival studies have also been conducted on a variety of both laboratory and field strains (AWWA, 1979). All of the virus inactivation tests in the AWWA study were performed at a free chlorine residual of 0.4 mg/L, a pH of 7.0, a temperature of 5°C, and contact times of 10, 100, or 1000 minutes. Test results showed that, of the 20 cultures tested, only 2 poliovirus strains reached 99.99% inactivation after 10 minutes (CT = 4 mg · min/L), 6 poliovirus strains reached 99.99% inactivation after 100 minutes (CT = 40 mg · min/L), and 11 of the 12 polioviruses plus one *Coxsackievirus* strain (12 out of a total of 20 viruses) reached 99.99% inactivation after 1000 minutes (CT = 400 mg · min/L).

Chlorine has found only limited success in inactivating protozoa. Data obtained during a 1984 study (Hoff et al., 1984) indicated that the resistance of *Giardia* cysts is two orders of magnitude higher than that of enteroviruses and more than three orders of magnitude higher than the enteric bacteria. CT requirements for *Giardia* cyst inactivation when using chlorine as a disinfectant have been determined for various pH and temperature conditions. The CT values increase at low temperatures and high pH. Chlorine has little impact on the viability of *Cryptosporidium* oocysts when used at the relatively low doses encountered in water treatment (e.g., 5 mg/L). Approximately 40% removals (0.2 log) of *Cryptosporidium* were achieved at CT values of both 30 and 3600 mg · min/L (Finch et al., 1994). Another study determined that no practical inactivation was observed when oocysts were exposed to free chlorine concentrations ranging from 5 to 80 mg/L at pH 8, a temperature of 22°C, and contact times of 48 to 245 minutes (Gyurek et al., 1996). CT values ranging from 3000 to 4000 mg · min/L were required to achieve 1-log *Cryptosporidium* inactivation at pH 6.0 and a temperature of 22°C. During this study, when oocysts were exposed to 80 mg/L of free chlorine for 120 minutes, inactivation greater than 3 logs was produced.

Disinfection Byproducts

Halogenated organics are formed when natural organic matter (NOM) reacts with free chlorine or free bromine. Free chlorine is normally introduced into water directly as a primary or secondary disinfectant. Free bromine results form the oxidation by chlorine of the bromide ion in the source water. Factors affecting the formation of these halogenated DBPs include type and concentration of NOM, chlorine form and dose, time, bromide ion concentration, pH, organic nitrogen concentration, and temperature. Organic nitrogen significantly influenced the formation of nitrogen-containing DBPs, including haloacetonitriles (Reckhow et al., 1990), halopicrins, and cyanogen halides. Because most water treatment systems have been required to monitor for total trihalomethanes (TTHMs) in the past, most water treatment operators are probably familiar with some of the requirements of DBP regulations. The key points of the DBP rule and some of the key changes with which water supply systems are required to comply are summarized below:

- *Chemical limits and testing*—Testing requirements include total trihalomethanes (TTHMs) and five haloacetic acids (HAA5). The maximum contaminant level (MCL) for TTHM is 0.080 mg/L for surface water systems. In addition, a new MCL of 0.060 mg/L has been established for haloacetic acids. New MCLs have been established for bromate (0.010 mg/L) and chlorite (1.0 mg/L). Bromate monitoring is required of systems that use ozone. Chlorite monitoring is required only for systems that use chlorine dioxide (i.e., sodium and calcium hypochlorite are not included). Maximum residual disinfectant levels (MRDLs) were established for total chlorine (4.0 mg/L) and chlorine dioxide (0.8 mg/L).
- *Operational requirements*—Analytical requirements for measuring chlorine residual have been changed to require digital equipment (i.e., no color wheels or analog test kits). The test kit must have a detection limit of at least 0.1 mg/L.
- *Monitoring and reporting*—Individual state requirements will differ, but at a minimum the following requirements are in effect:

- Surface water system monitoring requirements include four quarterly samples per treatment plant (Source Treatment Unit, or STU) for TTHMs and HAA5. One of these quarterly samples, or 25% of the total samples, must be collected at the maximum residence time location. The remaining samples must be collected at representative locations throughout the entire distribution system. Compliance is based on a running annual average computed quarterly.
- For those surface water systems using conventional filtration or lime softening, a D/DBP monthly operating report for total organic carbon (TOC) removal must be completed and filed with the state EPA. This report will include TOC, alkalinity, and specific ultraviolet absorption (SUVA) parameters. There will also be an additional monthly operating report for bromate, chlorite, chlorine dioxide, and chlorine residual.
- TTHM monitoring results may indicate the possible need for additional treatment to include best available technology for the reduction of DBP. This may include the use of granular activated carbon, enhanced coagulation (for surface water systems using conventional filtration), or enhanced softening (for systems using lime softening).
- Operators are required to develop and implement a sample-monitoring plan for disinfectant residual and disinfection byproducts. The plan must be submitted to and approved by the state EPA. Disinfection residual monitoring compliance for total chlorine, including chloramines, is based on a running annual average, computed quarterly, of the monthly average of all samples collected under this rule. Disinfectant residual monitoring compliance for chlorine dioxide is based upon consecutive daily samples. Disinfectant residual monitoring is required at the same distribution point and time as total coliform monitoring. In addition, if the operator feeds ozone or chlorine dioxide, a sample monitoring plan for bromate or chlorite, respectively, must be submitted to and approved by the state EPA.

ARSENIC REMOVAL FROM DRINKING WATER

(Much of the following information is based on USEPA, 2000.) Operators may be familiar with the controversy created when newly elected President George W. Bush placed the pending arsenic standard on temporary hold. The President prevented implementation of the arsenic standard to give scientists time to review the standard, to take a closer look at the possible detrimental affects on the health and well-being of consumers in certain geographical areas of the United States, and to give economists time to determine the actual cost of implementation. President Bush's decision caused quite a stir, especially among environmentalists, the media, and others who felt that the arsenic standard should be enacted immediately to protect affected consumers. The President was aware of the emotional and political implications of shelving the arsenic standard and understood the staggering economical implications involved in implementing the new, tougher standard. Many view the President's decision as wrong, but others consider his decision to be the right one, basing their opinion on the old adage, "It is best to make scientific judgments based on good science instead of on 'feel good' science." Whether the reader shares the latter view or not, the point is that arsenic levels in potable water supplies must be reduced to a set level and in the future will have to be reduced to an even lower level. Accordingly, water treatment plants affected by the existing arsenic requirements and the pending tougher arsenic requirements should be familiar with the technologies for removal of arsenic from water supplies. In this section, we describe a number of these technologies.

ARSENIC EXPOSURE

Arsenic (As) is a naturally occurring element present in food, water, and air. Known for centuries to be an effective poison, some animal studies suggest that arsenic may be an essential nutrient at low concentrations. Nonmalignant skin alterations, such as keratosis and hypo- and hyperpigmentation, have been linked to arsenic ingestion, and skin cancers have developed in some patients. Additional studies indicate that arsenic ingestion may result in internal malignancies, including cancers of the kidney, bladder, liver, lung, and other organs. Vascular system effects have also been observed, including peripheral vascular disease, which in its most severe form results in gangrene or blackfoot disease. Other potential effects include neurologic impairment. The primary route of exposure to arsenic for humans is ingestion. Exposure via inhalation is considered minimal, although in some areas of the world elevated levels of airborne arsenic occur periodically (Hering and Chiu, 1998). Arsenic occurs in two primary forms: organic and inorganic. Organic species of arsenic are predominately found in foodstuffs, such as shellfish, and include such forms as monomethyl arsenic acid (MMAA), dimethyl arsenic acid (DMAA), and arseno-sugars. Inorganic arsenic occurs in two valence states, arsenite and arsenate. In natural surface waters arsenate is the dominant species.

ARSENIC REMOVAL TECHNOLOGIES

Some of the arsenic removal technologies discussed here are traditional treatment processes that have been tailored to improve removal of arsenic from drinking water. Several treatment techniques are at the experimental stage with regard to arsenic removal, and some have not been demonstrated at full scale. Although some of these processes may be technically feasible, their costs may be prohibitive. Technologies discussed in this section are grouped into four broad categories: *prescriptive processes*, *adsorptive processes*, *ion exchange processes*, and *separation* (membrane) *processes*. Each category is presented with at least one treatment technology.

Prescriptive Processes

Coagulation–Flocculation

Coagulation–flocculation is a treatment process by which the physical or chemical properties of dissolved, colloidal, or suspended matter are altered such that agglomeration is enhanced to an extent that the resulting particles will settle out of solution by gravity or will be removed by filtration. Coagulants change surface charge properties of solids to allow agglomeration and/or enmeshment of particles into a flocculated precipitate. In either case, the final products are larger particles, or floc, which more readily filter or settle under the influence of gravity.

The coagulation–flocculation process has traditionally been used to remove solids from drinking water supplies; however, the process is not restricted to the removal of particles. Coagulants render some dissolved species, such as natural organic matter (NOM), inorganics, and hydrophobic synthetic organic compounds (SOCs), insoluble, and the metal hydroxide particles produced by the addition of metal salt coagulants (typically aluminum sulfate, ferric chloride, or ferric sulfate) can adsorb other dissolved species. Major components of a basic coagulation–flocculation facility include chemical feed systems, mixing equipment, basins for rapid mix, flocculation, settling, filter media, sludge handling equipment, and filter backwash facilities. Settling may not be necessary in situations where the influent particle concentration is very low. Treatment plants without settling are known as direct filtration plants.

Iron/Manganese Oxidation

Iron/manganese (Fe/Mn) oxidation is commonly used by facilities treating groundwater. The oxidation process used to remove iron and manganese leads to the formation of hydroxides that remove soluble arsenic by precipitation or adsorption reactions. Arsenic removal during iron precipitation is fairly efficient. Removal of 2 mg/L of iron achieved a 92.5% removal of arsenic from an initial 10-µg/L arsenate concentration by adsorption alone. Even removal of 1 mg/L of iron resulted in the removal of 83% of influent arsenic from a source with 22 µg/L arsenate. Indeed, field studies of iron removal plants have indicated that this treatment can feasibly reach 3 g/L.

The removal efficiencies achieved by iron removal are not as high or as consistent as those realized by activated alumina or ion exchange (Edwards, 1994). Note, however, that arsenic removal during manganese precipitation is relatively ineffective when compared to iron even when removal by both adsorption and coprecipitation are considered. Precipitation of 3 mg/L manganese removed only 69% of arsenate in a 12.5-µg/L arsenate influent concentration.

Oxidation filtration technologies may be effective arsenic removal technologies. Research of oxidation filtration technologies has primarily focused on greensand filtration. As a result, the following discussion focuses on the effectiveness of greensand filtration as an arsenic removal technology. Substantial arsenic removal has been achieved using greensand filtration (Subramanian et al., 1997). The active material in greensand is glauconite, a green, iron-rich, clay-like mineral that has ion exchange properties. Glauconite often occurs in nature as small pellets mixed with other sand particles, giving a green color to the sand. The glauconite sand is treated with $KMnO_4$ until the sand grains are coated with a layer of manganese oxides, particularly manganese dioxide. The mechanisms behind this arsenic removal treatment are multifaceted and include oxidation, ion exchange, and adsorption. Arsenic compounds displace species from the manganese oxide (presumably OH^- and H_2O), becoming bound to the greensand surface—in effect, an exchange of ions occurs. The oxidative nature of the manganese surface converts arsenite to arsenate, and arsenate is adsorbed to the surface. As a result of the transfer of electrons and adsorption of arsenate, reduced manganese (Mn) is released from the surface.

The effectiveness of greensand filtration for arsenic filtration for arsenic removal is dependent on the influent water quality. Surmanian et al. (1997) demonstrated a strong correlation between influent Fe concentration and arsenic percent removal. Removal increased from 41% to more than 80% as the Fe/As ratio increased from 0 to 20 when treating a tap water with a spiked arsenite concentration of 200 mg/L. The tap water contained 366 mg/L sulfate and 321 mg/L total dissolved solids (TDS); neither constituent seemed to affect arsenic removal. The authors suggested that the influent manganese concentration may play an important role. Divalent ions, such as calcium, can also compete with arsenic for adsorption sites. Water quality would have to be carefully evaluated for applicability for treatment using greensand. Other researchers have also reported substantial arsenic removal using this technology, including arsenic removals of greater than 90% for treatment of groundwater.

As with other treatment media, greensand must be regenerated when its oxidative and adsorptive capacity has been exhausted. Greensand filters are regenerated using a solution of excess potassium permanganate ($KMnO_4$). Like other treatment media, the regeneration frequency will depend on the influent water quality in terms of constituents that will degrade the filter capacity. Regenerant disposal for greensand filtration has not been addressed in previous research.

Coagulation-Assisted Microfiltration

Arsenic is removed effectively by the coagulation process. Microfiltration is used as a membrane separation process to remove particulates, turbidity, and microorganisms. In coagulation-assisted microfiltration technology, microfiltration is used in a manner similar to a conventional gravity filter. The advantages of microfiltration over conventional filtration include (Muilenberg, 1997):

- More effective microorganism barrier during coagulation process upsets
- Removal of smaller floc sizes (smaller amounts of coagulants are required)
- Increased total plant capacity

Vickers et al. (1997) reported that microfiltration exhibited excellent arsenic removal capability. This report was corroborated by pilot studies conducted by Clifford et al. (1997), who found that coagulation-assisted microfiltration could reduce arsenic levels below 2 g/L in waters with a pH of between 6 and 7, even when the influent concentration of Fe was approximately 2.5 mg/L. These studies also found that the same level of arsenic removal could be achieved by this treatment process even if source water sulfate and silica levels were high. Further, coagulation-assisted microfiltration can reduce arsenic levels to an even greater extent at a slightly lower pH (approximately 5.5).

The addition of a coagulant did not significantly affect the membrane-cleaning interval, although the solids level to the membrane system increased substantially. With an iron and manganese removal system, it is critical that all of the iron and manganese be fully oxidized before reaching the membrane to prevent fouling (Muilenberg, 1997).

Enhanced Coagulation

The Disinfectant/Disinfection Byproduct (D/DBP) Rule requires the use of enhanced coagulation treatment for the reduction of disinfection byproduct precursors for surface water systems that have sedimentation capabilities. The enhanced process involves modifications to the existing coagulation process such as increasing the coagulant dosage or reducing the pH, or both. Cheng et al. (1994) conducted bench-, pilot-, and demonstration-scale studies to examine arsenate removals during enhanced coagulation. The enhanced coagulation conditions in these studies included an increase in alum and ferric chloride coagulant dosage from 10 to 30 mg/L or a decrease in pH from 7 to 5.5, or both. Results from these studies indicated the following:

- Greater than 90% arsenate removal can be achieved under enhanced coagulation conditions. Arsenate removals greater than 90% were easily attained under all conditions when ferric chloride was used.
- Enhanced coagulation using ferric salts is more effective for arsenic removal than enhanced coagulation using alum. At an influent arsenic concentration of 5 μg/L, ferric chloride achieved 96% arsenate removal with a dosage of 10 mg/L and no acid addition. When alum was used, 90% arsenate removal could not be achieved without reducing the pH.
- Lowering pH during enhanced coagulation improved arsenic removal by alum coagulation. With ferric coagulation, pH does not have a significant effect between 5.5 and 7.0.

Note: Posttreatment pH adjustment may be required for corrosion control when the process is operated at a low pH.

Lime Softening

Recall that hardness is predominately caused by calcium and magnesium compounds in solution. Lime softening removes this hardness by creating a shift in the carbonate equilibrium. The addition of lime to water raises the pH. Bicarbonate is converted to carbonate as the pH increases, and as a result calcium is precipitated as calcium carbonate. Soda ash (sodium carbonate) is added if insufficient bicarbonate is present in the water to remove hardness to the desired level. Softening for calcium removal is typically accomplished at a pH range of 9 to 9.5. For magnesium removal, excess lime is added beyond the point of calcium carbonate precipitation. Magnesium hydroxide precipitates at pH levels greater than 10.5. Neutralization is required if the pH of the softened water is excessively high (above 9.5) for potable use. The most common form of pH adjustment in softening plants is recarbonation with carbon dioxide.

Lime softening has been widely used in the United States for reducing hardness in large water treatment systems. Lime softening, excess lime treatment, split lime treatment, and lime–soda softening are all common in municipal water systems. All of these treatment methods are effective in reducing arsenic. Considerable amounts of sludge are produced in a lime softening system, and its disposal is expensive. Large-capacity systems may find it economically feasible to install recalcination equipment to recover and reuse the lime sludge and thus reduce disposal problems. Construction of a new lime softening plant for the removal of arsenic would not generally be recommended unless hardness must also be reduced.

Adsorptive Processes

Activated Alumina

Activated alumina is a physicochemical process by which ions in the feed water are sorbed to the oxidized activated alumina surface. Activated alumina is considered an adsorption process, although the chemical reactions involved are actually an exchange of ions. Activated alumina is prepared through dehydration of $Al(OH)_3$ at high temperatures and consists of amorphous and gamma alumina oxide (AWWA, 1990; Clifford et al., 1985). Activated alumina is used in packed beds to remove contaminants such as fluoride, arsenic, selenium, silica, and NOM. Feed water is continuously passed through the bed to remove contaminants. The contaminant ions are exchanged with the surface hydroxides on the alumina. When adsorption sites on the activated alumina surface become filled, the bed must be regenerated. Regeneration is accomplished through a sequence of rinsing with regenerant, flushing with water, and neutralizing with acid. The regenerant is a strong base, typically sodium hydroxide; the neutralizer is a strong acid, typically sulfuric acid. Many studies have shown that activated alumina is an effective treatment technique for arsenic removal. Factors such as pH, arsenic oxidation state, competing ions, empty bed contact time, and regeneration have significant effects on the removals achieved with activated alumina. Other factors include spent regenerant disposal, alumina disposal, and secondary water quality.

Ion Exchange

Ion exchange is a physicochemical process by which an ion on the solid phase is exchanged for an ion in the feed water. This solid phase is typically a synthetic resin that has been chosen to preferentially adsorb the particular contaminant of concern. To accomplish this exchange of ions, feed water is continuously passed through a bed of ion exchange resin beads in a downflow or upflow mode until the resin is exhausted. Exhaustion occurs when all sites on the resin beads have been filled by contaminant ions. At this point, the bed is regenerated by rinsing the ion exchange column with a regenerant—a concentrated solution of ions initially exchanged from the resin. The number of bed volumes that can be treated before exhaustion varies with resin type and influent water quality. Typically, from 300 to 60,000 bed volume (BV) can be treated before regeneration is required. In most cases, regeneration of the bed can be accomplished with only 1 to 5 BV of regenerant followed by 2 to 20 BV of rinse water. Important considerations in the applicability of the ion exchange process for removal of a contaminant include water quality parameters such as pH, competing ions, resin type, alkalinity, and influent arsenic concentration. Other factors include the affinity of the resin for the contaminant, spent regenerant and resin disposal requirements, secondary water quality effects, and design operating parameters.

Membrane Processes

Membranes are a selective barrier, allowing some constituents to pass while blocking the passage of others. The movement of constituents across a membrane requires a driving force (i.e., a potential difference between the two sides of the membrane). Membrane processes are often classified by the type of driving force, including pressure, concentration, electrical potential, and temperature. The processes discussed here include only pressure-driven and electrical potential-driven types.

Pressure-driven membrane processes are often classified by pore size into four categories: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). NF and UF are high-pressure processes. Typical pressure ranges for these processes are given in Table 8.19. NF and RO primarily remove constituents through chemical diffusion. MF and UF primarily remove constituents through physical sieving. An advantage of high-pressure processes is that they tend to remove a broader range of constituents than low-pressure processes; however, the drawback to broader removal is the increase in energy required for high-pressure processes (Aptel and Buckley, 1996). Electrical potential-driven membrane processes can also be used for arsenic removal. These

TABLE 8.19
Typical Pressure Ranges for Membrane Processes

Membrane Process	Pressure Range (psi)
Microfiltration (MF)	5–45
Ultrafiltration (UF)	7–100
Nanofiltration (NF)	50–150
Reverse osmosis (RO)	100–150

processes include, for the purposes of this document, only electrodialysis reversal (EDR). In terms of achievable contaminant removal, EDR is comparable to RO. The separation process used in EDR, however, is ion exchange.

Alternative Technologies

Iron-Oxide-Coated Sand

Iron-oxide-coated sand is a rare process that has shown some tendency for arsenic removal. Iron-oxide-coated sand consists of sand grains coated with ferric hydroxide which are used in fixed-bed reactors to remove various dissolved metal species. The metal ions are exchanged with the surface hydroxides on the iron-oxide-coated sand. Iron-oxide-coated sand exhibits selectivity in the adsorption and exchange of ions present in the water. Like other processes, when the bed is exhausted it must be regenerated by a sequence of operations consisting of rinsing with regenerant, flushing with water, and neutralizing with strong acid. Sodium hydroxide is the most common regenerant and sulfuric acid the most common neutralizer. Several studies have shown that iron-oxide-coated sand is effective for arsenic removal, depending on such factors such as pH, arsenic oxidation state, competing ions, and regeneration.

Sulfur-Modified Iron

A patented sulfur-modified iron (SMI) process for arsenic removal (Hydrometrics, 1998) consists of three components: (1) finely divided metallic iron, (2) powdered elemental sulfur or other sulfur compounds, and (3) an oxidizing agent. The powdered iron, powdered sulfur, and oxidizing agent (H_2O_2 in preliminary tests) are thoroughly mixed and then added to the water to be treated. The oxidizing agent serves to convert arsenite to arsenate. The solution is then mixed and settled. Using the sulfur-modified iron process on several water types, high adsorptive capacities were obtained with a final arsenic concentration of 0.050 mg/L. Arsenic removal was influenced by pH. Approximately 20 mg/L arsenic per gram of iron was removed at pH 8, and 50 mg arsenic per gram of iron was removed at pH 7. Arsenic removal seems to be very dependent on the iron-to-arsenic ratio.

Packed-bed column tests demonstrated significant arsenic removal at residence times of 5 to 15 minutes. Significant removal of both arsenate and arsenite was measured. The highest adsorption capacity measured was 11 mg arsenic removed per gram of iron. Flow distribution problems were evident, as several columns became partially plugged, and better arsenic removal was observed with reduced flow rates.

Spent media from the column tests were classified as nonhazardous waste. Projected operating costs for sulfur-modified iron, when the process is operated below a pH of 8, are much lower than alternative arsenic removal technologies such as ferric chloride addition, reverse osmosis, and activated alumina. Cost savings would increase proportionally with increased flow rates and increased arsenic concentrations.

Possible treatment systems using sulfur-modified iron include continuous stirred tank reactors, packed-bed reactors, fluidized bed reactors, and passive *in situ* reactors. Packed-bed and fluidized bed reactors appear to be the most promising for successful arsenic removal in pilot-scale and full-scale treatment systems based on current knowledge of the sulfur-modified iron process.

Granular Ferric Hydroxide

A new removal technique for arsenate that has recently been developed at the Technical University of Berlin, Department of Water Quality Control, is adsorption on granular ferric hydroxide (GFH) in fixed-bed reactors. This technique combines the advantages of the coagulation–filtration process (efficiency and small residual mass) with the fixed-bed adsorption on activated alumina and sample processing. Demers and Renner (1992) reported that the application of granular ferric hydroxide in test adsorbers showed a high treatment capacity of 30,000 to 40,000 BV with an effluent arsenate concentration never exceeding 10 µm/L. The typical residual mass was in the range of 5 to 25 g/m^3 treated water. The residue was a solid with an arsenate content of 1 to 10 g/kg.

The competition of sulfate on arsenate adsorption was not very strong. Phosphate, however, competed strongly with arsenate, which reduced arsenate removal with GFH. Arsenate adsorption decreased with pH, which is typical for anion adsorption. At high pH values, GFH outperformed alumina. Below a pH of 7.6, the performance is comparable. A field study reported by Simms et al. (2000) confirmed the efficacy of GFH for arsenic removal. Over the course of this study, a 5.3-MGD GHF facility located in the United Kingdom was found to reliably and consistently reduce average influent arsenic concentrations of 20 g/L to less than 10 g/L for 200,000 BV (over a year of operation) at an empty bed contact time (EBCT) of 3 minutes. Despite insignificant head loss, routine backwashing was conducted on a monthly basis to maintain media condition and to reduce the possibility of bacterial growth. The backwash was not hazardous and could be recycled or disposed to a sanitary sewer. At the time of replacement, arsenic loading on the media was 2.3%. Leachate tests conducted on the spent media found that arsenic did not leach from the media.

The most significant weakness of this technology appears to be its cost. Currently, GFH media costs approximately $4000 per ton; however, if a GFH bed can be used several times longer than an alumina bed, for example, it may prove to be the more cost-effective technology. Indeed, the system profiled in the field study presented here tested activated alumina as well as GFH and found the GFH was sufficiently more efficient that smaller adsorption vessels and smaller quantities of media could be used to achieve the same level of arsenic removal (reducing costs). In addition, unlike activated alumina, GFH does not require preoxidation.

A treatment for leaching arsenic from the media to enable regeneration of GFH seems feasible, but it results in the generation of an alkaline solution with high levels of arsenate, which requires further treatment to obtain a solid waste. Thus, direct disposal of spent GFH should be favored.

Iron Filings

Iron filings and sand may be used to reduce inorganic arsenic species to iron coprecipitates, mixed precipitates, and, in conjunction with sulfates, arsenopyrites. This type of process is essentially a filter technology, much like greensand filtration, wherein the source water is filtered through a bed of sand and iron filings. Unlike some technologies (ion exchange, for example), sulfate is actually introduced in this process to encourage arsenopyrite precipitation. This arsenic removal method was originally developed as a batch arsenic remediation technology. It appears to be quite effective in this use. Bench-scale tests indicate an average removal efficiency of 81% with much higher removals at lower influent concentrations. This method was tested at arsenic levels of 20,000 ppb and at 2000 ppb and consistently reduced arsenic levels to less than 50 ppb (the current MCL). Although it is quite effective in this capacity, its use as a drinking water treatment technology appears to be limited. In batch tests, a residence time of approximately 7 days was required to reach the desired arsenic removal. In flowing conditions, even though removals averaged 81% and reached greater than 95% at 2000 ppb arsenic, there is no indication that this technology can reduce arsenic levels to below approximately 25 ppb. No data are available that indicate how the technology can reduce arsenic levels below approximately 25 ppb, nor do data exist regarding how the technology performs at normal source water arsenic levels. This technology must be further evaluated before it can be recommended as an approved arsenic removal technology for drinking water.

Photooxidation

Researchers at the Australian Nuclear Science and Technology Organization (ANSTO) have found that, in the presence of light and naturally occurring light-absorbing materials, the oxidation rate of arsenite by oxygen can be increased 10,000-fold. The oxidized arsenic, now arsenate, can then be effectively removed by coprecipitation. ANSTO evaluated both UV lamp reactors and sunlight-assisted photooxidation using acidic, metal-bearing water from an abandoned gold, silver, and lead mine. Air sparging was required for sunlight-assisted oxidation due to the high initial arsenate concentration (12 mg/L). Tests demonstrated that near-complete oxidation of arsenite could be achieved using the photochemical process. Analysis of process waters indicated that 97% of the arsenic in the process stream was present as arsenate. Researchers concluded that arsenite was preferentially oxidized in the presence of excess dissolved Fe (22:1 iron-to-arsenic mole ratio). This is in contrast to conventional plants where dissolved iron represents an extra chemical oxidant demand that has to be satisfied during oxidation of arsenite (ANSTO, 1999).

Photooxidation of the mine water followed by coprecipitation reduced arsenic concentrations to as low as 17 g/L, which meets the current MCL for arsenic. Initial total arsenic concentrations were unknown, although the arsenite concentration was given as approximately 12 mg/L, which is considerably higher than typical raw water arsenic concentrations. ANSTO reported that residuals from this process are environmentally stable and passed the Toxicity Characteristic Leaching Procedure (TCLP) test necessary to declare waste nonhazardous suitable for landfill disposal. Based on the removals achieved and residuals characteristics, it is expected that photooxidation followed by coprecipitation would be an effective arsenic removal technology; however, this technology is still largely experimental and should be further evaluated before being recommended as an approved arsenic removal technology for drinking water.

WASTEWATER TREATMENT

Regulations were established in the late 1970s and early 1980s under 40 CFR Part 403 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, and cause the POTW to have an effluent violation or increase 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.

Unit operations (unit processes), which are the components that are linked together to form a process train (as shown in Figure 8.8; keep in mind the caboose attached to this train is treated and cleaned wastewater, which when outfalled is usually cleaner than the water in the receiving body), are commonly divided on the basis of the fundamental mechanisms acting with them (i.e., physical, chemical, and biochemical). Physical operations are those, such as sedimentation, that are governed by the laws of physics (gravity). Chemical operations are those in which strictly chemical reactions occur, such as precipitation. Biochemical operations are those that use living microorganisms to destroy or transform pollutants through enzymatically catalyzed chemical reactions (Grady et al., 2011).

Figure 8.8 shows a basic schematic or model of a wastewater treatment process that provides primary and secondary treatment using the *activated sludge* process. In secondary treatment, which provides biochemical oxygen demand (BOD) removal beyond what is achievable by simple sedimentation, three approaches are commonly used: trickling filter, activated sludge, and oxidation ponds. These systems are discussed in detail later in the text, as are biological nutrient removal (BNR) and standard tertiary or advanced wastewater treatment. The purpose of the model shown in Figures 8.8 is to allow readers to visually follow the water and wastewater treatment processes step-by-step as they are presented in this text. The figures will help the reader

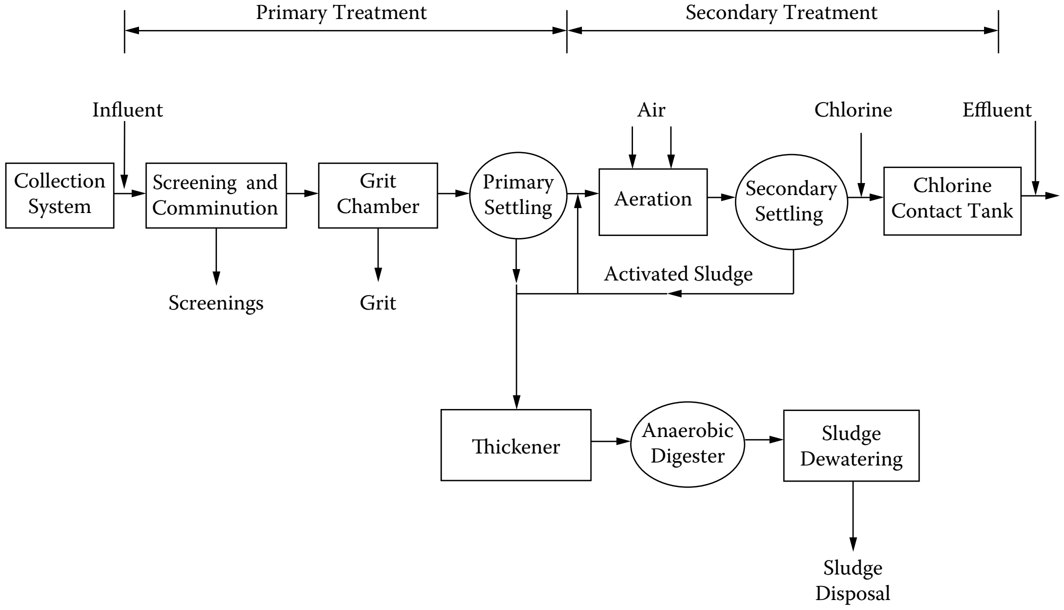

FIGURE 8.8 Schematic of an example wastewater treatment process providing primary and secondary treatment using the activated sludge process.

understand how all the various unit processes sequentially follow and tie into each other. This format simply provides a pictorial presentation along with pertinent written information to enhance the learning process. Thus, it logically follows that a pictorial presentation along with pertinent written information enhance the learning process. It should also be pointed out, however, that even though the model shown in Figure 8.8 does not include all unit processes currently used in wastewater treatment we do not ignore the other major processes: trickling filters, rotating biological contactors (RBCs), and oxidation ponds.

WASTEWATER TERMINOLOGY AND DEFINITIONS

Wastewater treatment technology, like many other technical fields, has its own unique terms with their own meanings. Although some of the terms are unique, many are common to other professions. Remember that the science of wastewater treatment is a combination of engineering, biology, mathematics, hydrology, chemistry, physics, and other disciplines; therefore, many of the terms used in engineering, biology, mathematics, hydrology, chemistry, physics, and other fields are also used in wastewater treatment. Those terms not listed or defined in the following section will be defined as they appear in the text.

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

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

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

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

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

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

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

Biochemical oxygen demand (BOD)—The oxygen used to meet the metabolic needs of aerobic microorganisms in water that is rich in organic matter.

Biosolids[*]—Solid organic matter recovered from a sewage treatment process and used especially as fertilizer [or soil amendment]—usually used in plural (*Merriam-Webster's Collegiate Dictionary*, 10th ed., 1998).

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

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

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

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

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

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

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

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

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

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

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

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

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

Dissolved oxygen (DO)—Free or elemental oxygen dissolved in water.

Effluent—The flow leaving a tank, channel, or treatment process.

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

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

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

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

Flume—A flow-rate measurement device.

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

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

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

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

Industrial wastewater—Wastes associated with industrial manufacturing processes.

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

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

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

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

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

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

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

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

Inorganic—Refers to mineral materials such as salt, ferric chloride, iron, sand, or gravel.

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

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

Mixed liquor—A mixture of activated sludge and water containing organic matter undergoing activated sludge treatment in an aeration tank.

Mixed liquor suspended solids (MLSS)—The suspended solids concentration of mixed liquor.

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

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

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

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

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

Organic—Refers to materials that consist of carbon, hydrogen, oxygen, sulfur, and nitrogen. Many organics are biologically degradable. All organic compounds can be converted to carbon dioxide and water when subjected to high temperatures.

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

Pathogenic—Disease causing; a pathogenic organism is capable of causing illness.

Point source—Any discernible, defined, discrete conveyance from which pollutants are or may be discharged.

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

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

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

Septic—Refers to a wastewater that has no dissolved oxygen present; generally characterized by black color and rotten egg (hydrogen sulfide) odors.

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

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

Sewage—Wastewater containing human wastes.

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

Sludge retention time—See mean cell residence time.

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

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

Stormwater—Runoff resulting from rainfall and snowmelt.

Supernatant—The liquid standing above a sediment or precipitate.

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

Wastewater—The water supply of a community after it has been soiled by use.

Weir—A device used to measure wastewater flow.

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

MEASURING PLANT PERFORMANCE

To evaluate how well a plant or unit process is performing, performance efficiency or percent removal is used. The results obtained can be compared with those listed in the plant's O&M manual to determine if the facility is performing as expected. In this section, sample calculations often used to measure plant performance or efficiency are presented.

Plant Performance and Efficiency

The calculation used for determining the performance (percent removal) for a digester is different from that used for performance (percent removal) for other processes. Care must be taken to select the correct formula:

$$\%\ \text{Removal} = \frac{(\text{Influent concentration} - \text{Effluent concentration}) \times 100}{\text{Influent concentration}} \tag{8.14}$$

■ EXAMPLE 8.5

Problem: The influent BOD_5 is 247 mg/L, and the plant effluent BOD is 17 mg/L. What is the percent removal?

Solution:

$$\%\ \text{Removal} = \frac{(247\ \text{mg/L} - 17\ \text{mg/L}) \times 100}{247\ \text{mg/L}} = 93\%$$

Equation 8.14 is again used to determine unit process efficiency. The concentration entering the unit and the concentration leaving the unit (e.g., primary, secondary) are used to determine the unit performance:

$$\%\ \text{Removal} = \frac{(\text{Influent concentration} - \text{Effluent concentration}) \times 100}{\text{Influent concentration}}$$

■ EXAMPLE 8.6

Problem: The primary influent BOD is 235 mg/L, and the primary effluent BOD is 169 mg/L. What is the percent removal?

$$\%\ \text{Removal} = \frac{(235\ \text{mg/L} - 169\ \text{mg/L}) \times 100}{235\ \text{mg/L}} = 28\%$$

Percent Volatile Matter Reduction in Sludge

The calculation used to determine *percent volatile matter reduction* is more complicated because of the changes occurring during biosolids digestion:

$$\%\text{VM reduction} = \frac{(\%\text{VM}_{\text{in}} - \%\text{VM}_{\text{out}}) \times 100}{\%\text{VM}_{\text{in}} - (\%\text{VM}_{\text{in}} \times \%\text{VM}_{\text{out}})} \tag{8.15}$$

■ EXAMPLE 8.7

Problem: Using the digester data provided below, determine the percent volatile matter reduction for the digester.

Raw biosolids volatile matter = 74%
Digested biosolids volatile matter = 54%

Solution:

$$\%\text{VM reduction} = \frac{(0.74 - 0.54) \times 100}{0.74 - (0.74 \times 0.54)} = 59\%$$

Hydraulic Detention Time

The term *detention time* or *hydraulic detention time* (HDT) refers to the average length of time (theoretical time) a drop of water, wastewater, or suspended particles remains in a tank or channel. It is calculated by dividing the water/wastewater in the tank by the flow rate through the tank. The units of flow rate used in the calculation are dependent on whether the detention time is to be calculated in seconds, minutes, hours, or days. Detention time is used in conjunction with various treatment processes, including sedimentation and coagulation–flocculation. Generally, in practice, detention time is associated with the amount of time required for a tank to empty. The range of detention time varies with the process; for example, in a tank used for sedimentation, detention time is commonly measured in minutes. The calculation methods used to determine detention time are illustrated in the following sections.

Hydraulic Detention Time in Days

$$\text{HDT (days)} = \frac{\text{Tank volume (ft}^3) \times 7.48 \text{ gal/ft}^3}{\text{Flow (gal/day)}} \tag{8.16}$$

■ EXAMPLE 8.8

Problem: An anaerobic digester has a volume of 2,400,000 gal. What is the detention time in days when the influent flow rate is 0.07 MGD?

Solution:

$$\text{HDT (days)} = \frac{2{,}400{,}000 \text{ gal}}{0.07 \text{ MGD} \times 1{,}000{,}000 \text{ gal/MG}} = 34 \text{ days}$$

Hydraulic Detention Time in Hours

$$\text{HDT (hr)} = \frac{\text{Tank volume (ft}^3) \times 7.48 \text{ gal/ft}^3 \times 24 \text{ hr/day}}{\text{Flow (gal/day)}} \tag{8.17}$$

■ EXAMPLE 8.9

Problem: A settling tank has a volume of 44,000 ft³. What is the detention time in hours when the flow is 4.15 MGD?

Solution:

$$\text{HDT} = \frac{44{,}000 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 \times 24 \text{ hr/day}}{4.15 \text{ MGD} \times 1{,}000{,}000 \text{ gal/MG}} = 1.9 \text{ hr}$$

Detention Time in Minutes

$$\text{HDT (min)} = \frac{\text{Tank volume (ft}^3) \times 7.48 \text{ gal/ft}^3 \times 1440 \text{ min/day}}{\text{Flow (gal/day)}} \tag{8.18}$$

■ EXAMPLE 8.10

Problem: A grit channel has a volume of 1340 ft³. What is the detention time in minutes when the flow rate is 4.3 MGD?

Solution:

$$\text{HDT} = \frac{1340 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 \times 1440 \text{ min/day}}{4{,}300{,}000 \text{ gal/day}} = 3.36 \text{ min}$$

Note: The tank volume and the flow rate must be in the same dimensions before calculating the hydraulic detention time.

WASTEWATER SOURCES AND CHARACTERISTICS

Wastewater treatment is designed to use the natural purification processes (self-purification processes of streams and rivers) to the maximum level possible. It is also designed to complete these processes in a controlled environment rather than over many miles of stream or river. Moreover, the treatment plant is also designed to remove other contaminants that are not normally subjected to natural processes, in addition to treating the solids that are generated through the treatment unit steps. The typical wastewater treatment plant is designed to achieve many different purposes:

- Protect public health.
- Protect public water supplies.
- Protect aquatic life.
- Preserve the best uses of the waters.
- Protect adjacent lands.

Wastewater treatment is a series of steps. Each of the steps can be accomplished using one or more treatment processes or types of equipment. The major categories of treatment steps are as follows:

1. *Preliminary treatment*—Removes materials that could damage plant equipment or would occupy treatment capacity without being treated
2. *Primary treatment*—Removes settleable and floatable solids (may not be present in all treatment plants)
3. *Secondary treatment*—Removes BOD_5 and dissolved and colloidal suspended organic matter by biological action; organics are converted to stable solids, carbon dioxide, and more organisms
4. *Advanced wastewater treatment*—Uses physical, chemical, and biological processes to remove additional BOD_5, solids, and nutrients (not present in all treatment plants)
5. *Disinfection*—Removes microorganisms to eliminate or reduce the possibility of disease when the flow is discharged
6. *Sludge treatment*—Stabilizes the solids removed from wastewater during treatment, inactivates pathogenic organisms, and reduces the volume of the sludge by removing water.

The various treatment processes described above are discussed in detail later.

Wastewater Sources

The principal sources of domestic wastewater in a community are the residential areas and commercial districts. Other important sources include institutional and recreational facilities, stormwater (runoff), and groundwater (infiltration). Each source produces wastewater with specific characteristics. In this section, wastewater sources and the specific characteristics of wastewater are described.

Generation of Wastewater

Wastewater is generated by five major sources: human and animal wastes, household wastes, industrial wastes, stormwater runoff, and groundwater infiltration:

- *Human and animal wastes*—Wastes that contain the solid and liquid discharges of humans and animals and are considered by many to be the most dangerous from a human health viewpoint. The primary health hazard is presented by the millions of bacteria, viruses, and other microorganisms (some of which may be pathogenic) present in the waste stream.
- *Household wastes*—Wastes, other than human and animal wastes, discharged from the home. Household wastes usually contain paper, household cleaners, detergents, trash, garbage, and other substances homeowners discharge into the sewer system.

- *Industrial wastes*—Materials discharged from industrial processes into the collection system. Industrial wastes typically contain chemicals, dyes, acids, alkalis, grit, detergents, and highly toxic materials.
- *Stormwater runoff*—Many collection systems are designed to carry both the wastes of the community and stormwater runoff. In this type of system, when a storm event occurs the waste stream can contain large amounts of sand, gravel, and other grit as well as excessive amounts of water.
- *Groundwater infiltration*—Groundwater will enter older, improperly sealed collection systems through cracks or unsealed pipe joints. This can add not only large amounts of water to wastewater flows but also additional grit.

Classification of Wastewater

Wastewater can be classified according to the sources of flows:

- *Domestic (sewage) wastewater*—Mainly contains human and animal wastes, household wastes, small amounts of groundwater infiltration, and small amounts of industrial wastes.
- *Sanitary wastewater*—Consists of domestic wastes and significant amounts of industrial wastes. In many cases, the industrial wastes can be treated without special precautions; however, in some cases the industrial wastes will require special precautions or a pretreatment program to ensure that the wastes do not cause compliance problems for the wastewater treatment plant.
- *Industrial wastewater*—Industrial wastes only; often, the industry will determine that it is safer and more economical to treat its waste independent of domestic waste.
- *Combined wastewater*—The combination of sanitary wastewater and stormwater runoff. All of the wastewater and stormwater of the community is transported through one system to the treatment plant.
- *Stormwater*—A separate collection system (no sanitary waste) that carries stormwater runoff including street debris, road salt, and grit.

Wastewater Characteristics

Wastewater contains many different substances that can be used to characterize it. The specific substances and amounts or concentrations of each will vary, depending on the source; thus, it is difficult to precisely characterize wastewater. Instead, wastewater characterization is usually based on and applied to an average domestic wastewater. Wastewater is characterized in terms of its physical, chemical, and biological characteristics.

Note: Keep in mind that other sources and types of wastewater can dramatically change the characteristics.

Physical Characteristics

The physical characteristics of wastewater are based on color, odor, temperature, and flow:

- *Color*—Fresh wastewater is usually a light brownish-gray color; however, typical wastewater is gray and has a cloudy appearance. The color of the wastewater will change significantly if allowed to go septic (if travel time in the collection system increases). Typical septic wastewater will have a black color.
- *Odor*—Odors in domestic wastewater are usually caused by gases produced by the decomposition of organic matter or by other substances added to the wastewater. Fresh domestic wastewater has a musty odor. If the wastewater is allowed to go septic, this odor will change significantly to a rotten-egg odor associated with the production of hydrogen sulfide (H_2S).

- *Temperature*—The temperature of wastewater is commonly higher than that of the water supply because of the addition of warm water from households and industrial plants; however, significant amounts of infiltration or stormwater flow can cause major temperature fluctuations.
- *Flow*—The actual volume of wastewater is commonly used as a physical characterization of wastewater and is normally expressed in terms of gallons per person per day. Most treatment plants are designed using an expected flow of 100 to 200 gallons per person per day. This figure may have to be revised to reflect the degree of infiltration or storm flow the plant receives. Flow rates will vary throughout the day. This variation, which can be as much as 50 to 200% of the average daily flow, is known as the *diurnal flow variation*.

Note: *Diurnal* means "occurs in a day or each day; daily."

Chemical Characteristics

When describing the chemical characteristics of wastewater, the discussion generally includes topics such as organic matter, the measurement of organic matter, inorganic matter, and gases. For the sake of simplicity, in this handbook we specifically describe chemical characteristics in terms of alkalinity, biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved gases, nitrogen compounds, pH, phosphorus, solids (organic, inorganic, suspended, and dissolved solids), and water:

- *Alkalinity* is a measure of the capability of the wastewater to neutralize acids. It is measured in terms of bicarbonate, carbonate, and hydroxide alkalinity. Alkalinity is essential to buffer (hold the neutral pH of) the wastewater during the biological treatment processes.
- *Biochemical oxygen demand (BOD)* is a measure of the amount of biodegradable matter in the wastewater. It is normally measured by a 5-day test conducted at 20°C. The BOD_5 domestic waste is normally in the range of 100 to 300 mg/L.
- *Chemical oxygen demand (COD)* is a measure of the amount of oxidizable matter present in the sample. The COD is normally in the range of 200 to 500 mg/L. The presence of industrial wastes can increase this significantly.
- *Dissolved gases* are gases that are dissolved in wastewater. The specific gases and normal concentrations are based on the composition of the wastewater. Typical domestic wastewater contains oxygen in relatively low concentrations, carbon dioxide, and hydrogen sulfide (if septic conditions exist).
- The type and amount of *nitrogen compounds* present will vary from the raw wastewater to the treated effluent. Nitrogen follows a cycle of oxidation and reduction. Most of the nitrogen in untreated wastewater will be in the forms of organic nitrogen and ammonia nitrogen. Laboratory tests exist for determination of both of these forms. The sum of these two forms of nitrogen is also measured and is known as *total Kjeldahl nitroge*n (TKN). Wastewater will normally contain between 20 to 85 mg/L of nitrogen. Organic nitrogen will normally be in the range of 8 to 35 mg/L, and ammonia nitrogen will be in the range of 12 to 50 mg/L.
- *pH* is used to express the acid condition of the wastewater. pH is expressed on a scale of 1 to 14. For proper treatment, wastewater pH should normally be in the range of 6.5 to 9.0 (ideal is 6.5 to 8.0).
- *Phosphorus* is essential to biological activity and must be present in at least minimum quantities or secondary treatment processes will not perform. Excessive amounts can cause stream damage and excessive algal growth. Phosphorus will normally be in the range of 6 to 20 mg/L. The removal of phosphate compounds from detergents has had a significant impact on the amounts of phosphorus in wastewater.
- Most pollutants found in wastewater can be classified as *solids*. Wastewater treatment is generally designed to remove solids or to convert solids to a form that is more stable or can be removed. Solids can be classified by their chemical composition (organic or inorganic) or

by their physical characteristics (settleable, floatable, and colloidal). Concentrations of total solids in wastewater are normally in the range of 350 to 1200 mg/L.

  - *Organic solids* consist of carbon, hydrogen, oxygen, and nitrogen and can be converted to carbon dioxide and water by ignition at 550°C; they are also known as *fixed solids* or *loss on ignition*.
  - *Inorganic solids* are mineral solids that are unaffected by ignition; they are also known as *fixed solids* or *ash*.
  - *Suspended solids* will not pass through a glass-fiber filter pad; they can be further classified as total suspended solids (TSS), volatile suspended solids, and fixed suspended solids. They can also be separated into three components based on settling characteristics: settleable solids, floatable solids, and colloidal solids. Total suspended solids in wastewater are normally in the range of 100 to 350 mg/L.
  - *Dissolved solids* will pass through a glass-fiber filter pad. They can also be classified as total dissolved solids (TDS), volatile dissolved solids, and fixed dissolved solids. Total dissolved solids are normally in the range of 250 to 850 mg/L.
- *Water* is always the major constituent of wastewater. In most cases, water makes up 99.5 to 99.9% of the wastewater. Even in the strongest wastewater, the total amount of contamination present is less than 0.5% of the total, and in average-strength wastes it is usually less than 0.1%.

Biological Characteristics and Processes

After undergoing the physical aspects of treatment (i.e., screening, grit removal, and sedimentation) in preliminary and primary treatment, wastewater still contains some suspended solids and other solids that are dissolved in the water. In a natural stream, such substances are a source of food for protozoa, fungi, algae, and several varieties of bacteria. In secondary wastewater treatment, these same microscopic organisms (which are one of the main reasons for treating wastewater) are allowed to work as fast as they can to biologically convert the dissolved solids to suspended solids that will physically settle out at the end of secondary treatment. Raw wastewater influent typically contains millions of organisms. The majority of these organisms are not pathogenic; however, several pathogenic organisms may also be present (these may include the organisms responsible for diseases such as typhoid, tetanus, hepatitis, dysentery, gastroenteritis, and others). Many of the organisms found in wastewater are microscopic (microorganisms); they include algae, bacteria, protozoa (such as amoeba, flagellates, free-swimming ciliates, and stalked ciliates), rotifers, and viruses. Table 8.20 provides a summary of typical domestic wastewater characteristics.

TABLE 8.20
Typical Domestic Wastewater Characteristics

Characteristic	Typical Characteristic
Color	Gray
Odor	Musty
Dissolved oxygen	>1.0 mg/L
pH	6.5–9.0
TSS	100–350 mg/L
BOD_5	100–300 mg/L
COD	200–500 mg/L
Flow	100–200 gallons per person per day
Total nitrogen	20–85 mg/L
Total phosphorus	6–20 mg/L
Fecal coliform	500,000–3,000,000 MPN/100 mL

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.

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 system lines at a reasonable depth, wastewater must be lifted (pumped) periodically so it can continue flowing downhill to the treatment plant. Pump stations are installed at selected points within the system for this purpose.

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, as the contents of the lines are under pressure.

> ***Note:*** Extra care must be taken when performing maintenance on force main systems because the contents of the collection system are under pressure.

Vacuum 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 of collection systems are not economically feasible.

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.

Wet Well/Dry Well Pumping Stations

The wet well/dry well pumping station consists of two separate spaces or sections separated by a common wall. Wastewater is collected in one section (wet well section) and the pumping equipment (and, in many cases, the motors and controllers) are 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 when selecting the centrifugal design are that (1) it allows for the separation of mechanical equipment (pumps, motors, controllers, wiring, etc.) from the potentially corrosive atmosphere (sulfides) of the wastewater, and (2) it is usually safer for workers because they can monitor, maintain, operate, and repair equipment without entering the pumping station wet well.

> ***Note:*** Most pumping station wet wells are confined spaces. To ensure safe entry into such spaces compliance with OSHA's 29 CFR 1910.146 (Confined Space Entry Standard) is required.

Wet Well Pumping Stations

Another type of pumping station design is the wet well type. The wet well consists of a single compartment that collects the wastewater flow. The pump is submerged in the wastewater with motor controls located in the space or has a weatherproof motor housing located above the wet well. In this type of station, a submersible centrifugal pump is normally used.

Pneumatic Pumping Stations

The pneumatic pumping station consists of a wet well and a control system that controls the inlet and outlet valve operations and provides pressurized air to force or push the wastewater through the system. The exact method of operation depends on the system design. When 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 waste stream out the discharge line.

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 (to check the pumping rate of the constant speed pump) or pump capacity with influent (to check how many gallons per minute the pump is discharging). In this section, we use examples to describe instances when these two calculations are made.

■ EXAMPLE 8.11

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 information, we can find the volume of water removed by the pump during the test:

$$\text{Area} \times \text{Depth} = \text{Volume}$$

$$90 \text{ ft}^2 \times 2.2 \text{ ft} = 198 \text{ ft}^3$$

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:

$$\frac{1481 \text{ gal}}{5 \text{ min}} = \frac{296.2}{1 \text{ min}} = 296.2 \text{ gpm}$$

PRELIMINARY WASTEWATER 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 (trash). The purpose of preliminary treatment is to protect plant equipment by removing these materials, which can 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 collection—influent pumping, screening, shredding, grit removal, flow measurement, preaeration, chemical addition, and flow equalization; the major processes are shown in Figure 8.8.

> ***Note:*** Not all treatment plants will include all of the processes shown in Figure 8.8. 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.

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 8.9). The waste stream passes through the screen and the large solids (*screenings*) are trapped on the bars for removal.

> ***Note:*** The screenings must be removed frequently enough to prevent accumulation that will block the screen and cause the water level in front of the screen to build up.

The bar screen may be coarse (2- to 4-in. openings) or fine (0.75- to 2.0-in. openings). The bar screen may be manually cleaned (bars or screens are placed at an angle of 30° for easier solids removal; see Figure 8.9) or mechanically cleaned (bars are placed at an angle of 45° to 60° to improve mechanical cleaner operation). The screening method employed depends on the design of the plant, the amount of solids expected, and whether the screen is for constant or emergency use only.

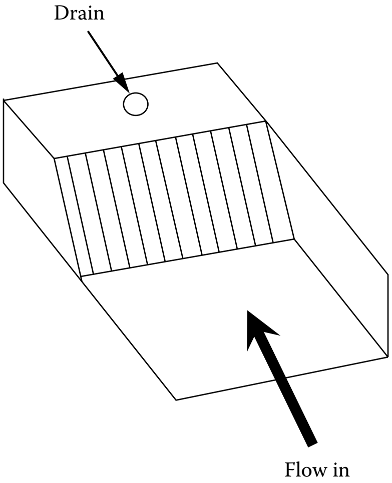

FIGURE 8.9 Basic bar screen.

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 being stored in a covered container. The area around the screen should be cleaned frequently to prevent a buildup of grease or other materials that can cause odors, slippery conditions, and insect and rodent problems. Because screenings may contain organic matter as well as large amounts of grease, they should be stored in a covered container. Screenings can be disposed of by burial in approved landfills or by incineration. Some treatment facilities grind the screenings into small particles, which are then returned to the wastewater flow for further processing and removal later in the process.

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 might be 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.

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 the 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 the manufacturer's recommendations or the plant's operation and maintenance (O&M) manual. Screenings from mechanically operated bar screens are disposed of in the same manner as screenings from manually operated screen: landfill disposal, incineration, or being ground into smaller particles for return to the wastewater flow.

Many of the operational problems associated with mechanically cleaned bar screens are the same as those for manual screens: septic wastes enter the primary tank, surge flows occur after cleaning, the bar screen channel has excessive grit, or the screen clogs frequently. 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 other problems, including the cleaner not operating at all or the rake not operating even though the motor is running. 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.

Screenings Removal Computations

Operators responsible for screenings disposal are typically required to keep a record of the amount of screenings removed from the wastewater flow. To keep and maintain accurate screening records, the volume of screenings withdrawn must be determined. Two methods are commonly used to calculate the volume of screenings withdrawn:

$$\text{Screenings removed (ft}^3\text{/day)} = \frac{\text{Screenings (ft}^3\text{)}}{\text{Days}} \tag{8.19}$$

$$\text{Screenings removed (ft}^3\text{/MG)} = \frac{\text{Screenings (ft}^3\text{)}}{\text{Flow (MG)}} \tag{8.20}$$

■ EXAMPLE 8.12

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 8.13

Problem: During one week, a total of 310 gal of screenings was removed from the wastewater screens. What is the average screening removal in ft^3/day?

Solution: Gallons screenings must first be converted to cubic feet of screenings:

$$\frac{310\text{ gal}}{7.48\text{ gal/ft}^3} = 41.4\text{ ft}^3\text{ screenings}$$

$$\text{Screenings removed} = \frac{41.4\text{ ft}^3}{7} = 5.9\text{ ft}^3\text{/day}$$

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.

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 in addition to corrective and preventive maintenance performed in accordance with the plant O&M manual.

Common operational problems associated with comminutors include output containing coarse solids. When this occurs it is usually a sign that the cutters are dull or misaligned. If the system does not operate at all, then the unit is clogged or jammed, a shear pin or coupling is broken, or electrical power is shut off. If the unit stalls or jams frequently, this usually indicates cutter misalignment, excessive debris in influent, or dull cutters.

Note: Only qualified maintenance operators should perform maintenance of shredding equipment.

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. 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 above for comminutors. Preventive and corrective maintenance as well as lubrication must be performed by qualified personnel and in accordance with the plant O&M manual. Because of higher maintenance requirements, the barminutor is less frequently used.

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 that should be kept in suspension for treatment in following processes. Grit removal may be accomplished in grit chambers or by the centrifugal separation of sludge. Processes use gravity/velocity, aeration, or centrifugal force to separate the solids from the wastewater.

Gravity/Velocity-Controlled Grit Removal

Gravity/velocity-controlled grit removal is normally accomplished in a channel or tank where the speed or velocity of the wastewater is controlled to about 1 foot per second (ideal), so the grit will settle while organic matter remains suspended. As long as the velocity is controlled in the range of 0.7 to 1.4 fps, the grit removal will remain effective. Velocity is controlled by the amount of water flowing through the channel, the depth of the water in the channel, the width of the channel, or the cumulative width of channels in service.

Process Control Calculations Velocity of the flow in a channel can be determined either by the float and stop watch method or by channel dimensions.

■ EXAMPLE 8.14. VELOCITY BY FLOAT AND STOPWATCH

$$\text{Velocity (ft/sec)} = \frac{\text{Distance traveled (ft)}}{\text{Time required (sec)}} \tag{8.21}$$

Problem: A float requires 25 sec to travel 34 ft in a grit channel. What is the velocity of the flow in the channel?

Solution:

$$\text{Velocity} = 34\text{ ft} \div 25\text{ sec} = 1.4\text{ fps}$$

■ EXAMPLE 8.15. VELOCITY BY FLOW AND CHANNEL DIMENSIONS

This calculation can be used for a single channel or tank or for multiple channels or tanks with the same dimensions and equal flow. If the flows through each unit of the unit dimensions are unequal, the velocity for each channel or tank must be computed individually.

$$\text{Velocity (fps)} = \frac{\text{Flow (MGD)} \times 1.55 \text{ cfs/MGD}}{\text{No. of channels in service} \times \text{Channel width (ft)} \times \text{Water depth (ft)}} \tag{8.22}$$

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 8.16. REQUIRED SETTLING TIME

This calculation can be used to determine the time required for a particle to travel from the surface of the liquid to the bottom at a given settling velocity. To compute the settling time, the settling velocity in feet per second must be provided or determined experimentally in a laboratory.

$$\text{Settling time (sec)} = \frac{\text{Liquid depth (ft)}}{\text{Settling velocity (fps)}} \tag{8.23}$$

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:

$$\text{Settling time} = \frac{2.2 \text{ ft}}{0.085 \text{ fps}} = 25.9 \text{ sec}$$

■ EXAMPLE 8.17. REQUIRED CHANNEL LENGTH

This calculation can be used to determine the length of channel required to remove an object with a specified settling velocity.

$$\text{Required channel length (ft)} = \frac{\text{Channel depth (ft)} \times \text{Flow velocity (fps)}}{\text{Settling velocity (fps)}} \tag{8.24}$$

Problem: The grit channel of a plant 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.

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 carry-over into the rest of the plant.

> ***Note:*** Before and during cleaning activities always ventilate the area thoroughly.

Aeration Aerated grit removal systems use aeration to keep the lighter organic solids in suspension while allowing the heavier grit particles to settle out. Aerated grit removal systems may be manually or mechanically cleaned; however, the majority of the systems are mechanically cleaned. In normal operation, the aeration rate is adjusted to produce the desired separation, which requires observation of mixing and aeration and sampling of fixed suspended solids. Actual grit removal is controlled by the rate of aeration. If the rate is too high, all of the solids remain in suspension. If the rate is too low, both 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.

Cyclone Degritter

The cyclone degritter uses a rapid spinning motion (i.e., 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 on the entire wastewater flow. The critical control factor for the process is the inlet pressure. If the inlet pressure exceeds the recommendations of the manufacturer, then the unit will flood, and grit will be carried through with the flow. Grit is separated from the 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/repairs to correct them.

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/million gal; combined wastewater systems, 4 to 15 ft^3/million gal), with higher ranges 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:

$$\text{Grit removed (ft}^3\text{/MG)} = \frac{\text{Grit volume (ft}^3\text{)}}{\text{Flow (MG)}} \tag{8.25}$$

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.

$$\text{Grit (yd}^3) = \frac{\text{Total grit (ft}^3)}{27\ \text{ft}^3/\text{yd}^3} \tag{8.26}$$

■ EXAMPLE 8.18

Problem: A treatment plant removes 10 ft^3 of grit in one day. How many cubic feet of grit are removed per million gallons if the plant flow was 9 MGD?

Solution:

$$\text{Grit removed} = \frac{\text{Grit volume (ft}^3)}{\text{Flow (MG)}} = \frac{10\ \text{ft}^3}{9\ \text{MG}} = 1.1\ \text{ft}^3/\text{MG}$$

■ EXAMPLE 8.19

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 MG flow?

Solution: First, convert gallon grit removed to ft^3:

$$\frac{250\ \text{gal}}{7.48\ \text{gal/ft}^3} = 33\ \text{ft}^3$$

Next, complete the calculation of ft^3/MG:

$$\text{Grit removal} = \frac{\text{Grit volume (ft}^3)}{\text{Flow (MG)}} = \frac{33\ \text{ft}^3}{12.2\ \text{MGD}} = 2.7\ \text{ft}^3/\text{MGD}$$

■ EXAMPLE 8.20

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:

$$\frac{(2.5\ \text{ft}^3)}{\text{MG}} \times (2.5\ \text{MGD}) = 6.25\ \text{ft}^3$$

The ft^3 grit generated for 90 days would be

$$\frac{(6.25\ \text{ft}^3)}{\text{day}} \times (90\ \text{days}) = 562.5\ \text{ft}$$

Convert ft^3 grit to yd^3 grit:

$$\frac{562.5\ \text{ft}^3}{27\ \text{ft}^3/\text{yd}^3} = 21\ \text{yd}^3$$

Preaeration

In the preaeration process (diffused or mechanical), we aerate wastewater to achieve and maintain an aerobic state (to freshen septic wastes), strip off hydrogen sulfide (to reduce odors and corrosion), agitate solids (to release trapped gases and improve solids separation and settling), and reduce BOD_5. All of this can be accomplished by aerating the wastewater for 10 to 30 min. To reduce BOD_5, preaeration must be conducted from 45 to 60 min. 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.

Chemical Addition

Chemical addition is made (either via dry chemical metering or solution feed metering) to the waste stream 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 depends 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. When adding chemicals to the waste stream 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.

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 that are above the 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 additional costs associated with construction and operation of the flow equalization facilities. During normal operations, the operator must monitor all mechanical systems involved with flow equalization, watch for mechanical problems, and be prepared to take the 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 necessary adjustments.

PRIMARY WASTEWATER TREATMENT (SEDIMENTATION)

The purpose of primary treatment (primary sedimentation or primary clarification) is to remove settleable organic and floatable solids. Normally, each primary clarification unit can be expected to remove 90 to 95% settleable solids, 40 to 60% total suspended solids, and 25 to 35% 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 section, we focus on primary treatment or primary clarification, which uses large basins where primary settling is achieved under relatively quiescent conditions (see Figure 8.8). 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. In primary sedimentation, wastewater enters a settling tank or basin. Velocity is reduced to approximately 1 foot per minute.

> ***Note:*** 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 ft/sec would be 60 ft/min.

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.

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 ft/min 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, as well as the settled sludge solids, and collect them for pumped transfer to disposal or further treatment.
- 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 the 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 the following concepts:

$$\text{Retention time (hr)} = \frac{\text{Vol. (gal)} \times 24\ \text{hr/day}}{\text{Flow (gpd)}}$$

$$\text{Surface loading rate (gpd/ft}^2\text{)} = \frac{Q\ \text{(gpd)}}{\text{Surface area (ft}^2\text{)}}$$

$$\text{Solids loading rate (lb/day/ft}^2\text{)} = \frac{\text{Solids in clarifier (lb/day)}}{\text{Surface area (ft}^2\text{)}}$$

$$\text{Weir overflow rate (gpd/linear ft)} = \frac{Q\ \text{(gpd)}}{\text{Weir length (linear ft)}}$$

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.

Septic Tanks

Septic tanks are prefabricated tanks that serve as a combined settling and skimming tank and as an unheated, unmixed anaerobic digester. Septic tanks provide long settling times (6 to 8 hr or more) but do not separate decomposing solids from the wastewater flow. When the tank becomes full, solids will be discharged with the flow. The process is suitable for small facilities (e.g., schools, motels, homes), but, due to the long detention times and lack of control, it is not suitable for larger applications.

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 and 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.

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 can vary from 1 to 3 hr (2 hr on average). Sludge removal is accomplished frequently on either a continuous or an intermittent basis. Continuous removal requires additional sludge treatment processes to remove the excess water resulting from the removal of sludge containing less than 2 to 3% solids. Intermittent sludge removal requires 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 (which prevent floatable solids and 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 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.

Sedimentation 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.

Percent Removal

The expected ranges of percent removal for a primary clarifier are

- Settleable solids, 90 to 95%
- Suspended solids, 40 to 60%
- BOD_5, 25 to 35%

Detention Time

The primary purpose of primary settling is to remove settleable solids. This is accomplished by slowing the flow down to approximately 1 ft/min. 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 the *hydraulic detention time*.

Surface Loading Rate (Surface Settling Rate, Surface Overflow Rate)

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 gal/day/ft^2. Other terms used synonymously with surface loading rate include *surface overflow rate* and *surface settling rate*.

$$\text{Surface overflow rate (gpd/ft}^2\text{)} = \frac{\text{Flow (gpd)}}{\text{Settling tank area (ft}^2\text{)}} \tag{8.27}$$

■ EXAMPLE 8.21

Problem: The settling tank is 120 ft in diameter and flow to the unit is 4.5 MGD. What is the surface loading rate in gal/day/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 8.22

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:

$$\text{Area} = 0.785 \times 50\text{ ft} \times 50\text{ ft}$$

$$\text{Surface overflow rate} = \frac{\text{Flow (gpd)}}{\text{Area (ft}^2\text{)}} = \frac{2{,}150{,}000}{0.785 \times 50\text{ ft} \times 50\text{ ft}} = 1096\text{ gpd/ft}^2$$

Weir Overflow Rate (Weir Loading Rate)

The weir overflow rate or 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 gal/day/ft are used in the design of a settling tank.

$$\text{Weir overflow rate (gpd/ft)} = \frac{\text{Flow (gpd)}}{\text{Weir length (ft)}} \tag{8.28}$$

■ EXAMPLE 8.23

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 gal/day/ft?

Solution:

$$\text{Weir overflow} = \frac{2.55\text{ MGD} \times 1{,}000{,}000\text{ gal/MG}}{3.14 \times 90\text{ ft}} = 9023\text{ gpd/ft}$$

Sludge Pumping

Determination of sludge pumping (the quantity of solids and volatile solids removed from the sedimentation tank) provides accurate information needed for process control of the sedimentation process.

$$\text{Solids pumped (lb/day)} = \text{Pump rate} \times \text{Pump time} \times 8.34\text{ lb/gal} \times \%\text{ Solids} \tag{8.29}$$

$$\text{Volatile solids (lb/day)} = \text{Pump rate} \times \text{Pump time} \times 8.34 \times \%\text{ Solids} \times \%\text{ Volatile solids} \tag{8.30}$$

■ EXAMPLE 8.24

Problem: The sludge pump operates 20 min/hr. The pump delivers 20 gal/min 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:

$$\text{Volatile solids} = 20\text{ gpm} \times (20\text{ min/hr} \times 24\text{ hr/day}) \times 8.34\text{ lb/gal} \times 0.052 \times 0.66 = 2748\text{ lb/day}$$

Percent Total Solids (%TS)

■ EXAMPLE 8.25

Problem: A settling tank sludge sample is tested for solids. The sample and dish weighed 74.69 g. The dish alone weighed 21.2 g. After drying, the dish with dry solids weighed 22.3 g. What is the percent total solids (%TS) of the sample?

Solution:

Sample + Dish	74.69 g	Dish + Dry solids	22.3 g
Dish alone	–21.20 g	Dish alone	–21.2 g
Sample weight	53.49 g	Dry solids weight	1.1 g

$$\frac{1.1\text{ g}}{53.49\text{ g}} \times 100\% = 2\%$$

BOD and SS Removal

To calculate the pounds of BOD or suspended solids removed each day, we need to know the mg/L BOD or SS removed and the plant flow. Then, we can use the mg/L to lb/day equation:

$$\text{SS removed} = \text{mg/L} \times \text{MGD} \times 8.34\text{ lb/gal} \tag{8.31}$$

■ EXAMPLE 8.26

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 6,230,000 gpd?

Solution:

$$\text{SS removed} = \text{mg/L} \times \text{MGD} \times 8.34\text{ lb/gal} = 120\text{ mg/L} \times 6.25\text{ MGD} \times 8.34\text{ lb/gal} = 6255\text{ lb/day}$$

■ EXAMPLE 8.27

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 the mg/L BOD removed, calculate the lb/day BOD removed:

$$\text{BOD removed} = 130\text{ mg/L} \times 1.6\text{ MGD} \times 8.34\text{ lb/gal} = 1{,}735\text{ lb/day}$$

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 waste stream. 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 section.

> **Note:** Two of the most important nutrients left to remove are phosphorus and ammonia. Although we want to remove these two nutrients from the waste stream, we do not want to remove too much. Carbonaceous microorganisms in secondary treatment (biological treatment) require both phosphorus and ammonia.

SECONDARY TREATMENT

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 section, 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. We then shift focus to the activated sludge process—the secondary treatment process used primarily in large installations and which 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 no more than 30 mg/L BOD_5 and 30 mg/L total suspended solids.

> **Note:** The CWA also states that ponds and trickling filters will be included in the definition of secondary treatment even if they do not meet the effluent quality requirements continuously.

Most secondary treatment processes decompose solids aerobically, producing carbon dioxide, stable solids, and more organisms. Because solids are produced, all of the biological processes must include some form of solids removal (e.g., settling tank, filter). Secondary treatment processes can be separated into two large categories: fixed-film systems and suspended-growth systems.

Fixed-film systems are processes that use a biological growth (biomass or slime) 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.

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 factor 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.

Stabilization (treatment) ponds have been used for the treatment of wastewater for over 3000 years. The first recorded construction of a pond system in the United States was in San Antonio, Texas, in 1901. Today, over 8000 wastewater treatment ponds are in place, involving more than 50% of the wastewater treatment facilities in the United States. Facultative ponds account for 62%, aerated ponds 25%, anaerobic ponds 0.04%, and total containment 12% of pond treatment systems. They treat a variety of wastewaters from domestic wastewater to complex industrial wastes, and they function under a wide range of weather conditions, from tropical to arctic. Ponds can be used alone or in combination with other wastewater treatment processes. As our understanding of pond operating mechanisms has increased, different types of ponds have been developed for application in specific types of wastewater under local environmental conditions. This text focuses on municipal wastewater treatment pond systems.

Although the tendency in the United States has been for smaller communities to build ponds, in other parts of the world, including Australia, New Zealand, Mexico and Latin America, Asia, and Africa, treatment ponds have been built to serve large cities. As a result, our understanding of the biological, biochemical, physical, and climatic factors that interact to transform the organic compounds, nutrients, and pathogenic organisms found in sewage into less harmful chemicals and unviable organisms (i.e., dead or sterile) has grown since 1983. A wealth of experience has been developed as civil, sanitary, and environmental engineers; operators; public works managers; and public health and environmental agencies have worked with these systems. Although some of this information makes its way into technical journals and textbooks, there is a need for a less formal presentation of the subject for those working in the field every day (USEPA, 2011).

Ponds are designed to enhance the growth of natural ecosystems that are anaerobic (providing conditions for bacteria that grow in the absence of oxygen environments), aerobic (promoting the growth of oxygen-producing and/or oxygen-requiring organisms, such as algae and bacteria), or facultative (a combination of the two). Ponds are managed to reduce concentrations of biochemical oxygen demand (BOD), TSS, and coliform numbers (fecal or total) to meet water quality requirements. Ponds can be classified 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 of wastes they receive: *raw sewage stabilization ponds* (see Figure 8.10), *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*.

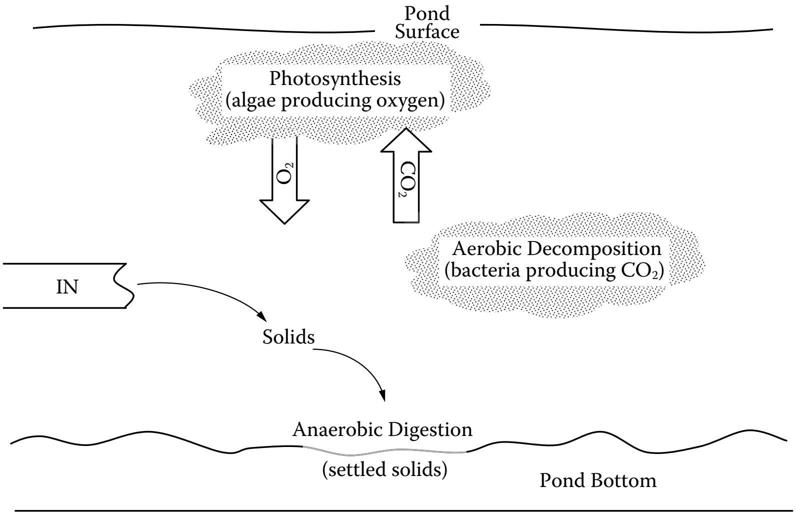

FIGURE 8.10 Stabilization pond processes.

Ponds Based on Location and Types of Wastes They Receive

Raw Sewage Stabilization Pond The raw sewage stabilization pond is the most common type of pond (see Figure 8.10). 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 removal. 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 feet. The process occurring in the pond involves bacteria decomposing the organics in the wastewater (aerobically and anaerobically) and algae using the products of the bacterial action to produce oxygen (photosynthesis). Because this type of pond is the most commonly used in wastewater treatment, the process that occurs within the pond is described in greater detail in the following text.

When wastewater enters the stabilization pond, several processes begin to occur. These include settling, aerobic decomposition, anaerobic decomposition, and photosynthesis (see Figure 8.10). 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 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 (hydrogen sulfide, methane, etc.) 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:*** Dissolved oxygen and pH levels in the pond will vary throughout the day. Normal operation will result in very high DO and pH levels due to the natural processes occurring.

> ***Note:*** When operating properly, the stabilization pond will exhibit a wide variation in both dissolved oxygen and pH. This is due to photosynthesis occurring in the system.

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.

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 algae growth, which increases influent suspended solids concentrations.

Ponds Based on the Type of Processes Occurring Within

The type of processes occurring within the pond may also classify ponds. These include the aerobic, anaerobic, facultative, and aerated processes.

Aerobic Ponds Not widely used, aerobic ponds (also known as *oxidation ponds* or *high-rate aerobic ponds*) have oxygen present throughout the pond. All biological activity is aerobic decomposition. They are usually 30 to 45 cm deep, which allows light to penetrate throughout the pond. Mixing is often provided, keeping algae at the surface to maintain maximum rates of photosynthesis and O_2 production and to prevent algae from settling and producing an anaerobic bottom layer. The rate of photosynthetic production of O_2 may be enhanced by surface re-aeration; O_2 and aerobic bacteria biochemically stabilize the waste. Detention time is typically 2 to 6 days. These ponds are appropriate for treatment in warm, sunny climates. They are used where a high degree of BOD_5 removal is desired but land area is limited. The chief advantage of these ponds is that they produce a stable effluent during short detention times with low land and energy requirements. However, their operation is somewhat more complex than that of facultative ponds and, unless the algae are removed, the effluent will contain high TSS. While the shallow depths allow penetration of ultraviolet (UV) light that may reduce pathogens, shorter detention times may work against effective coliform and parasite die-off. Because they are shallow, bottom paving or veering is usually necessary to prevent aquatic plants from colonizing the ponds. The Advanced Integrated Wastewater Pond System® (AIWPS®) uses the high-rate pond to maximize the growth of microalgae using a low-energy paddle-wheel (USEPA, 2011).

Anaerobic Ponds Anaerobic ponds are normally used to treat high-strength industrial wastes; that is, they receive heavy organic loading, so much so that there is no aerobic zone—no oxygen is present and all biological activity is anaerobic decomposition. They are usually 2.5 to 4.5 m in depth and have detention times of 5 to 50 days. The predominant biological treatment reactions are bacterial acid formation and methane fermentation. Anaerobic ponds are usually used for treatment of strong industrial and agricultural (food processing) wastes, as a pretreatment step in municipal systems, or where an industry is a significant contributor to a municipal system. The biochemical reactions in an anaerobic pond produce hydrogen sulfide (H_2S) and other odorous compounds. To reduce odors, the common practice is to recirculate water from a downstream facultative or aerated pond. This provides a thin aerobic layer at the surface of the anaerobic pond which prevents odors from escaping into the air. A cover may also be used to contain odors. The effluent from anaerobic ponds usually requires further treatment prior to discharge (USEPA, 2011).

Facultative Pond The facultative pond, which may also be called an *oxidation* or *photosynthetic 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 occur. No oxygen is present in the lower levels of the pond where processes occurring are anoxic and anaerobic. Facultative ponds are usually 0.9 to 2.4 m deep or deeper, with an aerobic layer overlying an anaerobic layer. Recommended detention times vary from 5 to 50 days in warm climates and 90 to 180 days in colder climates (NEIWPCC, 1998). Aerobic treatment processes in the upper layer provide odor control as well as nutrient and BOD removal. Anaerobic fermentation processes, such as sludge digestion, denitrification, and some BOD removal, occur in the lower layer. The key to successful operation of this type of pond is O_2 production by photosynthetic algae and/or re-aeration at the surface. Facultative ponds are used to treat raw municipal wastewater in small communities and for primary or secondary effluent treatment for small or large cities. They are also used in industrial applications, usually in the process line after aerated or anaerobic ponds, to provide additional treatment prior to discharge. Commonly achieved effluent BOD values, as measured in the BOD_5 test, range from 20 to 60 mg/L, and TSS levels may range from 30 to 150 mg/L. The size of the pond needed to treat BOD loadings depends on specific conditions and regulatory requirements.

Aerated Ponds Facultative ponds overloaded due to unplanned additional sewage volume or higher strength influent from a new industrial connection may be modified by the addition of mechanical aeration. Ponds originally designed for mechanical aeration are generally 2 to 6 m deep with detention times of 3 to 10 days. For colder climates, a detention time of 20 to 40 days is recommended. Mechanically aerated ponds require less land area but have greater energy requirements. When aeration is used, the depth of the pond and/or the acceptable loading levels may increase. Mechanical or diffused aeration is often used to supplement natural oxygen production or to replace it.

Pond Organisms

Although our understanding of wastewater pond ecology is far from complete, general observations about the interactions of macro- and microorganisms in these biologically driven systems support our ability to design, operate, and maintain them.

Bacteria Bacteria found in ponds help to decompose complex, organic constituents in the influent to simple, nontoxic compounds. Certain pathogen bacteria and other microbial organism (viruses, protozoa) associated with human waste enter in that system with the influent; the wastewater treatment process is designed so that these organisms will be reduced adequately to meet public health standards.

- *Aerobic bacteria* are found in the aerobic zone of a wastewater pond and are primarily the same type as those found in an activated sludge process or in the zoogleal mass of a trickling filter. The most frequently isolated bacteria include *Beggiatoa alba*, *Sphaerotilus natans*, *Achromobacter*, *Alcaligenes*, *Flavobacterium*, *Pseudomonas*, and *Zoogoea* spp. (Lynch and Poole, 1979; Pearson, 2005; Spellman, 2000). These organisms decompose the organic materials present in the aerobic zone into oxidized end products.
- *Anaerobic bacteria* are hydrolytic bacteria that convert complex organic material into simple alcohols and acids, primarily amino acids, glucose, fatty acid, and glycerols (Brocket, 1976; Paterson and Curtis, 2005; Pearson, 2005; Spellman, 2000). Acidogenic bacteria convert the sugars and amino acids into acetate, ammonia (NH_3), hydrogen (H), and carbon dioxide (CO_2). Methanogenic bacteria break down these products further to methane (CH_4) and CO_2 (Gallert and Winter, 2005).
- *Cyanobacteria*, formerly classified as blue–green algae, are autotrophic organisms that are able to synthesize organic compounds using CO_2 as the major carbon source. Cyanobacteria produce O_2 as a byproduct of photosynthesis, providing an O_2 source for other organisms in the ponds. They are found in very large numbers as blooms when environmental conditions are suitable (Gaudy and Gaudy, 1980). Commonly encountered cyanobacteria include *Oscillatoria*, *Arthrospira*, *Spirulina*, and *Microcystis* (Spellman, 2000; Vasconcelos and Pereira, 2001).
- *Purple sulfur bacteria* (Chromatiaceae) may grow in any aquatic environment to which light of the required wavelength penetrates, provided that CO_2, nitrogen (N), and a reduced form of sulfur (S) or hydrogen (H) are available. Purple sulfur bacteria occupy the anaerobic layer below the algae, cyanobacteria, and other aerobic bacteria in a pond. They are commonly found at a specific depth, in a thin layer where light and nutrient conditions are at an optimum (Gaudy and Gaudy, 1980; Pearson, 2005). Their biochemical conversion of odorous sulfide compounds to elemental S or sulfate (SO_4) helps to control odor in facultative and anaerobic ponds.

Algae Algae constitute a group of aquatic organisms that may be unicellular or multicellular, motile or immotile, and, depending on the phylogenetic family, have different combinations of photosynthetic pigments. As autotrophs, algae need only inorganic nutrients, such as nitrogen, phosphorus, and a suite of microelements, to fix CO_2 and grow in the presence of sunlight. Algae do not fix atmospheric nitrogen; they require an external source of inorganic nitrogen in the form of nitrate

(NO_3) or NH_3. Some algal species are able to use amino acids and other organic nitrogen compounds. Oxygen is a byproduct of these reactions. Algae are generally divided into three major groups, based on the color reflected from the cells by the chlorophyll and other pigments involved in photosynthesis. Green and brown algae are common to wastewater ponds; red algae occur infrequently. The algal species that is dominant at any particular time is thought to be primarily a function of temperature, although the effects of predation, nutrient availability, and toxins are also important. Green algae (Chlorophyta) include unicellular, filamentous, and colonial forms. Some green algal genera commonly found in facultative and aerobic ponds are *Euglena*, *Phacus*, *Chlamydomonas*, *Ankistrodesmus*, *Chlorella*, *Micractinium*, *Scenedesmus*, *Selenastrum*, *Dictyosphaerium*, and *Volvox*. Chrysophytes, or brown algae, are unicellular and may be flagellated, and include the diatoms. Certain brown algae are responsible for toxic red blooms. Brown algae found in wastewater ponds include the diatoms *Navicula* and *Cyclotella*. Red algae (Rhodophyta) include a few unicellular forms but are primarily filamentous (Gaudy and Gaudy, 1980; Pearson, 2005).

It is generally accepted that the presence of both algae and bacteria is essential for the proper functioning of a treatment pond. Bacteria break down the complex organic waste components found in anaerobic and aerobic pond environments into simple compounds, which are then available for uptake by the algae. Algae, in turn, produce the O_2 necessary for the survival of aerobic bacteria. In the process of pond reactions of biodegradation and mineralization of waste material by bacteria and the synthesis of new organic compounds in the form of algal cells, a pond effluent might contain a higher than acceptable TSS. Although this form of TSS does not contain the same constituents as the influent TSS, it does contribute to turbidity and must be removed before the effluent is discharged. Once concentrated and removed, depending on regulatory requirements, algal TSS may be used as a nutrient for use in agriculture or as a feed supplement (Grönlund, 2002).

Invertebrates Although bacteria and algae are the primary organisms through which waste stabilization is accomplished, predator life forms do play a role in wastewater pond ecology. It has been suggested that the planktonic invertebrate *Cladocera* spp. and the benthic invertebrate family Chironomidae are the most significant fauna in the pond community in terms of stabilizing organic material. The cladocerans feed on the algae and promote flocculation and settling of particulate matter, resulting in better light penetration and algal growth at greater depths. Settled matter is further broken down and stabilized by the benthic feeding Chironomidae. Predators, such as rotifers, often control the population levels of certain of the smaller life forms in the pond, thereby influencing the succession of species throughout the seasons. Mosquitoes can present a problem in some ponds. Aside from their nuisance characteristics, certain mosquitoes are also vectors for such diseases as encephalitis, malaria, and yellow fever and constitute a hazard to public health that must be controlled. *Gambusia*, commonly called mosquito fish, have been introduced to eliminate mosquito problems in some ponds in warm climates (Pearson, 2005; Pipes, 1961; Ullrich, 1967), but their introduction has been problematic as they can out-compete native fish that also feed on mosquito larvae. There are also biochemical controls, such as the larvicides *Bacillus thuringiensis israelensis* (Bti), and Abate®, which may be effective if the product is applied directly to the area containing mosquito larvae. The most effective means of control of mosquitoes in ponds is the control of emergent vegetation (USEPA, 2011).

Biochemistry in a Pond

Photosynthesis Photosynthesis is the process whereby organisms use solar energy to fix CO_2 and obtain the reducing power to convert it to organic compounds. In wastewater ponds, the dominant photosynthetic organisms include algae, cyanobacteria, and purple sulfur bacteria (Pearson, 2005; Pipes, 1961). Photosynthesis may be classified as oxygenic or anoxygenic, depending on the source of reducing power used by a particular organism. In oxygenic photosynthesis, water serves as the source of reducing power, with O_2 as a byproduct. The equation representing oxygenic photosynthesis is

$$H_2O + \text{Sunlight} \rightarrow 1/2O_2 + 2H^+ + 2e^- \quad (8.32)$$

Oxygenic photosynthetic algae and cyanobacteria convert CO_2 to organic compounds, which serve as the major source of chemical energy for other aerobic organisms. Aerobic bacteria need the O_2 produced to function in their role as primary consumers in degrading complex organic waste material.

Anoxygenic photosynthesis does not produce O_2 and, in fact, occurs in the complete absence of O_2. The bacteria involved in anoxygenic photosynthesis are largely strict anaerobes, unable to function in the presence of O_2. They obtain energy by reducing inorganic compounds. Many photosynthetic bacteria utilize reduced S compounds or element S in anoxygenic photosynthesis according to the following equation:

$$H_2S \rightarrow S^0 + 2H^+ + 2e^- \quad (8.33)$$

Respiration Respiration is a physiological process by which organic compounds are oxidized into CO_2 and water. Respiration is also an indicator of cell material synthesis. It is a complex process that consists of many interrelated biochemical reactions (Pearson, 2005). Aerobic respiration, common to species of bacteria, algae, protozoa, invertebrates, and higher plants and animals, may be represented by the following equation:

$$C_2H_{12}O_6 + 6O_2 + \text{Enzymes} \rightarrow 6CO_2 + 6H_2O + \text{New cells} \quad (8.34)$$

The bacteria involved in aerobic respiration are primarily responsible for degradation of waste products. In the presence of light, respiration and photosynthesis can occur simultaneously in algae. However, the respiration rate is low compared to the photosynthesis rate, which results in a net consumption of CO_2 and production of O_2. In the absence of light, on the other hand, algal respiration continues while photosynthesis stops, resulting in a net consumption of O_2 and production of CO_2 (USEPA, 2011).

Nitrogen Cycle The nitrogen cycle occurring in a wastewater treatment pond consists of a number of biochemical reactions mediated by bacteria. A schematic representation of the changes in nitrogen speciation in wastewater ponds over a year is shown in Figure 8.11. Organic nitrogen and NH_3 enter with the influent wastewater. Organic nitrogen in fecal matter and other organic materials undergo conversion to NH_3 and ammonium ion NH_4^+ by microbial activity. The NH_3 may volatize into the atmosphere. The rate of gaseous NH_3 losses to the atmosphere is primarily a function of pH, surface-to-volume ratio, temperature, and the mixing conditions. An alkaline pH shifts the equilibrium of NH_3 gas and NH_4^+ towards gaseous NH_3 production, while the mixing conditions affect the magnitude of the mass transfer coefficient.

Ammonium is nitrified to nitrite (NO_2^-) by the bacterium *Nitrosomonas* and then to NO_3^- by *Nitrobacter*. The overall nitrification reaction is

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O \quad (8.35)$$

The NO_3^- produced in the nitrification process, as well as a portion of the NH_4^- produced from ammonification, can be assimilated by organisms to produce cell protein and other nitrogen-containing compounds. The NO_3^- may also be denitrified to form NO_2^{2-} and then nitrogen gas. Several species of bacteria may be involved in the denitrification process, including *Pseudomonas*, *Micrococcus*, *Achromobacter*, and *Bacillus*. The overall denitrification reaction is

$$6NO_3^- + 5CH_3OH \rightarrow 3N_2 + 5CO_2 + 7H_2O + 6OH^- \quad (8.36)$$

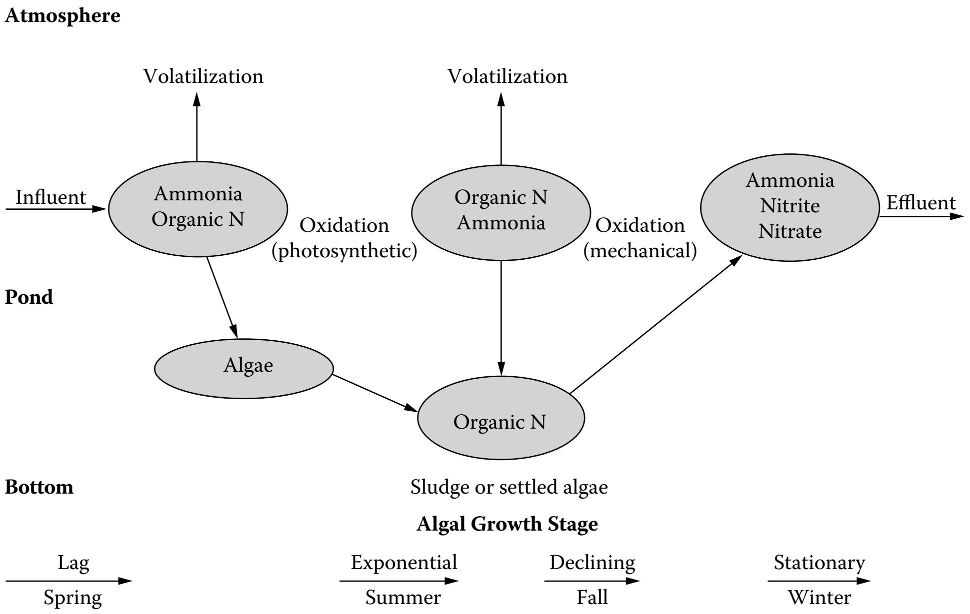

FIGURE 8.11 The nitrogen cycle in wastewater pond system.

Nitrogen gas may be fixed by certain species of cyanobacteria when nitrogen is limited. This may occur in nitrogen-poor industrial ponds, but rarely in municipal or agricultural ponds (USEPA, 1975, 1993). Nitrogen removal in facultative wastewater ponds can occur through any of the following processes: (1) gaseous NH_3 stripping to the atmosphere, (2) NH_4^- assimilation in algal biomass, (3) NO_3^- uptake by floating vascular plants and algae, and (4) biological nitrification–denitrification. Whether NH_4^- is assimilated into algal biomass depends on the biological activity in the system and is affected by several factors such as temperature, organic load, detention time, and wastewater characteristics.

Dissolved Oxygen (DO) Oxygen is a partially soluble gas. Its solubility varies in direct proportion to the atmospheric pressure at any given temperature. Dissolved oxygen (DO) concentrations of approximately 8 mg/L are generally considered to be maximum available under local ambient conditions. In mechanically aerated ponds, the limited solubility of O_2 determines its absorption rate (Sawyer et al., 1994). The natural sources of DO in ponds are photosynthetic oxygenation and surface re-aeration. In areas of low wind activity, surface re-aeration may be relatively unimportant, depending on the water depth. Where surface turbulence is created by excessive wind activity, surface re-aeration can be significant. Experiments have shown that DO in wastewater ponds varies almost directly with the level of photosynthetic activity, which is low at night and early morning and rises during daylight hours to a peak in the early afternoon. At increased depth, the effects of photosynthetic oxygenation and surface re-aeration decrease, as the distance from the water–atmosphere interface increases and light penetration decreases. This can result in the establishment of a vertical gradient. The microorganisms in the pond will segregate along the gradient.

pH and Alkalinity In wastewater ponds, the hydrogen ion concentration, expressed as pH, is controlled through the carbonate buffering system represented by the following equations:

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow HCO_3^- + H^+ \tag{8.37}$$

$$HCO_3^- \rightarrow CO_3^{2-} + H^+ \tag{8.38}$$

$$CO_3^{2-} + H_2O \rightarrow HCO_3^- + OH^- \tag{8.39}$$

$$OH^- + H^+ \rightarrow H_2O \tag{8.40}$$

The equilibrium of this system is affected by the rate of algal photosynthesis. In photosynthetic metabolism, CO_2 is removed from the dissolved phase, forcing the equilibrium of the first expression (Eq. 8.37) to the left. This tends to decrease the hydrogen ion (H^+) concentration and the bicarbonate (HCO_3^-) alkalinity. The effect of the decrease in HCO_3^- concentration is to force the third equation (Eq. 8.39) to the left and the fourth (Eq. 8.40) to the right, both of which decrease total alkalinity. The decreased alkalinity associated with photosynthesis will simultaneously reduce the carbonate hardness present in the waste. Because of the close correlation between pH and photosynthetic activity, there is a diurnal fluctuation in pH when respiration is the dominant metabolic activity.

Physical Factors

Light The intensity and spectral composition of light penetrating a pond surface significantly affect all resident microbial activity. In general, activity increases with increasing light intensity until the photosynthetic system becomes light saturated. The rate at which photosynthesis increases in proportion to an increase in light intensity, as well as the level at which an organism's photosynthetic system becomes light saturated, depends upon the particular biochemistry of the species (Lynch and Poole, 1979; Person, 2005). In ponds, photosynthetic O_2 production has been shown to be relatively constant with the range of 5380 to 53,8000 lumens/m^2 light intensity with a reduction occurring at higher and lower intensities (Paterson and Curtis, 2005; Pies, 1961). The spectral composition of available light is also crucial in determining photosynthetic activity. The ability of photosynthetic organisms to utilize available light energy depends primarily upon their ability to absorb the available wavelengths. This absorption ability is determined by the specific photosynthetic pigment of the organism. The main photosynthetic pigments are chlorophylls and phycobilins. Bacterial chlorophyll differs from algal chlorophyll in both chemical structure and absorption capacity. These differences allow the photosynthetic bacteria to live below dense algal layers where they can utilize light not absorbed by the algae (Lynch and Poole, 1979; Pearson, 2005). The quality and quantity of light penetrating the pond surface to any depth depend on the presence of dissolved and particulate matter as well as the water absorption characteristics. The organisms themselves contribute to water turbidity, further limiting the depth of light penetration. Given the light penetration interferences, photosynthesis is significant only in the upper pond layers. This region of net photosynthetic activity is called the *euphotic zone* (Lynch and Poole, 1979; Pearson, 2005). Light intensity from solar radiation varies with the time of day and difference in latitudes. In cold climates, light penetration can be reduced during the winter by ice and snow cover. Supplementing the treatment ponds with mechanical aeration may be necessary in these regions during that time of year.

Temperature Temperature at or near the surface of the aerobic environment of a pond determines the succession of predominant species of algae, bacteria, and other aquatic organisms. Algae can survive at temperatures of 5 to 40°C. Green algae show most efficient growth and activity at temperatures of 30 to 35°C. Aerobic bacteria are viable within a temperature range of 10 to 40°C; 35 to 40°C is optimum for cyanobacteria (Anderson and Zwieg, 1962; Crites et al., 2006; Gloyna, 1976; Paterson and Curtis, 2005). As the major source of heat for these systems is solar radiation, a temperature gradient can develop in a pond with depth. This will influence the rate of anaerobic decomposition of solids that have settled at the bottom of the pond. The bacteria responsible for anaerobic degradation are active in temperatures from 15 to 65°C. When they are exposed to lower temperatures, their activity is reduced. The other major source of heat is the influent water. In sewerage systems with no major inflow or infiltration problems, the influent temperature is higher than that of the pond contents. Cooling influences are exerted by evaporation, contact with cooler groundwater, and wind action. The overall effect of temperature in combination with light intensity is reflected in the fact that nearly all investigators report improved performance during summer and autumn months when both temperature and light are at their maximum. The maximum practical temperature of wastewater ponds is likely less than 30°C, indicating that most ponds operate at less than optimum temperature for anaerobic activity (Crites et al., 2006; Oswald, 1996; Paterson and Curtis, 2005; USEPA, 2011). During certain times of the year, cooler, denser water remains at depth, while the warmer water stays at the surface. Water temperature differences may cause ponds to stratify throughout their depth. As the temperature decreases during the fall and the surface water cools, stratification decreases and the deeper water mixes with the cooling surface water. This phenomenon is call *mixis*, or pond or lake overturn. As the density of water decreases and the temperature falls below 4°C, winter stratification can develop. When the ice cover breaks up and the water warms, a spring overturn can also occur (Spellman, 1996). Pond overturn, which releases odorous compounds into the atmosphere, can generate complaints from property owners living downwind of the pond. The potential for pond overturn during certain times of the year is the reason why regulations may specify that ponds be located downwind, based on prevailing winds during overturn periods, and away from dwellings.

Wind Prevailing and storm-generated wind should be factored into pond design and siting as they influence performance and maintenance in several significant ways:

- *Oxygen transfer and dispersal*—By producing circulatory flows, winds provide the mixing needed for O_2 transfer and diffusion below the surface of facultative ponds. This mixing action also helps disperse microorganisms and augments the movement of algae, particularly green algae.
- *Prevention of short-circuiting and reduction of odor events*—Care must be taken during design to position the pond inlet/outlet axis perpendicular to the direction of prevailing winds to reduce short-circuiting, which is the most common cause of poor performance. Consideration must also be made for the transport and fate of odors generated by treatment byproducts in anaerobic and facultative ponds.
- *Disturbance of pond integrity*—Waves generated by strong prevailing or storm winds are capable of eroding or overtopping embankments. Some protective material should extend one or more feet above and below the water level to stabilize earthen berms.
- *Hydraulic detention time*—Wind effects can reduce hydraulic retention time.

Pond Nutritional Requirements

In order to function as designed, the wastewater pond must provide sufficient macro- and micronutrients for the microorganisms to grow and populate the system adequately. It should be understood that a treatment pond system should be neither overloaded nor underloaded with wastewater nutrients.

Nitrogen Nitrogen (N) can be a limiting nutrient for primary productivity in a pond. The conversion of organic nitrogen to various other nitrogen forms results in a total net loss (Assenzo and Reid, 1966; Craggs, 2005; Middlebrooks and Pano, 1983; Middlebrooks et al. 1982; Pano and Middlebrooks, 1982). This nitrogen loss may be due to algal uptake or bacterial action. It is likely that both mechanisms contribute to the overall total nitrogen reduction. Another factor contributing to the reduction of total nitrogen is the removal of gaseous NH_3 under favorable environmental conditions. Regardless of the specific removal mechanism involved, NH_3 removal in facultative wastewater ponds has been observed at levels greater than 90%, with the major removal occurring in the primary cell of a multicell pond system (Crites et al., 2006; Middlebrooks et al., 1982; Shilton, 2005; USEPA, 2011).

Phosphorus Phosphorus (P) is most often the growth-limiting nutrient in aquatic environments. Municipal wastewater in the United States is normally enriched in phosphorus even though restrictions on phosphorus-containing compounds in laundry detergents in some states have resulted in reduced concentrations since the 1970s. As of 1999, 27 states and the District of Columbia had passed laws prohibiting the manufacture and use of laundry detergents containing phosphorus. However, phosphate (PO_4^{3-}) content limits in automatic dishwashing detergents and other household cleaning agents containing phosphorus remain unchanged in most states. With a contribution of approximately 15%, the concentration of phosphorus from wastewater treatment plants is still adequate to promote growth in aquatic organisms. In aquatic environments, phosphorus occurs in three forms: (1) particulate phosphorus, (2) soluble organic phosphorus, and (3) inorganic phosphorus. Inorganic phosphorus, primarily in the form of orthophosphate ($OP(OR)_3$), is readily utilized by aquatic organisms. Some organisms may store excess phosphorus as polyphosphate. At the same time, some PO_4^{3-} is continuously lost to sediments, where it is locked up in insoluble precipitates (Craggs, 2005; Crites et al., 2006; Lynch and Poole, 1979). Phosphorus removal in ponds occurs via physical mechanisms such as adsorption, coagulation, and precipitation. The uptake of phosphorus by organisms in metabolic function as well as for storage can also contribute to its removal. Removal in wastewater ponds has been reported to range from 30 to 95% (Assenzo and Reid, 1966; Crites et al., 2006; Pearson, 2005). Algae discharged in the final effluent may introduce organic phosphorus to receiving waters. Excessive algal "afterblooms" observed in waters receiving effluents have, in some cases, been attributed to nitrogen and phosphorus compounds remaining in the treated wastewater.

Sulfur Sulfur (S) is a required nutrient for microorganisms, and it is usually present in sufficient concentration in natural waters. Because sulfur is rarely limiting, its removal from wastewater is usually not considered necessary. Ecologically, sulfur compounds such as hydrogen sulfide (H_2S) and sulfuric acid (H_2SO_4) are toxic, while the oxidation of certain sulfur compounds is an important energy source for some aquatic bacteria (Lynch and Poole, 1979; Pearson, 2005).

Carbon The decomposable organic carbon (C) content of a waste is traditionally measured in terms of its BOD_5, or the amount of O_2 required under standardized conditions for the aerobic biological stabilization of the organic matter over a certain period of time. Because complete treatment by biological oxidation can take several weeks, depending on the organic material and the organism present, standard practice is to use the BOD_5 as an index of the organic carbon content or organic strength of a waste. The removal of BOD_5 is a primary criterion by which treatment efficiency is evaluated. BOD_5 reduction in wastewater ponds ranging from 50 to 95% has been reported in the literature. Various factors affect the rate of reduction of BOD_5. A very rapid reduction occurs in a wastewater pond during the first 5 to 7 days. Subsequent reductions take place at a sharply reduced rate. BOD_5 removals are generally much lower during winter and early spring than in summer and early fall. Many regulatory agencies recommend that pond operations do not include discharge during cold periods.

Process Control Calculations for Stabilization Ponds

Process control calculations are an important part of wastewater treatment operations, including pond operations.

Determining Pond Area in Acres

$$\text{Area (ac)} = \frac{\text{Area (ft}^2)}{43{,}560 \text{ ft}^2/\text{ac}} \tag{8.41}$$

Determining Pond Volume in Ac-Ft

$$\text{Volume (ac-ft)} = \frac{\text{Volume (ft}^3\text{)}}{43{,}560\ \text{ft}^3\text{/ac-ft}} \tag{8.42}$$

Determining Flow Rate in Ac-Ft/Day

$$\text{Flow (ac-ft/day)} = \text{Flow (MGD)} \times 3.069\ \text{ac-ft/MG} \tag{8.43}$$

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-ac top and depth of 1 ft—but the top does not have to be an even number of acres in size to use acre-feet.

Determining Flow Rate in Ac-In./Day

$$\text{Flow (ac-in./day)} = \text{Flow (MGD)} \times 36.8\ \text{ac-in./MG} \tag{8.44}$$

Hydraulic Detention Time in Days

$$\text{Detention time (days)} = \frac{\text{Pond volume (ac-ft)}}{\text{Influent flow (ac-ft/day)}} \tag{8.45}$$

Note: Normally, hydraulic detention time ranges from 30 to 120 days for stabilization ponds.

■ EXAMPLE 8.28

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:

$$\text{Flow} = 0.30\ \text{MGD} \times 3.069\ \text{ac-ft/MG} = 0.92\ \text{ac-ft/day}$$

$$\text{Detention time} = \frac{53.5\ \text{ac}}{0.92\ \text{ac-ft/day}} = 58.2\ \text{days}$$

Hydraulic Loading in In./Day (Overflow Rate)

$$\text{Hydraulic loading (in./day)} = \frac{\text{Influent flow (ac-in./day)}}{\text{Pond area (ac)}} \tag{8.46}$$

Population Loading in People/Acre/Day

$$\text{Population loading (people/ac/day)} = \frac{\text{Population that system serves (people)}}{\text{Pond area (ac)}} \tag{8.47}$$

Note: Population loading normally ranges from 50 to 500 people per acre.

Organic Loading Organic loading can be expressed as pounds of BOD_5 per acre per day (most common), pounds BOD_5 per acre-foot per day, or people per acre per day.

$$\text{Organic loading (lb BOD}_5\text{/ac/day)} = \frac{\text{BOD}_5\text{ (mg/L)} \times \text{Influent flow (MGD)} \times 8.34}{\text{Pond area (ac)}} \tag{8.48}$$

Note: Normal range is 10 to 50 lb BOD_5 per day per acre.

■ EXAMPLE 8.29

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:

$$725\text{ ft} \times 380\text{ ft} \times \frac{1\text{ ac}}{43{,}560\text{ ft}^2} = 6.32\text{ ac}$$

$$0.12\text{ MGD} \times 160\text{ mg/L} \times 8.34\text{ lb/gal} = 160.1\text{ lb/day}$$

$$\frac{160.1\text{ lb/day}}{6.32\text{ ac}} = 25.3\text{ lb/day/ac}$$

Trickling Filters

Trickling filters have been used to treat wastewater since the 1890s. It was found that if settled wastewater was passed over rock surfaces, slime grew on the rocks and the water became cleaner. Today we still use this principle, but, in many installations, instead of rocks we use plastic media. In most wastewater treatment systems, the trickling filter follows primary treatment and includes a secondary settling tank or clarifier as shown in Figure 8.12. 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 8.13). 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 the media material. The organisms aerobically decompose the solids, producing more organisms and stable wastes, which either become part of the

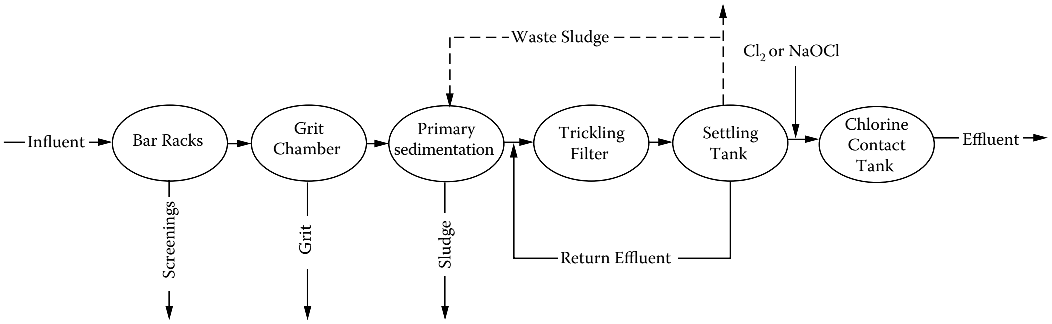

FIGURE 8.12 Simplified flow diagram of trickling filter used for wastewater treatment.

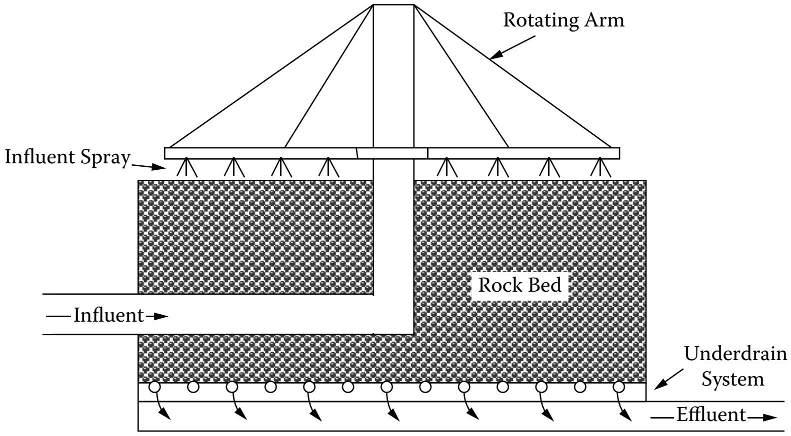

FIGURE 8.13 Schematic of cross-section of a trickling filter.

slime or are discharged back into the wastewater flowing over the media. This slime consists mainly of bacteria, but it may also include algae, protozoa, worms, snails, fungi, and insect larvae. The accumulating slime occasionally sloughs off (*sloughings*) individual media materials (see Figure 8.14); it is collected at the bottom of the filter, along with the treated wastewater, and is passed on to the secondary settling tank where it is removed. The overall performance of the trickling filter is dependent on hydraulic and organic loading, temperature, and recirculation.

Trickling Filter Definitions

To clearly understand the correct operation of the trickling filter, the operator must be familiar with certain terms.

> ***Note:*** The following list of terms applies to the trickling filter process. We assume that other terms related to other units within the treatment system (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-rate trickling filters.*

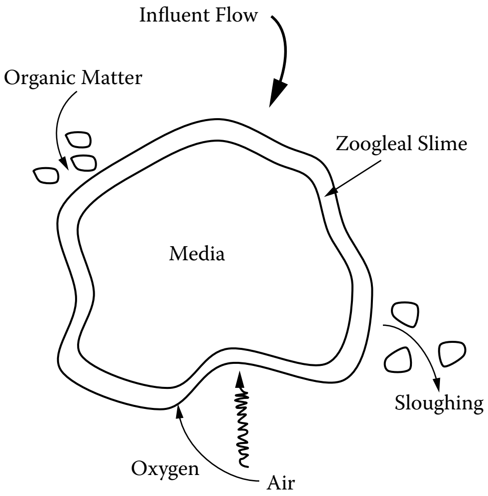

FIGURE 8.14 Filter media showing biological activities that take place on the surface area.

Biomass—The total mass of organisms attached to the media. Similar to the solids inventory in the activated sludge process, it is sometimes referred to as *zoogleal slime.*

Distribution arm—The device most widely used to apply wastewater evenly over the entire surface of the media. In most cases, the force of the wastewater being sprayed through the orifices moves the arm.

Filter underdrain—The open space provided under the media to collect the liquid (wastewater and sloughings) and to allow air to enter the filter. It has a sloped floor to collect the flow to a central channel for removal.

High-rate trickling filters—A classification (see Table 8.21) 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.

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 8.21) in which the organic 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 washes 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.

TABLE 8.21
Trickling Filter Classification

Filter Class	Standard	Intermediate	High Rate	Super High Rate	Roughing
Hydraulic loading (gpd/ft^2)	25–90	90–230	230–900	350–2,100	>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%

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 m 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.

No matter what type of media is selected, the primary consideration is that it must be capable of providing the desired film location for the development of the biomass. Depending on the type of media used and the filter classification, the media may be 3 to 20 ft or more in depth.

The underdrains are designed to support the media, collect the wastewater and sloughings, carry them out of the filter, and provide ventilation to the filter.

> ***Note:*** To ensure sufficient airflow to the filter, the under-drains 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 hr of detention time to separate the sloughing materials from the treated wastewater. The 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 (thus improving 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.

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. Standard-rate, high-rate, and roughing filters are the ones 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 an 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 a 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% removal rate and a 40 to 65% TSS removal rate.

Standard operating procedures for trickling filters include sampling and testing, observation, recirculation, maintenance, and expectations of performance. 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.

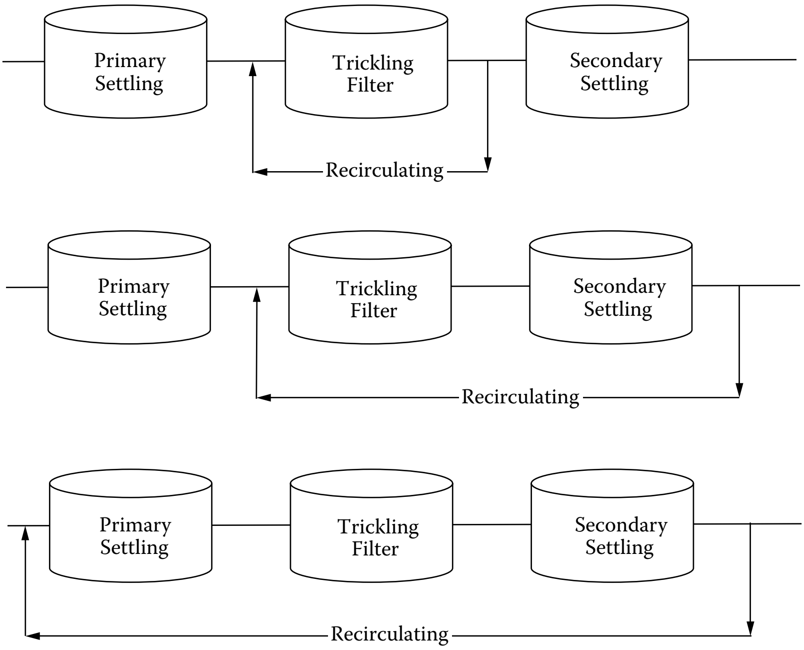

FIGURE 8.15 Common forms of recirculation.

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 MGD). In most cases, it is expressed as a ratio (e.g., 3:1, 0.5:1). The recirculation is always listed as the first number and the influent flow listed 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. 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 8.15. 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. 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, helminths 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:

$$\text{Organics} + \text{Organisms} + \text{O}_2 = \text{More organisms} + \text{CO}_2 + \text{Solid wastes}$$

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). 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 under-drains 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 provides 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 concepts:

  1. Hydraulic loading rate:

$$\frac{\text{gal/day}}{\text{ft}^2} = \frac{\text{Flow (gal/day) (including recirculation)}}{\text{Media top surface (ft}^2\text{)}}$$

  2. Organic loading rate:

$$\frac{\text{lb/day}}{1000\ \text{ft}^3} = \frac{\text{BOD in filter (lb/day)}}{\text{Media volume (1000 ft}^3\text{)}}$$

  3. Recirculation ratio:

$$\text{Recirculation ratio} = \frac{\text{Recirculation flow (MGD)}}{\text{Average influent flow (MGD)}}$$

Process Control Calculations

Several calculations are useful in the operation of a trickling filter, including total flow, hydraulic loading, and organic loading.

Total Flow If the recirculated flow rate is given, total flow is

$$\begin{aligned}\text{Total flow (MGD)} &= \text{Influent flow (MGD)} + \text{Recirculation flow (MGD)}\\ \text{Total flow (gpd)} &= \text{Total flow (MGD)} \times 1{,}000{,}000\ \text{gal/MG}\end{aligned} \tag{8.49}$$

> ***Note:*** The total flow to the tricking 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 8.30

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:

$$\text{Total flow} = 3.65\text{ MGD} \times (1.5 + 1.0) = 9.13\text{ MGD}$$

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 8.31

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 units gpd/ft^2.

Solution: The primary effluent and recirculated trickling filter effluent are applied together across the surface of the filter; therefore,

$$0.488\text{ MGD} + 0.566\text{ MGD} = 1.054\text{ MGD} = 1{,}054{,}000\text{ gpd}$$

$$\text{Circular surface area} = 0.785 \times (\text{Diameter})^2 = 0.785 \times (90\text{ ft})^2 = 6359\text{ ft}^2$$

$$\frac{1{,}054{,}000\text{ gpd}}{6359\text{ ft}^2} = 165.7\text{ gpd/ft}^2$$

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 8.32

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 900 ft^3 of media volume. The primary effluent BOD concentration is 85 mg/L. The media depth is 9 ft.

Solution:

$$0.445\text{ MGD} \times 85\text{ mg/L} \times 8.34\text{ lb/gal} = 315.5\text{ BOD}$$

$$\text{Surface area} = 0.785 \times (50)^2 = 1962.5\text{ ft}^2$$

$$\text{Area} \times \text{Depth} = \text{Volume}$$

$$1962.5\text{ ft}^2 \times 9\text{ ft} = 17{,}662.5\text{ ft}^3$$

> **Note:** 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:

$$\text{BOD} = \frac{315.5\ \text{lb} \times 1000}{17{,}662.5} \times \frac{\text{lb BOD/day}}{1000\ \text{ft}^3} = 17.9\ \text{lb BOD/day/1000 ft}^3$$

Settling Tanks In the operation of settling tanks that follow trickling filters, calculations routinely made include determining detention time, surface settling rate, hydraulic loading, and sludge pumping.

Rotating Biological Contactors

The rotating biological contactor (RBC) is a biological treatment system (see Figure 8.16) and is a variation of the attached-growth idea provided by the trickling filter. Still relying on microorganisms that grow on the surface of a medium, the RBC is instead a fixed-film biological treatment device, but the basic biological process is similar to that occurring in the trickling filter. An RBC consists of a series of closely spaced (mounted side by side), circular, plastic (synthetic) disks that are typically about 3.5 m in diameter and attached to a rotating horizontal shaft (see Figure 8.16). 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 required 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 8.17) 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 a RBC system is significant, especially when multiple stages are employed.

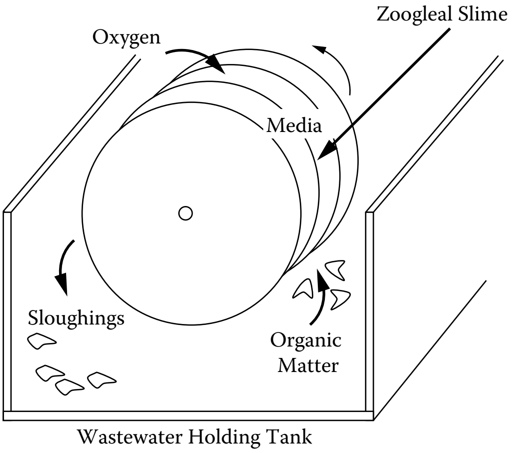

FIGURE 8.16 Rotating biological contactor (RBC) cross-section and treatment system.

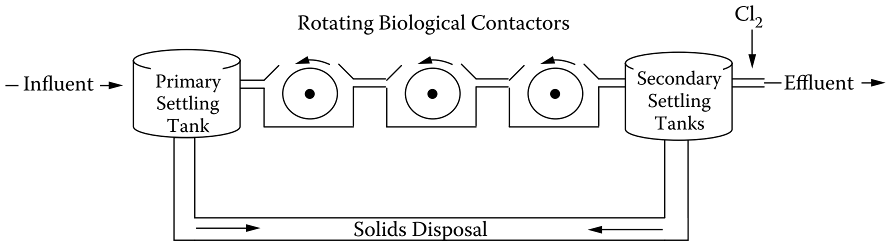

FIGURE 8.17 Rotating biological contactor (RBC) treatment system.

RBC Equipment

The equipment that makes up a 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 has indicated 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. Adjustments 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 provided to remove 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.

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, golden shaggy growth indicates nitrification.
- 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.

The RBC normally produces a high-quality effluent with BOD_5 at 85 to 95% and suspended solids removal at 85 to 95%. The RBC treatment process may also significantly reduce (if designed for this purpose) the levels of organic nitrogen and ammonia nitrogen.

Process Control Calculations

Several process control calculations may be useful in the operation of an RBC. These include soluble BOD, total media area, organic loading rate, and hydraulic loading rate. Settling tank calculations and sludge pumping calculations may be helpful for evaluation and control of the settling tank following the RBC.

RBC Soluble BOD The soluble BOD_5 concentration of the RBC influent can be determined experimentally in the laboratory, or it can be estimated using the suspended solids concentration and the K factor. The K factor is used to approximate the BOD_5 (particulate BOD) contributed by the suspended matter. The K factor must be provided or determined experimentally in the laboratory. The K factor for domestic wastes is normally in the range in the range of 0.5 to 0.7.

$$\text{Soluble BOD}_5 = \text{Total BOD}_5 - (K \text{ factor} \times \text{Total suspended solids}) \tag{8.50}$$

■ EXAMPLE 8.33

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?

Solution: The K value of 0.6 indicates that about 60% of the suspended solids are organic suspended solids (particulate BOD).

$$250 \text{ mg/L} \times 0.6 = 150 \text{ mg/L particulate BOD}$$

■ EXAMPLE 8.34

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:

$$\text{Total BOD} = \text{Particulate BOD} + \text{soluble BOD}$$

$$170 \text{ mg/L} = (140 \text{ mg/L} \times 0.7) + x \text{ mg/L}$$

$$170 \text{ mg/L} = 98 \text{ mg/L} + x \text{ mg/L}$$

$$170 \text{ mg/L} - 98 \text{ mg/L} = x \text{ mg/L}$$

$$x = 72 \text{ mg/L soluble BOD}$$

Now, we can determine the lb/day soluble BOD:

$$\text{Soluble BOD (mg/L)} \times \text{Flow (MGD)} \times 8.34 \text{ lb/gal} = \text{lb/day}$$

$$72 \text{ mg/L} \times 2.2 \text{ MGD} \times 8.34 \text{ lb/gal} = 1321 \text{ lb/day}$$

RBC Total Media Area Several process control calculations for the RBC use the total surface area of all 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.

$$\text{Total area} = \text{1st stage area} + \text{2nd stage area} + \ldots + n\text{th stage area} \tag{8.51}$$

RBC Organic Loading Rate If the soluble BOD concentration is known, the organic loading on a RBC can be determined. Organic loading on an RBC based on soluble BOD concentration can range from 3 to 4 lb/day/1000 ft^2.

■ EXAMPLE 8.35

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/1000 ft^2?

Solution:

$$0.269\text{ MGD} \times 159\text{ mg/L} \times 8.34\text{ lb/gal} = 356.7\text{ lb/day}$$

$$\frac{356.7\text{ lb/day}}{102{,}500\text{ ft}^2} \times \frac{1000\text{ (number)}}{1000\text{ (unit)}} = 3.48\text{ lb/day/1000 ft}^2$$

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 (ft^2). Hydraulic loading on a RBC can range from 1 to 3 gpd/ft^2.

■ EXAMPLE 8.36

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:

$$233{,}000\text{ gpd} \div 96{,}600\text{ ft}^2 = 2.41\text{ gpd/ft}^2$$

ACTIVATED SLUDGE

The biological treatment systems discussed to this point—ponds, trickling filters, and rotating biological contactors—have been around for years. The trickling filter, for example, has been 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.

> **Note:** 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.

As shown in Figure 8.8, 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 8.18). 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). A portion of the concentrated solids from the bottom of the settling tank must be removed from the process (waste activated sludge, or WAS). Clear supernatant from the final settling tank is the plant effluent.

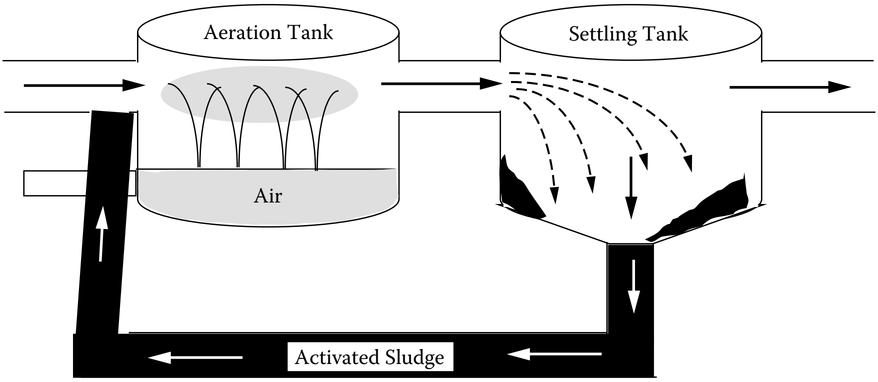

FIGURE 8.18 Activated sludge process.

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 list 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—To speed up 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 is agitated and aerated. The activated sludge is subsequently separated from the treated mixed liquor by sedimentation and is returned to the process as needed. The treated wastewater overflows the weir of the settling tank in which separation from the sludge takes place.

Adsorption—The adherence of dissolved, colloidal, or finely divided solids to the surface of solid bodies when they are brought into contact.

Aeration—Mixing air and a liquid by one of the following methods: spraying the liquid in the air, diffusing air into the liquid, or agitating the liquid to promote surface adsorption of air.

Aerobic—A condition in which free or dissolved oxygen is present in the aquatic environment. Aerobic organisms must be in the presence of dissolved oxygen to be active.

Bacteria—Single-cell plants that play a vital role in stabilization of organic waste.

Biochemical oxygen demand (BOD)—A measure of the amount of food available to 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.

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.

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.

Dissolved oxygen—Atmospheric oxygen dissolved in water or wastewater; usually abbreviated as DO. The typical required DO for a well-operated activated sludge plant is between 2.0 and 2.5 mg/L.

Facultative bacteria—Bacteria that can use 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-microorganism ratio—A process control calculation used to evaluate the amount of food (BOD or COD) available per pound of mixed liquor volatile suspended solids. This may be written as the 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.

Mean cell residence time (MCRT)—The average length of time particles of mixed liquor suspended solids remain in the activated sludge process; may also be referred to as the *sludge retention time*:

$$\text{MCRT (days)} = \frac{\text{Solids in activated sludge process (lb)}}{\text{Solids removed from process (lb/day)}}$$

Mixed liquor—The contribution of return activated sludge and wastewater (either influent or primary effluent) that flows into the aeration tank.

Mixed liquor suspended solids (MLSS)—The suspended solids concentration of the mixed liquor. Many references use this concentration to represent the amount of organisms in the activated sludge process.

Mixed liquor volatile suspended solids (MLVSS)—The organic matter in the mixed liquor suspended solids; 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 relatively short time.

Rotifers—Multicellular animals with flexible bodies and cilia near the mouth that are used to attract food. Bacteria and algae are their major sources 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 min 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. Requires the SSV_{30} and mixed liquor suspended solids test results to calculate:

$$\text{SVI (mL/g)} = \frac{\text{30-min settled volume (ml/L)} \times 1000\text{ mg/g}}{\text{Mixed liquor suspended solids (mg/L)}}$$

Solids—Material in the solid state.

- *Dissolved solids*—Solids present in solution; solids that will pass through a glass fiber filter.
- *Fixed solids*—Also known as the *inorganic solids*; the solids left after a sample is ignited at 550°C for 15 min.
- *Floatable solids (scum)*—Solids that will float to the surface of still water, sewage, or other liquid; usually composed of grease particles, oils, light plastic material, etc.
- *Nonsettleable solids*—Finely divided suspended solids that will not sink to the bottom in still water, sewage, or other liquid in a reasonable period, usually two hours; also known as *colloidal solids*.
- *Suspended solids*—Solids that will not pass through a glass-fiber filter.
- *Total solids*—Solids in water, sewage, or other liquids, including suspended solids and dissolved solids.
- *Volatile solids*—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.

Activated Sludge Process

Equipment requirements for the activated sludge process are more complex than other processes discussed. The equipment includes an *aeration tank*, *aeration system*, *system-settling tank*, *return sludge system*, and *waste sludge system*. These are discussed in the following.

Aeration Tank

The aeration tank is designed to provide the required detention time (depending 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.

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.

Settling Tank

Activated sludge systems are equipped with plain settling tanks designed to provide 2 to 4 hr of hydraulic detention time.

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.

Waste 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.

Overview of Activated Sludge Process

The activated sludge process is a treatment technique in which wastewater and reused biological sludge full of living microorganisms are mixed and aerated. The biological solids are then separated from the treated wastewater in a clarifier and are returned to the aeration process or wasted. The microorganisms are mixed thoroughly with the incoming organic material, and they grow and reproduce by using the organic material as food. As they grow and are mixed with air, the individual organisms cling together (flocculate). Once flocculated, they more readily settle in the secondary clarifiers.

The wastewater being treated flows continuously into an aeration tank where air is injected to mix the wastewater with the return activated sludge and to supply the oxygen 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.

Factors Affecting Operation of the Activated Sludge Process

A number of factors affect the performance of an activated sludge system, including 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 amounts 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 we 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.

Microorganism 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 8.19). 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. The actual operation of an activated sludge system is regulated by three factors: (1) the quantity of air supplied to the aeration tank, (2) the rate of activated sludge recirculation, and (3) the amount of excess sludge withdrawn from the system. Sludge wasting is an important operational practice because it allows the operator to establish the desired concentration of MLSS, food-to-microorganism ratio, and sludge age.

> ***Note:*** Air requirements in an activated sludge basin are governed by: (1) biochemical oxygen demand (BOD) loading and the desired removal effluent, (2) volatile suspended solids concentration in the aerator, and (3) suspended solids concentration of the primary effluent.

Activated Sludge Formation

The formation of activated sludge is dependent on three steps. The first step is the transfer of food from wastewater to organism. Second is the conversion of wastes to a usable form. Third is the flocculation step.

1. *Transfer*—Organic matter (food) is transferred from the water to the organisms. Soluble material is absorbed directly through the cell wall. Particulate and colloidal matter is adsorbed to the cell wall, where it is broken down into simpler soluble forms, then absorbed through the cell wall.
2. *Conversion*—Food matter is converted to cell matter by synthesis and oxidation into end products such as CO_2, H_2O, NH_3, stable organic waste, and new cells.

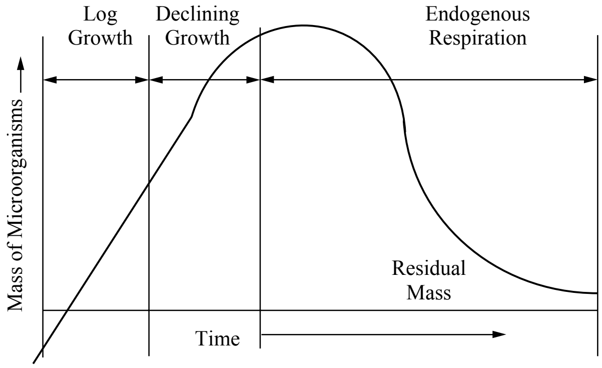

FIGURE 8.19 Microorganism growth curve.

3. *Flocculation*—Flocculation is the gathering of fine particles into larger particles. This process begins in the aeration tank and is the basic mechanism for removal of suspended matter in the final clarifier. The concentrated *biofloc* that settles and forms the sludge blanket in the secondary clarifier is known as activated sludge.

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, here, 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.

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.

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.

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.

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.

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.

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 added by operators is the uninhibited use of chlorine for odor control or control of filamentous organisms (prechlorination). Chlorination is for disinfection. Chlorine is a toxicant and should not be allowed to enter the activated sludge process; it is not selective with respect to the type of organisms damaged or killed. It may kill the organisms that should be retained in the process as workers. Chlorine is very effective in disinfecting the plant effluent after treatment by the activated sludge process, however.

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, then the system is hydraulically overloaded. If less flow is entering the system than it was designed for, then 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 causes. Underloading normally occurs during periods of drought or in the period following initial startup when the plant has not reached its design capacity. Excess hydraulic flow rates through the treatment plant will reduce the efficiency of the clarifier by allowing activated sludge solids to rise in the clarifier and pass over the effluent weir. This loss of solids in the effluent degrades effluent quality and reduces the amount of activated sludge in the system, in turn, reducing process performance.

Organic Loading

Organic loading is the amount of organic matter entering the treatment plant. It is usually measured as biochemical oxygen demand (BOD). An organic overload occurs when the amount of BOD entering the system exceeds the design capacity of the system. An organic underload occurs when the amount of BOD entering the system is significantly less than the design capacity of the plant. Organic overloading may occur when the system receives more waste than it was designed to handle. It can also occur when an industry or other contributor discharges more wastes to the system than originally planned. Wastewater treatment plant processes can also cause organic overloads when 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.

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.

1. *Conventional activated sludge*
    - Employing the conventional activated sludge modification requires primary treatment.
    - Conventional activated sludge provides excellent treatment; however, 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).
2. *Step aeration*
    - Step aeration requires primary treatment.
    - It provides excellent treatment.
    - Operation characteristics are similar to conventional.
    - It distributes organic loading by splitting influent flow.
    - It reduces oxygen demand at the head of the system.
    - It reduces solids loading on the settling tank.

3. *Complete mix*
    - Complete mix may or may not include primary treatment.
    - It distributes waste, return, and oxygen evenly throughout the tank.
    - Aeration may be more efficient.
    - It maximizes tank use.
    - It permits higher organic loading.

Note: During the complete mix, activated sludge process organisms are in the declining phase on the growth curve.

4. *Pure oxygen*
    - Pure oxygen requires primary treatment.
    - It permits higher organic loading.
    - It uses higher solids levels.
    - It operates at higher F/M ratios.
    - It uses covered tanks.
    - It poses a potential safety hazard.
    - Oxygen production is expensive.
5. *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 hours (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 MGD.
- A disadvantage is that common process control calculations do not provide usable information.

6. *Extended aeration*
    - Extended aeration does not require primary treatment.
    - It is used frequently for small flows such as for schools and subdivisions.
    - It uses 24-hour aeration.
    - It produces low BOD effluent.
    - It produces the least amount of waste activated sludge.
    - The process is capable of achieving 95% or greater removal of BOD.
    - It can produce effluent low in organic and ammonia nitrogen.
7. *Oxidation ditch*
    - The oxidation ditch does not require primary treatment. It is similar to the extended aeration process.

Table 8.22 lists the process parameters for each of the four most commonly used activated sludge modifications.

Extended Aeration: Package Plants

One of the most common types of modified active sludge processes that provides biological treatment for the removal of biodegradable organic waste under aerobic conditions is the extended aeration process called the *package plant*. Package plants are pre-manufactured treatment facilities used to treat wastewater in small communities or on individual properties. According to manufacturers, package plants can be designed to treat flows as low as 0.002 MGD or as high as 0.5 MGD, although they more commonly treat flows between 0.01 and 0.25 MGD (Metcalf & Eddy, 1991).

TABLE 8.22
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

In operation, air may be supplied to the extended aeration package plant by mechanical or diffused aeration to provide the oxygen required to sustain the aerobic biological process. Mixing must be provided by aeration or mechanical means to maintain the microbial organisms in contact with the dissolved organics. In addition, the pH must be controlled to optimize the biological process, and essential nutrients must be present to facilitate biological growth and the continuation of biological degradation.

As depicted in Figure 8.20, wastewater enters the treatment system and is typically screened immediately to remove large suspended, settleable, or floating solids that could interfere with or damage equipment downstream in the process. Wastewater may then pass through a grinder to reduce large particles that are not captured in the screening process. If the plant requires the flow to be regulated, the effluent will then flow into equalization basins that regulate peak wastewater flow rates. Wastewater then enters the aeration chamber, where it is mixed and oxygen is provided to the microorganisms. The mixed liquor then flows to a clarifier or settling chamber where most microorganisms settle to the bottom of the clarifier and a portion are pumped back to the incoming

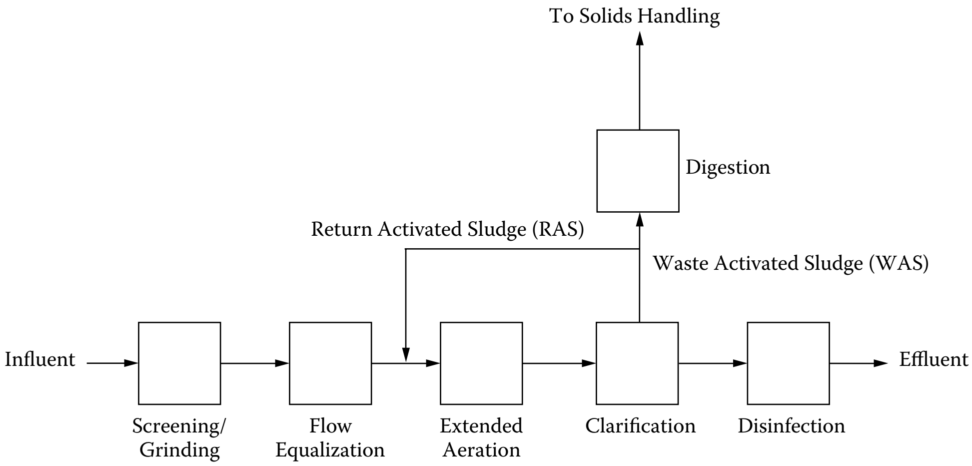

FIGURE 8.20 A typical extended aeration plant.

wastewater at the beginning of the plant. This returned material is the return activated sludge (RAS). The material that is not returned, the waste activated sludge (WAS), is removed for treatment and disposal. The clarified wastewater then flows over a weir and into a collection channel before being diverted to the disinfection system (USEPA, 2000b)

Package plants are typically located in small municipalities, suburban subdivisions, apartment complexes, highway rest areas, trailer parks, small institutions, and other sites where flow rates are below 0.1 MGD. Extended aeration systems are typically manufactured to treat wastewater flow rates between 0.002 and 0.1 MGD. Extended aeration package plants consist of a steel tank that is compartmentalized into flow equalization, aeration, clarification, disinfection, and aerated sludge holding/digestion segments. Use of concrete tanks may be preferable for large sizes (Sloan Equipment, 1999).

Extended aeration plants are usually started up using "seed sludge" from another sewage plant. It may take as many as 2 to 5 weeks from the time it is seeded for the plant to stabilize (Sloan Equipment, 1999). These systems are also useful for areas requiring nitrification. Key internal components of extended aeration treatment package plants consist of the following: transfer pumps to move wastewater between the equalization and aeration zones; a bar screen and/or grinder to decrease the size of large solids; an aeration system consisting of blowers and diffusers for the equalization, aeration, and sludge holding zones; transfer pumps to move wastewater between the equalization and aeration zones; an airlift pump for returning sludge; a skimmer and effluent weir for the clarifier; and UV light, liquid hypochlorite, or tablet modules used in the disinfection zone. Blowers and the control panel containing switches, lights, and motor starters are typically attached to either the top or one side of the package plant (Sloan Equipment, 1999). The advantages and disadvantages are provided below.

Advantages

- Plants are easy to operate, as many are manned for a maximum of two or three hours per day.
- Extended aeration processes are often better at handling organic loading and flow fluctuations, as there is a greater detention time for the nutrients to be assimilated by microbes.
- Systems are easy to install, as they are shipped in one or two pieces and then mounted on an onsite concrete pad, above or below grade.
- Systems are odor free, can be installed in most locations, have a relatively small footprint, and can be landscaped to match the surrounding area.
- Extended aeration systems have a relatively low sludge yield due to long sludge ages, can be designed to provide nitrification, and do not require a primary clarifier.

Disadvantages

- Extended aeration plants do not achieve denitrification of phosphorus removal without additional unit processes.
- Flexibility is limited to adapt to changing effluent requirements resulting from regulatory changes.
- A longer aeration period requires more energy.
- Systems require a larger amount of space and tankage than other "higher rate" processes, which have shorter aeration detention times.

Oxidation Ditches

An oxidation ditch is a modified extended aeration activated sludge biological treatment process that utilizes long solids retention times (SRTs) to remove biodegradable organics. Oxidation ditches are typically complete mix systems, but they can be modified to approach plug flow conditions. (Note: As conditions approach plug flow, diffused air must be used to provide enough mixing. The system will also no longer operate as an oxidation ditch.) Typical oxidation ditch treatment systems

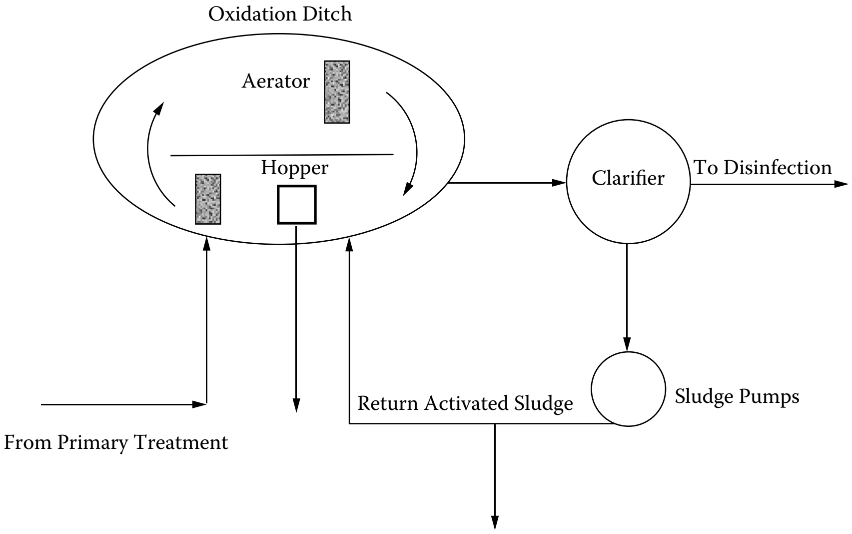

FIGURE 8.21 Typical oxidation ditch activated sludge system.

consist of a single or multi-channel configuration within a ring, oval, or horseshoe-shaped basin. As a result, oxidation ditches are called "racetrack type" reactors. Horizontally or vertically mounted aerators provide circulation, oxygen transfer, and aeration in the ditch.

Preliminary treatment, such as bar screens and grit removal, normally precedes the oxidation ditch. Primary settling prior to an oxidation ditch is sometimes practiced but is not typical in this design. Tertiary filters may be required after clarification, depending on the effluent requirements. Disinfection is required and reaeration may be necessary prior to final discharge. Flow to the oxidation ditch is aerated and mixed with return sludge from a secondary clarifier. A typical process flow diagram for an activated sludge plant using an oxidation ditch is shown in Figure 8.21. Surface aerators, such as brush rotors, disc aerators, draft tube aerators, or fine bubble diffusers, are used to circulate the mixed liquor. The mixing process entrains oxygen into the mixed liquor to foster microbial growth and the motive velocity ensures contact of microorganisms with the incoming wastewater. The aeration sharply increases the dissolved oxygen concentration but it decreases when the biomass uptakes oxygen as the mixed liquor travels through the ditch. Solids are maintained in suspension as the mixed liquor travels through the ditch. If design SRTs are selected for nitrification, a high degree of nitrification will occur. Oxidation ditch effluent is usually settled in a separate secondary clarifier. An anaerobic tank may be added prior to the ditch to enhance biological phosphorus removal.

An oxidation ditch may also be operated to achieve partial denitrification. One of the most common design modifications for enhanced nitrogen removal is known as the Modified Ludzack–Ettinger (MLE) process. In this process, illustrated in Figure 8.22, an anoxic tank is added upstream of the ditch along with mixed liquor recirculation from the aerobic zone to the tank to achieve higher levels of denitrification. In the aerobic basin, autotrophic bacteria (nitrifiers) convert ammonia nitrogen to nitrite nitrogen and then to nitrate nitrogen. In the anoxic zone, heterotrophic bacteria convert nitrate nitrogen to nitrogen gas, which is released to the atmosphere. Some mixed liquor from the aerobic basin is recirculated to the anoxic zone to provide mixed liquor with a high-concentration of nitrate nitrogen to the anoxic zone.

Several manufacturers have developed modifications to the oxidation ditch design to remove nutrients in conditions cycled or phased between the anoxic and aerobic states. Although the mechanics of operation differ by manufacturer, in general the process consists of two separate aeration basins, the first anoxic and the second aerobic. Wastewater and return activated sludge (RAS) are introduced into the first reactor, which operates under anoxic conditions. Mixed liquor then

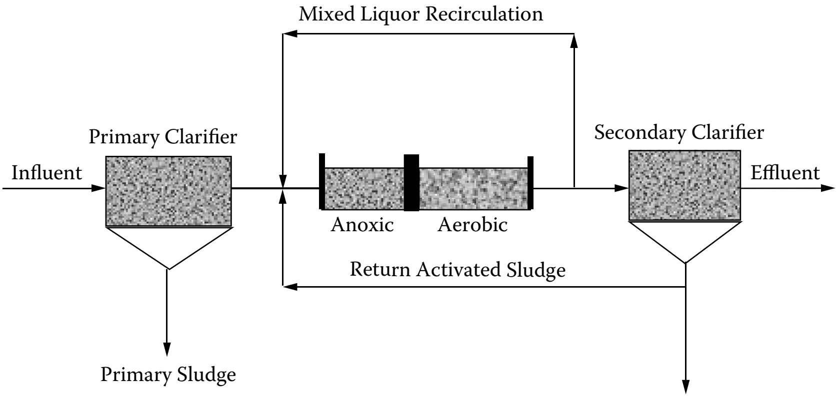

FIGURE 8.22 The Modified Ludzack–Ettinger (MLE) process.

flows into the second reactor, which operates under aerobic conditions. The process is then reversed, and the second reactor begins to operate under anoxic conditions. With regard to applicability, the oxidation ditch process is a fully demonstrated secondary wastewater treatment technology, applicable in any situation where activated sludge treatment (conventional or extend aeration) is appropriate. Oxidation ditches are applicable in plants that require nitrification because the basins can be sized using an appropriate SRT to achieve nitrification at the mixed liquor minimum temperature. This technology is very effective in small installations, small communities, and isolated institutions, because it requires more land than conventional treatment plants (USEPA, 2000).

There are currently more than 9000 municipal oxidation ditch installations in the United States (Spellman, 2007). Nitrification to less than 1 mg/L ammonia nitrogen consistently occurs when ditches are designed and operated for nitrogen removal. An excellent example of an upgrade to the MLE process is provided in the case study that follows. Keep in mind that the motivation for this upgrade was twofold: to improve plant operation (DO optimization) and to conserve energy. The advantages and disadvantages are provided below.

Advantages The main advantage of the oxidation ditch is the ability to achieve removal performance objectives with low operational requirements and low operation and maintenance (O&M) costs. Some specific advantages of oxidation ditches include the following:

- An added measure of reliability and performance is provided compared to other biological processes due to a constant water level and continuous discharge which lowers the weir overflow rate and eliminates the periodic effluent surge common to other biological processes, such as SBRS.
- Long hydraulic retention time and complete mixing minimize the impact of a shock load or hydraulic surge.
- It produces less sludge than other biological treatment processes due to extended biological activity during the activated sludge process.
- Energy efficient operations result in reduced energy costs compared with other biological treatment processes.

Disadvantages

- Effluent suspended solids concentrations are relatively high compared to other modifications of the activated sludge process.
- The process requires a larger land area than other activated sludge treatment options. This can prove costly, limiting the feasibility of oxidation ditches in urban, suburban, or other areas where land acquisition costs are relatively high (USEPA, 2000).

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.

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.

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.

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.

Mixed Liquor Suspended Solids, Mixed Liquor Volatile Suspended Solids, and Mixed Liquor Total Suspended Solids

The mixed liquor suspended solids (MLSS) or mixed liquor volatile suspended solids (MLVSS) can be used to represent the activated sludge or microorganisms present in the process. Process control calculations, 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 mixed liquor total suspended solids (MLTSS) are 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.

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.

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.

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 microorganism populations or process performance.

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 carryover 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-in. intervals; the pipe is equipped with a ball valve at the bottom.

DISINFECTION OF WASTEWATER

Like drinking water, liquid wastewater effluent is disinfected. Unlike drinking water, however, wastewater effluent is disinfected not to directly 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 as 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 chlorine's unique ability 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. In this section, we discuss basic chlorination and dechlorination. In addition, we describe the use of ultraviolet (UV) irradiation, ozonation, bromine chloride, and no disinfection. Keep in mind that much of the chlorination material presented in the following is similar to the chlorination information presented earlier in the water disinfection section.

Chlorine Disinfection

Chlorination for disinfection, as shown in Figure 8.8, follows all other steps in conventional wastewater treatment. The purpose of chlorination is to reduce the population of organisms in the wastewater to levels low enough to ensure that pathogenic organisms will not be present in sufficient quantities to cause disease when discharged. 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 (chloramines) are extremely toxic to aquatic organisms.

> ***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:*** The safest action to take in the event of a major chlorine container leak is to call the fire department.

Chlorination Terminology

Remember that several key terms are used when discussing disinfection by chlorination. Because it is important for the operator to be familiar with these terms, we repeat them here.

Chlorine—Strong oxidizing agent which has strong disinfecting capability. A yellow-green gas which is extremely corrosive, and is toxic to humans in extremely low concentrations in air.

Contact time—The length of time the 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, which 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.

Wastewater Chlorination Facts

- Elemental chlorine (Cl_2, gaseous) is a yellow–green gas, 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 known as *breakpoint chlorination*. For nitrogen removal, enough chlorine is added to the wastewater to convert all the ammonium nitrogen gas. To do this, 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 min to destroy disease-causing microorganisms (pathogens) found in treated wastewater.
- Chlorine may be applied as a gas or a solid or in liquid hypochlorite form.
- Chlorine 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 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, addition of more chlorine will produce free residual chlorine. Producing free residual chlorine in wastewater requires very large additions of chlorine.

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.

Wastewater Chlorination Process Description

Chlorine is a very reactive substance. Chlorine is added to wastewater to satisfy all of the chemical demands—in other words, 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, also have disinfecting capability. This produces a combined residual, which can be measured using residual chlorine test methods. If additional chlorine is added, free residual chlorine 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 residual chlorine of at least 1.0 mg/L for a contact time of at least 30 min at design flow.

> ***Note:*** Residual level, contact time, and effluent quality affect disinfection. Failure to maintain the desired residual levels for the required contact time will result in lower efficiency and increased probability that disease organisms will be discharged.

Based on water quality standards, total residual limitations on chlorine are as follows:

- Freshwater—Less than 11 ppb total residual chlorine
- Estuaries—Less that 7.5 ppb for halogen-produced oxidants
- Endangered species—Use of chlorine prohibited

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 dispense the hypochlorite, which is then mixed with the flow. The treated wastewater then enters the contact tank to provide the required contact time.

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 gas is withdrawn, liquid will be converted to the gas form. This requires heat energy and may result in chlorine line freeze-up if the withdrawal rate exceeds the available energy levels.

In either type of system, normal operation requires adjustment of feed rates to ensure that 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 (respirator/air pack, safety lines, etc.). 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 residual chlorine and may also require collection and analysis of samples to determine the fecal coliform concentration in the effluent.

Chlorination Process Calculations

Several calculations that may be useful in operating a chlorination system. Many of these calculations are discussed and illustrated in this section.

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:

$$\text{Chlorine demand} = \text{Chlorine dose (mg/L)} - \text{Chlorine residual (mg/L)} \tag{8.52}$$

■ EXAMPLE 8.37

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:

$$\text{Chlorine demand (mg/L)} = 7.1\text{ mg/L} - 1.0\text{ mg/L} = 6.1\text{ mg/L}$$

Chlorine Feed Rate Chlorine feed rate is the amount of chlorine added to the wastewater in pounds per day.

$$\text{Chlorine feed rate} = \text{Dose (mg/L)} \times \text{Flow (MGD)} \times 8.34\text{ lb/MG/mg/L} \tag{8.53}$$

■ EXAMPLE 8.38

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:

$$\text{Feed rate} = 5.55\text{ mg/L} \times 22.89\text{ MGD} \times 8.34\text{ lb/MG/mg/L} = 1060\text{ lb/day}$$

Chlorine Dose Chlorine dose is the concentration of chlorine being added to the wastewater. It is expressed in milligrams per liter:

$$\text{Dose (mg/L)} = \frac{\text{Chlorine feed rate (lb/day)}}{\text{Flow (MGD)} \times 8.34\text{ lb/MG/mg/L}} \tag{8.54}$$

■ EXAMPLE 8.39

Problem: Each day, 320 lb of chlorine are added to a wastewater flow of 5.60 MGD. What is the chlorine dose in milligrams per liter?

Solution:

$$\text{Dose} = \frac{320\text{ lb/day}}{5.60\text{ MGD} \times 8.34\text{ lb/MG/mg/L}} = 6.9\text{ mg/L}$$

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:

$$\text{Available chlorine} = \text{Amount of hypochlorite} \times \%\ \text{Available chlorine} \tag{8.55}$$

■ EXAMPLE 8.40

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 pounds of calcium hypochlorite per day?

Solution:

$$\text{Quantity of chlorine} = 30\ \text{lb} \times 0.625 = 18.75\ \text{lb}$$

Required Quantity of Dry Hypochlorite This calculation is used to determine the amount of hypochlorite required to achieve the desired dose of chlorine:

$$\text{Hypochlorite (lb/day)} = \frac{\text{Required chlorine dose (mg/L)} \times \text{Flow (MGD)} \times 8.34\ \text{lb/MG/mg/L}}{\%\ \text{Available chlorine}} \tag{8.56}$$

■ EXAMPLE 8.41

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:

$$\text{Hypochlorite quantity} = \frac{8.8\ \text{mg/L} \times 3.28\ \text{MGD} \times 8.34\ \text{lb/MG/mg/L}}{0.71 \times 8.34\ \text{lb/gal} \times 1.25} = 32.5\ \text{gal/day}$$

Ordering Chlorine Because disinfection must be continuous, the supply of chlorine must never be allowed to run out. The following calculation provides a simple method for determining when additional supplies must be ordered. The process consists of three steps:

1. Adjust the flow and use variations if projected changes are provided.
2. If an increase in flow or required dosage is projected, the current flow rate or dose must be adjusted to reflect the projected change.
3. Calculate the projected flow and dose:

$$\text{Projected flow} = \text{Current flow (MGD)} \times (1.0 + \%\ \text{Change}) \tag{8.57}$$

$$\text{Projected dose} = \text{Current dose (mg/L)} \times (1.0 + \%\ \text{Change}) \tag{8.58}$$

■ EXAMPLE 8.42

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 8.43

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/month). How many pounds of chlorine should be ordered to provide the needed supply?

Solution:

$$\text{Chlorine required} = 90 \text{ lb/day} \times 124 \text{ days} = 11{,}160 \text{ lb}$$

> ***Note:*** In some instances, projections for flow or dose changes are not available but the plant operator wishes to include an extra amount of chlorine as a safety factor. This safety factor can be stated as a specific quantity or as a percentage of the projected usage. A safety factor as a specific quantity can be expressed as

$$\text{Total required } Cl_2 = \text{Chlorine required (lb)} + \text{Safety factor}$$

> ***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, all decimal parts of a cylinder are rounded up to the next highest number of full cylinders.

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 a resurgence in its use in the wastewater field, largely as a consequence of concern for discharge of toxic chlorine residual. Even more recently, UV has gained more attention because of the 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 substituting chlorine for other disinfection alternatives. Moreover, UV technology itself has made many improvements, which now makes UV attractive as a disinfection alternative. Ultraviolet light has very good germicidal qualities and is very 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)

For any one treatment plant, disinfection success is directly related to the concentration of colloidal and particulate constituents in the wastewater. 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 BOD_5 and total suspended solids. The main components of a UV disinfection system are mercury arc lamps, a reactor, and ballasts. The source of UV radiation is either a low-pressure or medium-pressure mercury arc lamp with low or high intensities.

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 hr 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 waste stream, they must be protected inside 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 the 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.

We stated earlier that turbidity problems have been a problem with UV wastewater treatment—and this is the case. 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 on bulb burnout, buildup of solids on quartz tubes, and UV light intensity is necessary.

Note: UV light is extremely hazardous to the eyes. Never enter an area where UV lights are in operation without proper eye protection. Never look directly into the ultraviolet light.

Advantages

- UV disinfection is effective at inactivating most viruses, spores, and cysts.
- UV disinfection is a physical process rather than a chemical disinfectant; it eliminates the need to generate, handle, transport, or store toxic, hazardous, or corrosive chemicals.
- There is no residual effect that is harmful to humans or aquatic life.
- UV disinfection is user friendly for operators.
- UV disinfection has a shorter contact time when compared with other disinfectants (approximately 20 to 30 seconds with low-pressure lamps).
- UV disinfection equipment requires less space than other methods.

Disadvantages

- Low dosages may not effectively inactivate some viruses, spores, and cysts.
- Organisms can sometimes repair and reverse the destructive effects of UV through a "repair mechanism," known as photoreactivation, or in the absence of light known as "dark repairs."
- A preventive maintenance program is necessary to control fouling of tubes.
- Turbidity and total suspended solids (TSS) in the wastewater can render UV disinfection ineffective. UV disinfection with low-pressure lamps is not as effective for secondary effluent with TSS levels above 30 mg/L.
- UV disinfection is not as cost competitive when chlorination dechlorination is used and fire codes are met (USEPA 1999a).

Applicability

When choosing a UV disinfection system, three critical areas must be considered. The first is primarily determined by the manufacturer; the second, by design and operation and maintenance (O&M); and the third has to be controlled at the treatment facility. Choosing a UV disinfection system depends on three critical factors listed below:

- *Hydraulic properties of the reactor*—Ideally, a UV disinfection system should have a uniform flow with enough axial motion (radial mixing) to maximize exposure to UV radiation. The path that an organism takes in the reactor determines the amount of UV radiation it will be exposed to before inactivation. A reactor must be designed to eliminate short-circuiting and/or dead zones, which can result in inefficient use of power and reduced contact time.
- *Intensity of the UV radiation*—Factors affecting the intensity are the age of the lamps, lamp fouling, and the configuration and placement of lamps in the reactor.
- *Wastewater characteristics*—These include the flow rate, suspended and colloidal solids, initial bacterial density, and other physical and chemical parameters. Both the concentration of TSS and the concentration of particle-associated microorganisms determine how much UV radiation ultimately reaches the target organism. The higher these concentrations, the lower the UV radiation absorbed by the organisms. UV disinfection can be used in plants of various sizes that provide secondary or advanced levels of treatment.

Operation and Maintenance

The proper O&M of a UV disinfection system can ensure that sufficient UV radiation is transmitted to the organisms to render them sterile. All surfaces between the UV radiation and the target organism must be clean, and the ballasts, lamps, and reactors must be functioning at peak efficiency. Inadequate cleaning is one of the most common causes of a UV system's ineffectiveness. The quartz sleeves or Teflon tubes must be cleaned regularly by mechanical wipes, ultrasonics, or chemicals. The cleaning frequency is very site specific; some systems need to be cleaned more often than others.

Chemical cleaning is most commonly accomplished with citric acid. Other cleaning agents include mild vinegar solutions and sodium hydrosulfite. A combination of cleaning agents should be tested to find the agent most suitable for the wastewater characteristics without producing harmful or toxic byproducts. Noncontact reactor systems are most effectively cleaned by using sodium hydrosulfite.

Any UV disinfection system should be pilot tested prior to full-scale platform to ensure that it will meet discharge permit requirements for a particular site. The average lamp life ranges from 8760 to 14,000 working hours, and the lamps are usually replaced after 12,000 hours of use. Operating procedures should be set to reduce the on/off cycles of the lamps, since efficacy is reduced with repeated cycles. The ballast must be compatible with the lamps and should be ventilated to protect it from excessive heating, which may shorten its life or even result in fires. Although the life cycle of ballasts is approximately 10 to 15 years, they are usually replaced every 10 years. Quartz sleeves will last about 5 to 8 years but are generally replaced every 5 years (USEPA, 1999a).

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.

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 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.

> ***Note:*** Ozone has certain advantages over chlorine for disinfection of wastewater, in that: (1) ozone increases DO 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.

Advantages

- Ozone is more effective than chlorine in destroying viruses and bacteria.
- The ozonation process utilizes a short contact time (approximately 10 to 30 minutes).
- There are no harmful residuals that need to be removed after ozonation because ozone decomposes rapidly.
- After ozonation, there is no regrowth of microorganisms, except those protected by the particulates in the wastewater stream.
- Ozone is generated onsite; thus, there are fewer safety problems associated with shipping and handling.
- Ozonation elevates the dissolved oxygen (DO) concentration of the effluent. The increase in DO can eliminate the need for reaeration and raise the level of DO in the receiving stream.

Disadvantages

- Low dosage may not effectively inactivate some viruses, spores, and cysts.
- Ozonation is a more complex technology than is chlorine or UV disinfection, requiring complicated equipment and efficient contacting systems.
- Ozone is very reactive and corrosive, thus requiring corrosion-resistant material such as stainless steel.
- Ozonation is not economical for wastewater with high levels of suspended solids (SS), biochemical oxygen demand (BOD), chemical oxygen demand, or total organic carbon.
- Ozone is extremely irritating and possibly toxic, so off-gases from the contactor must be destroyed to prevent worker exposure.
- The cost of treatment can be relatively high in capital and in power intensiveness.

Applicability

Ozone disinfection is generally used at medium to large sized plants after at least secondary treatment. In addition to disinfection, another common use for ozone in wastewater treatment is odor control. Ozone disinfection is the least used method in the United States, although this technology has been widely accepted in Europe for decades. Ozone treatment has the ability to achieve higher levels of disinfection than either chlorine or UV; however, the capital costs as well as maintenance expenditures are not competitive with available alternatives. Ozone is therefore used only sparingly, primarily in special cases where alternatives are not effective (USEPA, 1999b).

Operation and Maintenance

Ozone generation uses a significant amount of electrical power; thus, constant attention must be given to the system to ensure that power is optimized for controlled disinfection performance. There must be no leaking connections in or surrounding the ozone generator. The operator must on a regular basis monitor the appropriate subunits to ensure that they are not overheated; therefore, the operator must check for leaks routinely, since a very small leak can cause unacceptable ambient ozone concentrations. The ozone monitoring equipment must be tested and calibrated as recommended by the equipment manufacturer.

Like oxygen, ozone has limited solubility and decomposes more rapidly in water than in air. This factor, along with ozone reactivity, requires that the ozone contactor be well covered and that the ozone diffuses into the wastewater as effectively as possible. Ozone in gaseous form is explosive once it reaches a concentration of 240 g/m^3. Because most ozonation systems never exceed a gaseous ozone concentration of 50 to 200 g/m^3, this is generally not a problem. However, ozone in gaseous form will remain hazardous for a significant amount of time, so extreme caution is necessary when operating ozone gas systems. It is important that the ozone generator, distribution, contracting, off-gas, and ozone destructor inlet piping be purged before opening the various systems or subsystems.

When entering the ozone contactor, personnel must recognize the potential for oxygen deficiencies or trapped ozone gas in spite of best efforts to purge the system. The operator should be aware of all emergency operating procedures required if a problem occurs. All safety equipment should be available for operators to use in case of an emergency. Key O&M parameters include the following:

- Clean feed gas with a dew point of –60°C (–76°F), or lower, must be delivered to the ozone generator. If the supply gas is moist, the reaction of the ozone and the moisture will yield a very corrosive condensate on the inside of the ozonator. The output of the generator could be lowered by the formation of nitrogen oxides (such as nitric acid).
- Maintain the required flow of generator coolant (air, water, or other liquid).
- Lubricate the compressor or blower in accordance with the manufacturer's specifications. Ensure that all compressor sealing gaskets are in good conditions.
- Operate ozone generators within their design parameters. Regularly inspect and clean the ozonator, air supply, and dielectric assemblies, and monitor the temperature of the ozone generator.
- Monitor the ozone gas-feed and distribution system to ensure that the necessary volume comes into sufficient contact with the wastewater.
- Maintain ambient levels of ozone below the limits of applicable safety regulations.

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.

No Disinfection

In a very limited number of cases, treated wastewater discharges without disinfection are permitted. Such discharges 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.

ADVANCED WASTEWATER TREATMENT

Advanced wastewater treatment is defined as the methods and processes that remove more contaminants (suspended and dissolved substances) from wastewater than are taken out by conventional biological treatment. Put another way, advanced wastewater treatment is the application of a process or system that follows secondary treatment or that includes phosphorus removal or nitrification in conventional secondary treatment.

Advanced wastewater treatment is used to augment conventional secondary treatment because secondary treatment typically removes only between 85 and 95% of the biochemical oxygen demand (BOD) and total suspended solids (TSS) in raw sanitary sewage. Generally, this leaves 30 mg/L or less of BOD and TSS in the secondary effluent. To meet stringent water quality standards, this level of BOD and TSS in secondary effluent may not prevent violation of water quality standards—the plant may not make permit. Thus, advanced wastewater treatment is often used to remove additional pollutants from treated wastewater.

In addition to meeting or exceeding the requirements of water quality standards, treatment facilities use advanced wastewater treatment for other reasons, as well; for example, conventional secondary wastewater treatment is sometimes not sufficient to protect the aquatic environment. In a stream, for example, when periodic flow events occur, the stream may not provide the amount of dilution of effluent required to maintain the necessary dissolved oxygen (DO) levels for aquatic organism survival.

Secondary treatment has other limitations. It does not significantly reduce the effluent concentration of nitrogen and phosphorus (important plant nutrients) in sewage. An overabundance of these nutrients can overstimulate plant and algae growth such that they create water quality problems. If they are discharged into lakes, for example, these nutrients contribute to algal blooms and accelerated eutrophication (lake aging). Also, the nitrogen in the sewage effluent may be present mostly in the form of ammonia compounds. At high enough concentrations, ammonia compounds can be toxic to aquatic organisms. Yet another problem with these compounds is that they exert a *nitrogenous oxygen* demand in the receiving water, as they convert to nitrates. This process is called *nitrification*.

> ***Note:*** The term *tertiary treatment* is commonly used as a synonym for advanced wastewater treatment; however, these two terms do not have precisely the same meaning. Tertiary suggests a third step that is applied after primary and secondary treatment.

Advanced wastewater treatment can remove more than 99% of the pollutants from raw sewage and can produce an effluent of almost potable (drinking) water quality. Obviously, however, advanced treatment is not cost free. The cost of advanced treatment—costs of operation and maintenance, as well as retrofit of existing conventional processes—is very high (sometimes doubling the cost of secondary treatment). A plan to install advanced treatment technology calls for careful study—the benefit-to-cost ratio is not always significant enough to justify the additional expense.

Even considering the expense, application of some form of advanced treatment is not uncommon. These treatment processes can be physical, chemical, or biological. The specific process used is based on the purpose of the treatment and the quality of the effluent desired.

Chemical Treatment

The purpose of chemical treatment is to remove

- BOD
- Total suspended solids (TSS)
- Phosphorus
- Heavy metals
- Other substances that can be chemically converted to a settleable solid

Chemical treatment is often accomplished as an "add-on" to existing treatment systems or by means of separate facilities specifically designed for chemical addition. In each case, the basic process necessary to achieve the desired results remains the same:

- Chemicals are thoroughly mixed with the wastewater.
- The chemical reactions that occur form solids (coagulation).
- The solids are mixed to increase particle size (flocculation).
- Settling or filtration (separation) then removes the solids.

The specific chemical used depends on the pollutant to be removed and the characteristics of the wastewater. Chemicals may include the following:

- Lime
- Alum (aluminum sulfate)
- Aluminum salts
- Ferric or ferrous salts
- Polymers
- Bioadditives

Microscreening

Microscreening (also called *microstraining*) is an advanced treatment process used to reduce suspended solids. The microscreens are composed of specially woven steel wire fabric mounted around the perimeter of a large revolving drum. The steel wire cloth acts as a fine screen, with openings as small as 20 µm—small enough to remove microscopic organisms and debris. The rotating drum is partially submerged in the secondary effluent, which must flow into the drum then outward through the microscreen. As the drum rotates, captured solids are carried to the top, where a high-velocity water spray flushes them into a hopper or backwash tray mounted on the hollow axle of the drum. Backwash solids are recycled to plant influent for treatment. These units have found greatest application in treatment of industrial waters and final polishing filtration of wastewater effluents. Expected performance for suspended solids removal is 95 to 99%, but the typical suspended solids removal achieved with these units is about 55%. The normal range is from 10 to 80%. The functional design of the microscreen unit involves the following considerations: (1) characterization of the suspended solids with respect to the concentration and degree of flocculation, (2) selection of unit design parameter values that will not only ensure capacity to meet maximum hydraulic loadings with critical solids characteristics but also provide desired design performance over the expected range of hydraulic and solids loadings, and (3) provision of backwash and cleaning facilities to maintain the capacity of the screen (Metcalf & Eddy, 2003).

Filtration

The purpose of filtration processes used in advanced treatment is to remove suspended solids. The specific operations associated with a filtration system are dependent on the equipment used. In operation, wastewater flows to a filter (gravity or pressurized). The filter contains single, dual, or multimedia. Solids are removed when the wastewater flows through the media and remain in the filter. Backwashing the filter as needed removes the trapped solids. Backwash solids are returned to the plant for treatment. The processes typically remove 95 to 99% of the suspended matter.

Membrane Bioreactors

The use of microfiltration membrane bioreactors, a technology that has become increasingly used in the past 10 years, overcomes many of the limitations of conventional systems. These systems have the advantage of combining a suspended-growth biological reactor with solids removal via filtration. The membranes can be designed for and operated in small spaces and with high removal efficiency of contaminants such as nitrogen, phosphorus, bacteria, biochemical oxygen demand, and total suspended solids. The membrane filtration system in effect can replace the secondary clarifier and sand filters in a typical activated sludge treatment system. Membrane filtration allows a higher biomass concentration to be maintained, thereby allowing smaller bioreactors to be used (USEPA, 2007a).

For new installations, the use of MBR systems allows for higher wastewater flow or improved treatment performance in a smaller space than a conventional design (i.e., a facility using secondary clarifiers and sand filters). Historically, membranes have been used for smaller flow systems due to the high capital costs of the equipment and high operation and maintenance (O&M) costs. Today however, they are receiving increased use in larger systems. MBR systems are also well suited for some industrial and commercial applications. The high-quality effluent produced by MBRs makes them particularly applicable to reuse application for surface water discharge applications requiring extensive nutrient (nitrogen and phosphorus) removal (USEPA, 2007a).

Advantages

The advantages of MBR systems over conventional biological systems include better effluent quality, smaller space requirements, and ease of automation. Specifically, MBRs operate at higher volumetric loading rates, resulting in lower hydraulic retention times. The low retention times mean that less space is required compared to a conventional system. MBRs have often been operated with longer solids retention times (SRTs), which results in lower sludge production, but this is not a requirement, and more conventional SRTs have been used (Crawford et al., 2000). The effluent from MBRs contains low concentrations of bacteria, total suspended solids (TSS), biochemical oxygen demand (BOD), and phosphorus. This facilitates high-level disinfection. Effluents are readily discharged to surface streams or can be sold for reuse, such as irrigation (USEPA, 2007a).

Disadvantages

The primary disadvantage of MBR systems is the typically higher capital and operating costs than conventional systems have for the same throughput. O&M costs include membrane cleaning and fouling control, as well as eventual membrane replacement. Energy costs are also higher because of the need for air scouring to control bacterial growth on the membranes. In addition, the waste sludge from such a system might have a low settling rate, resulting in the need for chemicals to produce biosolids acceptable for disposal (Hermanowicz et al., 2006). Fleischer et al. (2005) demonstrated that waste sludge from MBRs can be processed using standard technologies used for activated sludge processes.

Biological Nitrification

Biological nitrification is the first basic step in the process of *biological nitrification–denitrification*. In nitrification, the secondary effluent is introduced into another aeration tank, trickling filter, or biodisc. Because most of the carbonaceous BOD has already been removed, the microorganisms that drive in this advanced step are the nitrifying bacteria *Nitrosomonas* and *Nitrobacter*. In nitrification, the ammonia nitrogen is converted to nitrate nitrogen, producing a *nitrified effluent*. At this point, the nitrogen has not actually been removed, only converted to a form that is not toxic to aquatic life and that does not cause an additional oxygen demand. The nitrification process can be limited (performance affected) by alkalinity (requires 7.3 parts alkalinity to 1.0 part ammonia nitrogen), pH, dissolved oxygen availability, toxicity (ammonia or other toxic materials), and process mean cell residence time (sludge retention time). As a general rule, biological nitrification is more effective and achieves higher levels of removal during the warmer times of the year.

Biological Denitrification

Biological denitrification removes nitrogen from the wastewater. When bacteria come in contact with a nitrified element in the absence of oxygen, they reduce the nitrates to nitrogen gas, which escapes the wastewater. The denitrification process can be carried out in either an anoxic activated sludge system (suspended-growth) or a column system (fixed-growth). The denitrification process can remove up to 85% or more of nitrogen. After effective biological treatment, little oxygen demanding material is left in the wastewater when it reaches the denitrification process. The denitrification reaction will only occur if an oxygen demand source exists when no dissolved oxygen is present in the wastewater. An oxygen demand source is usually added to reduce the nitrates quickly. The most common demand source added is soluble BOD or methanol. Approximately 3 mg/L of methanol are added for every 1 mg/L of nitrate-nitrogen. Suspended-growth denitrification reactors are mixed mechanically but only enough to keep the biomass from settling without adding unwanted oxygen. Submerged filters of different types of media may also be used to provide denitrification. A fine media downflow filter is sometimes used to provide both denitrification and effluent filtration. A fluidized sand bed—where wastewater flows upward through a media of sand or activated carbon at a rate to fluidize the bed—may also be utilized. Denitrification bacteria grow on the media.

Carbon Adsorption

The main purpose of carbon adsorption used in advanced treatment processes is the removal of refractory organic compounds (non-BOD_5) and soluble organic materials that are difficult to eliminate by biological or physicochemical treatment. In the carbon adsorption process, wastewater passes through a container filled either with carbon powder or carbon slurry. Organics adsorb onto the carbon (i.e., organic molecules are attracted to the activated carbon surface and are held there) with sufficient contact time. A carbon system usually has several columns or basins used as contactors. Most contact chambers are either open concrete gravity-type systems or steel pressure containers applicable to upflow or downflow operation. With use, carbon loses its adsorptive capacity. The carbon must then be regenerated or replaced with fresh carbon. As head loss develops in carbon contactors, they are backwashed with clean effluent in much the same way the effluent filters are backwashed. Carbon used for adsorption may be in a granular form or in a powdered form.

> ***Note:*** Powdered carbon is too fine for use in columns and is usually added to the wastewater, then later removed by coagulation and settling.

Land Application

The application of secondary effluent onto a land surface can provide an effective alternative to the expensive and complicated advanced treatment methods discussed previously and the biological nutrient removal (BNR) system discussed later. A high-quality polished effluent (i.e., effluent with high levels of TSS, BOD, phosphorus, and nitrogen compounds as well as reduced refractory organics) can be obtained by the natural processes that occur as the effluent flows over the vegetated ground surface and percolates through the soil. Limitations are involved with land application of wastewater effluent. For example, the process needs large land areas. Soil type and climate are also critical factors in controlling the design and feasibility of a land treatment process.

Three basic types or modes of land application or treatment are commonly used: *irrigation* (slow rate), *overland flow*, and *infiltration–percolation* (rapid rate). The basic objectives of these types of land applications and the conditions under which they can function vary. In irrigation (also called *slow rate*), wastewater is sprayed or applied (usually by ridge-and-furrow surface spreading or by sprinkler systems) to the surface of the land. Wastewater enters the soil. Crops growing on the irrigation area utilize available nutrients. Soil organisms stabilize the organic content of the flow. Water returns to the hydrologic cycle through evaporation or by entering the surface water or groundwater.

The irrigation land application method provides the best results (compared with the other two types of land application systems) with respect to advanced treatment levels of pollutant removal. Not only are suspended solids and BOD significantly reduced by filtration of the wastewater, but also biological oxidation of the organics occurs in the top few inches of soil. Nitrogen is removed primarily by crop uptake, and phosphorus is removed by adsorption within the soil. Expected performance levels for irrigation include the following:

- BOD_5, 98%
- Suspended solids, 98%
- Nitrogen, 85%
- Phosphorus, 95%
- Metals, 95%

The overland flow application method utilizes physical, chemical, and biological processes as the wastewater flows in a thin film down the relatively impermeable surface. In the process, wastewater sprayed over sloped terraces flows slowly over the surface. Soil and vegetation remove suspended solids, nutrients, and organics. A small portion of the wastewater evaporates. The remainder flows to collection channels. Collected effluent is discharged to surface waters. Expected performance levels for overland flow include the following:

- BOD_5, 92%
- Suspended solids, 92%
- Nitrogen, 70–90%
- Phosphorus, 40–80%
- Metals, 50%

In the infiltration–percolation application method, wastewater is sprayed or pumped to spreading basins (also known as recharge basins or large ponds). Some wastewater evaporates. The remainder percolates or infiltrates into the soil. Solids are removed by filtration. Water recharges the groundwater system. Most of the effluent percolates to the groundwater; very little of it is absorbed by vegetation. The filtering and adsorption action of the soil removes most of the BOD, TSS, and phosphorous from the effluent; however, nitrogen removal is relatively poor. Expected performance levels for infiltration–percolation include the following:

- BOD_5, 85–99%
- Suspended solids, 98%
- Nitrogen, 0–50%
- Phosphorus, 60–95%
- Metals, 50–95%

Biological Nutrient Removal

Nitrogen and phosphorus are the primary causes of cultural eutrophication (i.e., nutrient enrichment due to human activities) in surface waters. The most recognizable manifestations of this eutrophication are algal blooms that occur during the summer. Chronic symptoms of over-enrichment include low dissolved oxygen, fish kills, murky water, and depletion of desirable flora and fauna. In addition, the increase in algae and turbidity increases the need to chlorinate drinking water, which, in turn, leads to higher levels of disinfection byproducts that have been shown to increase the risk of cancer (USEPA, 2007c). Excessive amounts of nutrients can also stimulate the activity of microbes, such as *Pfisteria*, which may be harmful to human health (USEPA, 2001d).

Approximately 25% of all water body impairments are due to nutrient-related causes (e.g., nutrients, oxygen depletion, algal growth, ammonia, harmful algal blooms, biological integrity, turbidity) (USEPA, 2007d). In efforts to reduce the number of nutrient impairments, many point-source dischargers have received more stringent effluent limits for nitrogen and phosphorus. To achieve these new, lower effluent limits, facilities have begun to look beyond traditional treatment technologies.

Recent experience has reinforced the concept that biological nutrient removal (BNR) systems are reliable and effective in removing nitrogen and phosphorus. The process is based upon the principle that, under specific conditions, microorganisms will remove more phosphorus and nitrogen than is required for biological activity; thus, treatment can be accomplished without the use of chemicals. Not having to use and therefore having to purchase chemicals to remove nitrogen and phosphorus potentially has numerous cost–benefit implications. In addition, because chemicals are not required to be used, chemical waste products are not produced, reducing the need to handle and dispose of waste. Several patented processes are available for this purpose. Performance depends on the biological activity and the process employed.

A number of BNR process configurations are available. Some BNR systems are designed to remove only TN or TP, while others remove both. The configuration most appropriate for any particular system depends on the target effluent quality, operator experience, influent quality, and existing treatment processes, if retrofitting an existing facility. BNR configurations vary based on the sequencing of environmental conditions (i.e., aerobic, anaerobic, and anoxic) and timing (Jeyanayagam, 2005; USEPA, 2007c). Common BNR system configurations include

- *Modified Ludzack–Ettinger (MLE) process*—Continuous-flow suspended-growth process with an initial anoxic stage followed by an aerobic stage (used to remove TN)
- *A^2/O process*—MLE process preceded by an initial anaerobic stage (used to remove both TN and TP)
- *Step-feed process*—Alternating anoxic and aerobic stages; however, influent flow is split to several feed locations and the recycle sludge stream is sent to the beginning of the process (used to remove TN)
- *Bardenpho® process, four-stage*—Continuous-flow, suspended-growth process with alternating anoxic/aerobic/anoxic/aerobic stages (used to remove TN)
- *Modified Bardenpho® process*—Bardenpho® process with the addition of an initial anaerobic zone (used to remove both TN and TP)
- *Sequencing batch reactor (SBR) process*—Suspended-growth batch process sequenced to simulate the four-stage process (used to remove TN; TP removal is inconsistent)
- *Modified University of Cape Town (UCT) process*—A^2/O process with a second anoxic stage where the internal nitrate recycle is returned (used to remove both TN and TP)
- *Rotating biological contactor (RBC) process*—Continuous-flow process using RBCs with sequential anoxic/aerobic stages (used to remove TN)
- *Oxidation ditch*—Continuous-flow process using looped channels to create time-sequenced anoxic, aerobic, and anaerobic zones (used to remove both TN and TP)

Although the exact configurations of each system differ, BNR systems designed to remove TN must have an aerobic zone for nitrification and an anoxic zone for denitrification, and BNR systems designed to remove TP must have an anaerobic zone free of dissolved oxygen and nitrate. Often, sand or other media filtration is used as a polishing step to remove particulate matter when low TN and TP effluent concentrations are required.

Choosing which system is most appropriate for a particular facility primarily depends on the target effluent concentrations and whether the facility will be constructed as new or retrofit with BNR to achieve more stringent effluent limits. New plants have more flexibility and options when deciding which BNR configuration to implement because they are not constrained by existing treatment units and sludge handling procedures. Retrofitting an existing plant with BNR capabilities should involve consideration of the following factors (Park, 2012):

- Aeration basin size and configuration
- Clarifier capacity
- Type of aeration system
- Sludge processing units
- Operator skills

The aeration basin size and configuration dictate the most economical and feasible BNR system configurations. Available excess capacity reduces the need for additional basins and may allow for a more complex configuration (e.g., five-stage Bardenpho® vs. four-state Bardenpho® configuration). The need for additional basins can result in the need for more land if the space needed is not available. If land is not available, another BNR process configuration may have to be considered.

Clarifier capacity influences the return activated sludge (RAS) rate and effluent suspended solids, which in turn, affects effluent TN and TP levels. If the existing facility configuration does not allow for a preanoxic zone so nitrates can be removed prior to the anaerobic zone, then the clarifier should be modified to have a sludge blanket just deep enough to prevent the release of phosphorus to the liquid. However, if a preanoxic zone is feasible, a sludge blanket in the clarifier may not be necessary. The exiting clarifiers also remove suspended solids including particulate nitrogen and phosphorus and thus reduce total nitrogen and phosphorus concentrations. The aeration system will most likely have to be modified to accommodate an anaerobic zone and to reduce the DO concentration in the return sludge. Such modifications could be as simple as removing aeration equipment from the zone designated for anaerobic conditions or changing the type of pump used for the recycled sludge stream (to avoid introducing oxygen).

The manner in which sludge is processed at a facility is important in designing nutrient removal systems. Sludge is recycled within the process to provide the organisms necessary for the TN and TP removal mechanism to occur. The content and volume of sludge recycled directly impacts the system's performance; thus, sludge handling processes may be modified to achieve optimal TN and TP removal efficiencies. For example, some polymers in sludge dewatering could inhibit nitrification when recycled. Also, due to aerobic digestion of sludge process nitrates, denitrification and phosphorus uptake rates may be lowered when the sludge is recycled.

Operators should be able to adjust the process to compensate for constantly varying conditions. BNR processes are very sensitive to influent conditions which are influenced by weather events, sludge processing, and other treatment processes (e.g., recycling after filter backwashing). Therefore, operator skills and training are essential for achieving target TN and TP effluent concentrations (USEPA, 2007c).

Enhanced Biological Nutrient Removal

Removing phosphorus from wastewater in secondary treatment processes has evolved into innovative *enhanced biological nutrient removal* (EBNR) technologies. An EBNR treatment process promotes the production of phosphorus-accumulating organisms, which utilize more phosphorus in their metabolic processes than a conventional secondary biological treatment process (USEPA, 2007). The average total phosphorus concentrations in raw domestic wastewater are usually between 6 and 8 mg/L, and the total phosphorus concentration in municipal wastewater after conventional secondary treatment is routinely reduced to 3 or 4 mg/L. EBNR incorporated into the secondary treatment system can often reduce total phosphorus concentrations to 0.3 mg/L and less.

Facilities using EBNR have significantly reduced the amount of phosphorus to be removed through the subsequent chemical addition and tertiary filtration process. This has improved the efficiency of the tertiary process and significantly reduced the costs of chemicals used to remove phosphorus. Facilities using EBNR reported that their chemical dosing was cut in half after EBNR was installed to remove phosphorus (USEPA, 2007).

Treatment provided by these EBNR processes also reduces other pollutants that commonly affect water quality to very low levels (USEPA, 2007). Biochemical oxygen demand (BOD) and total suspended solids (TSS) are routinely less than 2 mg/L and fecal coliform bacteria less than 10 cfu/100 mL. Turbidity of the final effluent is very low, which allows for effective disinfection using ultraviolet light, rather than chlorination. Recent studies report finding that wastewater treatment facilities using EBNR also significantly reduced the amount of pharmaceuticals and healthcare products from municipal wastewater, as compared to removal accomplished by conventional secondary treatment.

WASTEWATER SOLIDS (SLUDGE/BIOSOLIDS) HANDLING

The wastewater treatment unit processes described to this point remove solids and BOD from the waste stream 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*.

> ***Note:*** *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 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 such as heat treatment, vacuum filtration, and incineration.

Background Information on Sludge

When we speak of *sludge* or *biosolids*, we are speaking of the same substance or 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 the terms *sludge* and *biosolids* is determined by the way they are managed.

> ***Note:*** The task of disposing of, treating, or reusing wastewater solids is *sludge* or *biosolids management*.

Sludge is typically seen as wastewater solids that are disposed of. Biosolids are the same substance but managed for reuse, commonly called *beneficial reuse* (e.g., for land application as a soil amendment, such as biosolids compost). Note that even as wastewater treatment standards have become more stringent because of increasing environmental regulations, so has the volume of wastewater sludge 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. Sludge initially forms as a 3 to 7% suspension of solids; with each person typically generating about 4 gal 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.

Sources of Sludge

Wastewater sludge is generated in primary, secondary, and chemical treatment processes. In primary treatment, the solids that float or settle are removed. The floatable material makes up a portion of the solid waste known as *scum*. Scum is not normally considered sludge; however, it should be disposed of in an environmentally sound way. The settleable material that collects on the bottom of the clarifier is known as *primary sludge*. Primary sludge can also be referred to as *raw sludge* because it has not undergone decomposition. Raw primary sludge from a typical domestic facility is quite objectionable and has a high percentage of water, two characteristics that make handling difficult.

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.

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 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 contains 95 to 99% water (see Table 8.23). This high water content makes sludge handling and processing extremely costly in terms of both money and time. Sludge handling may represent up to 40% of the capital costs and 50% of the operating costs of a treatment plant. As a result, the importance of optimum design for handling and disposal of sludge cannot be overemphasized. The water content of the sludge is present in a number of different forms. Some forms can be removed by several 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 8.24. The forms of water associated with sludges include the following:

- *Free water*—Water that is not attached to sludge solids in any way and can be removed by simple gravitational settling.
- *Floc water*—Water that is trapped within the floc and travels with them; it can be removed by mechanical dewatering.
- *Capillary water*—Water that adheres to the individual particles and can be squeezed out of shape and compacted.
- *Particle water*—Water that is chemically bound to the individual particles and cannot be removed without inclination.

TABLE 8.23
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, DC, 1978.

TABLE 8.24
Distribution of Water in an 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, DC, 1978.

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 will burn or volatilize at 550°C after 15 min in a muffle furnace. The percent organic material 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 min in a muffle furnace. Inorganic solids are generally not subject to breakdown by biological action and are considered stable. Certain inorganic solids, however, can create problems when related to the environment—for example, heavy metals such as copper, lead, zinc, mercury, and others. These can be extremely harmful if discharged.

Organic solids may be subject to biological decomposition in either an aerobic or anaerobic environment. Decomposition of organic matter (with its production of objectionable byproducts) and the possibility of toxic organic solids within the sludge compound the problems of sludge disposal.

The pathogens in domestic sewage are primarily associated with insoluble solids. Primary wastewater treatment processes concentrate these solids into sewage sludge, so untreated or raw primary sewage sludges have higher quantities of pathogens than the incoming wastewater. Biological wastewater treatment processes such as lagoons, trickling filters, and activated sludge treatment may substantially reduce the number of pathogens in wastewater (USEPA, 1989). These processes may also reduce the number of pathogens in sewage sludge by creating adverse conditions for pathogen survival. Nevertheless, the resulting biological sewage sludges may still contain sufficient levels of pathogens to pose a public health and environmental concern. Moreover, insects, birds, rodents, and domestic animals may transport sewage sludge and pathogens from sewage sludge to humans and to animals. Vectors are attracted to sewage sludge as a food source, and reducing the attraction of vectors to sewage sludge to prevent the spread of pathogens is a focus of current regulations. Sludge-borne pathogens and vector attraction are discussed in the following section.

Sludge Pathogens and Vector Attraction

A pathogen is an organism capable of causing disease. Pathogens infect humans through several different pathways including ingestion, inhalation, and dermal contact. The infective dose, or the number of pathogenic organism to which a human must be exposed to become infected, varies depending on the organism and on the health status of the exposed individual. Pathogens that propagate in the enteric or urinary systems of humans and are discharged in feces or urine pose the greatest risk to public health with regard to the use and disposal of sewage sludge. Pathogens are also found in the urinary and enteric systems of other animals and may propagate in non-enteric settings.

The four major types of human pathogenic (disease-causing) organisms—bacteria, viruses, protozoa, and helminths—all may be present in domestic sewage. The actual species and quantity of pathogens present in the domestic sewage from a particular municipality (and the sewage sludge produced when treating the domestic sewage) depend on the health status of the local community and may vary substantially at different times. The level of pathogens present in treated sewage sludge (biosolids) also depends on the reductions achieved by the wastewater and sewage sludge treatment processes.

If improperly treated sewage sludge is illegally applied to land or placed on a surface disposal site, humans and animals could be exposed to pathogens directly by coming into contact with the sewage sludge or indirectly by consuming drinking water or food contaminated by sewage sludge pathogens. Insects, birds, rodents, and even farm workers could contribute to these exposure routes by transporting sewage sludge and sewage sludge pathogens away from the site. Potential routes of exposure include the following:

Direct contact

- Touching the sewage sludge
- Walking through an area (e.g., field, forest, reclamation area) shortly after sewage sludge application
- Handling soil from fields where sewage sludge has been applied
- Inhaling microbes that become airborne (via aerosols, dust, etc.) during sewage sludge spreading or by strong winds, plowing, or cultivating the soils after application

Indirect contact

- Consumption of pathogen-contaminated crops grown on sewage sludge-amended soil or of other food products that have been contaminated by contact with these crops or field workers, etc.
- Consumption of pathogen-contaminated milk or other food products from animal contaminated by grazing in pastures or fed crops grown on sewage sludge-amended fields
- Ingestion of drinking water or recreational waters contaminated by runoff from nearby land application sites or by organisms from sewage sludge migrating into groundwater aquifers
- Consumption of inadequately cooked or uncooked pathogen-contaminated fish from water contaminated by runoff from a nearby sewage sludge application site.
- Contact with sewage sludge or pathogens transported away from the land application or surface disposal site by rodents, insects, or other vectors, including grazing animals or pets

One of the lesser impacts to public health can be from inhalation of airborne pathogens. Pathogens may become airborne via the spray of liquid biosolids from a splash plate or high-pressure hose, or in fine particulate dissemination as dewatered biosolids are applied or incorporated. While high-pressure spray applications may result in some aerosolization of pathogens, this type of equipment is generally used on large, remote sites such as forests, where the impact on the public is minimal. Fine particulates created by the application of dewatered biosolids or the incorporation of biosolids into soil may cause very localized fine particulate/dusty conditions, but particles in dewatered biosolids are too large to travel far, and the fine particulates do not spread beyond the immediate area. The activity of applying and incorporating biosolids may create dusty conditions. However, the biosolids are moist materials and do not add to the dusty condition, and by the time biosolids have dried sufficiently to create fine particulates, the pathogens have been reduced (Yeager and Ward, 1981). With regard to vector attraction reduction, it can be accomplished in two ways: by treating the sewage sludge to the point at which vectors will no longer be attracted to the sewage sludge and by placing a barrier between the sewage sludge and vectors.

> ***Note:*** Before moving on to a discussion of the fundamentals of sludge treatment methods, it is necessary to begin by covering sludge pumping calculations. It is important to point out that it is difficult (if not impossible) to treat the sludge unless it is pumped to the specific sludge treatment process.

Sludge Pumping Calculations

Wastewater operators are often called upon to make various process control calculations. An important calculation involves sludge pumping. The sludge pumping calculations that the operator may be required to make during plant operations (and should know for licensure examinations) are covered in this section.

Estimating Daily Sludge Production

The calculation for *estimation of the required sludge pumping rate* provides a method to establish an initial pumping rate or to evaluate the adequacy of the current withdrawal rate:

$$\text{Estimated pump rate} = \frac{(\text{Influent TSS conc.} - \text{Effluent TSS conc.}) \times \text{Flow} \times 8.34}{\%\ \text{Solids in sludge} \times 8.34 \times 1440\ \text{min/day}} \tag{8.59}$$

■ EXAMPLE 8.44

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:

$$\text{Sludge withdrawal rate} = \frac{(285\ \text{mg/L} - 140\ \text{mg/L}) \times 5.55 \times 8.34}{0.014 \times 8.34 \times 1440\ \text{min/day}} = 40\ \text{gpm}$$

Sludge Pumping Time

The sludge pumping time is the total time (in minutes) that a pump operates during a 24-hr period:

$$\text{Pump operating time} = \text{Time (min/cycle)} \times \text{Frequency (cycles/day)} \tag{8.60}$$

> ***Note:*** The following information is used for Examples 8.45 to 8.49:

Operating time = 15 min/cycle
Frequency = 24 times per day
Pump rate = 120 gpm
Solids = 3.70%
Volatile matter = 66%

■ EXAMPLE 8.45

Problem: What is the pump operating time?

Solution:

$$\text{Pump operating time} = 15\ \text{min/cycle} \times 24\ \text{cycles/day} = 360\ \text{min/day}$$

Gallons of Sludge Pumped per Day

$$\text{Sludge (gpd)} = \text{Operating time (min/day)} \times \text{Pump rate (gpm)} \tag{8.61}$$

■ EXAMPLE 8.46

Problem: What is the sludge pumped per day in gallons?

Solution:

$$\text{Sludge (gpd)} = 360\ \text{min/day} \times 120\ \text{gpm} = 43{,}200\ \text{gpd}$$

Pounds Sludge Pumped per Day

$$\text{Sludge (lb/day)} = \text{Sludge pumped (gal)} \times 8.34\ \text{lb/gal} \tag{8.62}$$

■ EXAMPLE 8.47

Problem: What is the sludge pumped per day in gallons?

Solution:

$$\text{Sludge} = 43{,}200\ \text{gal/day} \times 8.34\ \text{lb/gal} = 360{,}300\ \text{lb/day}$$

Pounds Solids Pumped per Day

$$\text{Solids (lb/day)} = \text{Sludge pumped (gpd)} \times \%\ \text{Solids} \tag{8.63}$$

■ EXAMPLE 8.48

Problem: What are the solids pumped per day?

Solution:

$$\text{Solids} = 360{,}300\ \text{lb/day} \times 0.0370 = 13{,}331\ \text{lb/day}$$

Pounds Volatile Matter (VM) Pumped per Day

$$\text{VM (lb/day)} = \text{Solids pumped (lb/day)} \times \%\text{VM} \tag{8.64}$$

■ EXAMPLE 8.49

Problem: What is the volatile matter in pounds per day?

Solution:

$$\text{VM} = 13{,}331\ \text{lb/day} \times 0.66 = 8798\ \text{lb/day}$$

Note: If we 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:

$$\begin{aligned}\text{Solids (lb/day)} = \text{Pump time (min/cycle)} \times \text{Frequency (cycles/day)} \times \text{Rate (gpm)} \\ \times 8.34\text{ lb/gal} \times \text{Solids volume}\end{aligned} \tag{8.65}$$

$$\begin{aligned}\text{VM (lb/day)} = \text{Time (min/cycle)} \times \text{Frequency (cycles/day)} \times \text{Rate (gpm)} \times 8.34\text{ lb/gal} \\ \times \%\text{ Solids} \times \%\text{VM}\end{aligned} \tag{8.66}$$

Sludge Production in Pounds/Million Gallons

A common method of expressing sludge production is in pounds of sludge per million gallons of wastewater treated:

$$\text{Sludge (lb/MG)} = \frac{\text{Total sludge production (lb)}}{\text{Total wastewater flow (MG)}} \tag{8.67}$$

■ EXAMPLE 8.50

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:

$$\text{Sludge} = \frac{85{,}000\text{ gal} \times 8.34\text{ lb/gal}}{1.2\text{ MGD} \times 30\text{ days}} = 19{,}692\text{ lb/MG}$$

Sludge Production in Wet Tons/Year

Sludge production can also be expressed in terms of the amount of sludge (water and solids) produced per year. This is normally expressed in wet tons per year:

$$\text{Sludge (wet tons/yr)} = \frac{\text{Sludge produced (lb/MG)} \times \text{Average daily flow (MGD)} \times 365\text{ days/yr}}{2000\text{ lb/ton}} \tag{8.68}$$

■ EXAMPLE 8.51

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 per year in wet tons per year?

Solution:

$$\text{Sludge} = \frac{16{,}500\text{ lb/MG} \times 1.5\text{ MGD} \times 365\text{ days/yr}}{2000\text{ lb/ton}} = 4517\text{ wet tons/yr}$$

The release of wastewater solids without proper treatment could result in severe damage to the environment. Obviously, we must have a system to treat the volume of material removed as sludge throughout the system. Release without treatment would defeat the purpose of environmental protection. A design engineer can choose from many processes when developing sludge treatment systems. No matter what the system or combination of systems chosen, the ultimate purpose will be the same: the conversion of wastewater sludges into a form that can be handled economically and disposed of without damage to the environment or creating nuisance conditions. Leaving either condition unmet will require further treatment. The degree of treatment will generally depend on the proposed method of disposal. Sludge treatment processes can be classified into a number of major categories. In this handbook, we discuss the processes of *thickening*, *digestion* (or *stabilization*), *dewatering*, *incineration*, and *land application*. Each of these categories has then been further subdivided according to the specific processes that are used to accomplish sludge treatment.

The importance of adequate, efficient sludge treatment cannot be overlooked when designing wastewater treatment facilities. The inadequacies of a sludge treatment system can severely affect the overall performance capabilities of a plant. The inability to remove and process solids as quickly 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.

SLUDGE THICKENING

The solids content of primary, activated, trickling-filter, or even mixed sludge (i.e., primary plus activated sludge) varies considerably, depending on the characteristics of the sludge. Note that the sludge removal and pumping facilities and the method of operation also affect the solids content. *Sludge thickening* (or *concentration*) is a unit process used to increase the solids content of the sludge by removing a portion of the liquid fraction. By increasing the solids content, more economical treatment of the sludge can be effected. Sludge thickening processes include

- Gravity thickeners
- Flotation thickeners
- Solids concentrators

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.

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 the following:

- Type of sludge
- Condition of influent sludge
- Temperature
- Blanket depth
- Solids loading
- Hydraulic loading
- Solids retention time
- Hydraulic detention time

Flotation Thickening

Flotation thickening is used most efficiently for waste sludges from suspended-growth biological treatment process, such as the activated sludge process. In operation, recycled water from the flotation thickener is aerated under pressure. During this time, 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 waste stream 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 a dissolved air-thickening process depends on various factors:

- Bubble size
- Solids loading
- Sludge characteristics
- Chemical selection
- Chemical dose

Solids Concentrators

Solids concentrators (belt thickeners) usually consist of a mixing tank, chemical storage and metering equipment, and a moving porous belt. In operation, the process residual flow is chemically treated and then spread evenly over the surface of the moving porous belt. As the flow is carried down the belt (similar to a conveyor belt), the solids are mechanically turned or agitated and water drains through the belt. This process is primarily used in facilities where space is limited. 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 a negligible amount of solids are lost in the thickener overflow, the solids are the same. Note that the water is removed to thicken the sludge and results in higher percent solids.

Estimating Daily Sludge Production

Equation 8.52 provides a method for establishing an initial pumping rate or evaluating the adequacy of the current pump rate:

$$\text{Est. pump rate} = \frac{(\text{Influent TSS conc.} - \text{Effluent TSS conc.}) \times \text{Flow} \times 8.34}{\%\ \text{Solids in sludge} \times 8.34 \times 1440\ \text{min/day}} \tag{8.69}$$

■ EXAMPLE 8.52

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:

$$\text{Sludge rate} = \frac{(280\ \text{mg/L} - 141\ \text{mg/L}) \times 5.55\ \text{MGD} \times 8.34}{0.015 \times 8.34 \times 1440\ \text{min/day}} = 36\ \text{gpm}$$

Surface Loading Rate (gpd/ft²)

The surface loading rate (surface settling rate) is hydraulic loading—the amount of sludge applied per square foot of gravity thickener:

$$\text{Surface loading (gpd/ft}^2) = \frac{\text{Sludge applied to thickener (gpd)}}{\text{Thickener area (ft}^2)} \tag{8.70}$$

■ EXAMPLE 8.53

Problem: The 70-ft-diameter gravity thickener receives 32,000 gpd of sludge. What is the surface loading in gallons per square foot per day?

Solution:

$$\text{Surface loading} = \frac{32{,}000\ \text{gpd}}{0.785 \times 70\ \text{ft} \times 70\ \text{ft}} = 8.32\ \text{gpd/ft}^2$$

Solids Loading Rate (lb/day/ft²)

The solids loading rate is the pounds of solids per day being applied to 1 ft² of tank surface area. The calculation uses the surface area of the bottom of the tank. It assumes the floor of the tank is flat and has the same dimensions as the surface.

$$\text{Solids loading rate (lb/day/ft}^2) = \frac{\%\ \text{Solids} \times \text{Sludge flow (gpd)} \times 8.34\ \text{lb/gal}}{\text{Thickener area (ft}^2)} \tag{8.71}$$

■ EXAMPLE 8.54

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?

Solution:

$$\text{Solids loading rate} = \frac{0.016 \times 39{,}000\ \text{gpd} \times 8.34\ \text{lb/gal}}{0.785 \times 50\ \text{ft} \times 50\ \text{ft}} = 2.7\ \text{lb/day/ft}^2$$

Concentration Factor

The concentration factor (CF) represents the increase in concentration due to the thickener:

$$\text{CF} = \frac{\text{Thickened sludge concentration (\%)}}{\text{Influent sludge concentration (\%)}} \tag{8.72}$$

■ EXAMPLE 8.55

Problem: The influent sludge contains 3.5% solids. The thickened sludge solids concentration is 7.7%. What is the concentration factor?

Solution:

$$\text{CF} = 7.7\% \div 3.5\% = 2$$

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:

$$\text{Air/solids ratio} = \frac{\text{Air flow (ft}^3\text{/min)} \times 0.075 \text{ lb/ft}^3}{\text{Sludge flow (gpm)} \times \text{\% Solids} \times 8.34 \text{ lb/gal}} \tag{8.73}$$

■ EXAMPLE 8.56

Problem: The sludge pumped to the thickener is 0.85% solids. The air flow is 13 cfm. What is the air-to-solids ratio if the current sludge flow rate entering the unit is 50 gpm?

Solution:

$$\text{Air/solids ratio} = \frac{13 \text{ cfm} \times 0.075 \text{ lb/ft}}{50 \text{ gpm} \times 0.0085 \times 8.34 \text{ lb/gal}} = 0.28$$

Recycle Flow in Percent

The amount of recycle flow is expressed as a percent:

$$\text{\% Recycle} = \frac{\text{Recycle flow rate (gpm)} \times 100}{\text{Sludge flow (gpm)}} \tag{8.74}$$

■ EXAMPLE 8.57

Problem: The sludge flow to the thickener is 80 gpm. The recycle flow rate is 140 gpm. What is the percent recycle?

Solution:

$$\text{\% Recycle} = \frac{140 \text{ gpm} \times 100}{80 \text{ gpm}} = 175\%$$

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 the following:

- Aerobic digestion
- Anaerobic digestion
- Composting
- Lime stabilization
- Wet air oxidation (heat treatment)
- Chemical oxidation (chlorine oxidation)
- Incineration

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 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 solids are withdrawn for disposal. Process control testing should include alkalinity, pH, percent solids, percent volatile solids for influent sludge, supernatant, digested sludge, and digester contents. Normal operating levels for an aerobic digester are listed in Table 8.25. 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).

Environmental engineers who design treatment plant unit processes and wastewater operators who operate aerobic digesters are required to make certain process control calculations to ensure that proper operational parameters are engineered into the system and the parameters are operated correctly. These process control calculations are explained in the following sections.

Volatile Solids Loading

Volatile solids loading for the aerobic digester is expressed in pounds of volatile solids entering the digester per day per cubic foot of digester capacity:

$$\text{Volatile solids loading} = \frac{\text{Volatile solids added (lb/day)}}{\text{Digester volume (ft}^3\text{)}} \tag{8.75}$$

TABLE 8.25
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%

■ EXAMPLE 8.58

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:

$$\text{Volatile solids loading} = \frac{1350\text{ lb/day}}{0.785 \times 25\text{ ft} \times 25\text{ ft} \times 24\text{ ft}} = 0.11\text{ lb/day/ft}^3$$

Digestion Time, Days

Digestion time is the theoretical time the sludge remains in the aerobic digester:

$$\text{Digestion time (days)} = \frac{\text{Digester volume (gal)}}{\text{Sludge added (gpd)}} \tag{8.76}$$

■ EXAMPLE 8.59

Problem: Digester volume is 240,000 gal. Sludge is being added to the digester at the rate of 13,500 gpd. What is the digestion time in days?

Solution:

$$\text{Digestion time} = \frac{240{,}000\text{ gal}}{13{,}500\text{ gpd}} = 17.8\text{ days}$$

Digester Efficiency (% 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.

- Step 1: *Calculate volatile matter.* Because of the changes occurring during sludge digestion, the calculation used to determine percent volatile matter reduction is more complicated:

$$\%\text{VM reduction} = \frac{(\%\text{VM}_{\text{in}} - \%\text{VM}_{\text{out}}) \times 100}{\%\text{VM}_{\text{in}} - (\%\text{VM}_{\text{in}} \times \%\text{VM}_{\text{out}})} \tag{8.77}$$

■ EXAMPLE 8.60

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:

$$\%\text{VM reduction} = \frac{(0.71 - 0.53) \times 100}{0.71 - (0.71 \times 0.53)} = 53.9\text{ or }54\%$$

- Step 2: *Calculate moisture reduction:*

$$\% \text{ Moisture reduction} = \frac{(\% \text{ Moisture}_{\text{in}} - \% \text{ Moisture}_{\text{out}}) \times 100}{\% \text{ Moisture}_{\text{in}} - (\% \text{ Moisture}_{\text{in}} \times \% \text{ Moisture}_{\text{out}})} \tag{8.78}$$

■ EXAMPLE 8.61

Problem: Using the digester data provided below, determine the percent moisture reduction for the digester.

> ***Note:*** Percent moisture = 100% – Percent solids.

Solution:

Raw sludge:
  Percent solids = 6%
  Percent moisture = 100% – 6% = 94%
Digested sludge:
  Percent solids = 15%
  Percent moisture = 100% – 15% = 85%

$$\% \text{ Moisture reduction} = \frac{(0.94 - 0.85) \times 100}{0.94 - (0.94 \times 0.85)} = 64\%$$

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.

$$\text{Chemical required (lb)} = \left(\frac{\text{Chemical used in lab test (mg)}}{\text{Sample volume (L)}} \right) \times \text{Digester volume (MG)} \times 8.34 \tag{8.79}$$

■ EXAMPLE 8.62

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:

$$\text{Chemical required} = \frac{225 \text{ mg} \times 240{,}000 \text{ gal} \times 3.785 \text{ L/gal}}{1 \text{ L} \times 454 \text{ g/lb} \times 1000 \text{ mg/g}} = 450 \text{ lb}$$

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 are converted into new bacterial cells. Instead, most of the organics are converted into carbon dioxide and methane gas.

> ***Note:*** 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.

Equipment used in anaerobic digestion includes a sealed digestion tank with either a fixed or a floating cover, heating and mixing equipment, gas storage tanks, solids and supernatant withdrawal equipment, and safety equipment (e.g., vacuum relief, pressure relief, flame traps, explosion proof electrical equipment).

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.

Note: The primary purpose of a secondary digester is to allow for solids separation.

Various performance factors affect the operation of the anaerobic digester; for example, 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. 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 8.26.

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.

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.

Sludge Withdrawal

Digested sludge is withdrawn only when necessary—always leave at least 25% seed.

TABLE 8.26
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

pH Control

The 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 acid/alkalinity relationship. Decreases in alkalinity cause a corresponding increase in the ratio.

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.

Mixing

If the digester is equipped with mixers, mixing should be accomplished to ensure that organisms are exposed to food materials.

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 danger involved with working inside anaerobic digesters, they are automatically classified as *permit-required confined spaces*; therefore, all operations involving internal entry must be made in accordance with OSHA's confined space entry standard.

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.

Required Seed Volume in Gallons

$$\text{Seed volume (gal)} = \text{Digester volume} \times \%\ \text{Seed} \tag{8.80}$$

■ EXAMPLE 8.63

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:

$$\text{Seed volume} = 266{,}000 \times 0.25 = 66{,}500 \text{ gal}$$

Volatile Acids-to-Alkalinity Ratio The volatile acids-to-alkalinity ratio can be used to control operation of an anaerobic digester:

$$\text{Volatile acids-to-alkalinity ratio} = \frac{\text{Volatile acids concentration}}{\text{Alkalinity concentration}} \tag{8.81}$$

TABLE 8.27
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

■ EXAMPLE 8.64

Problem: The digester contains 240 mg/L volatile acids and 1860 mg/L alkalinity. What is the volatile acids-to-alkalinity ratio?

Solution:

$$\text{Volatile acids-to-alkalinity ratio} = 240\text{ mg/L} \div 1860\text{ mg/L} = 0.13$$

> ***Note:*** Increases in the ratio normally indicate a potential change in the operation condition of the digester, as shown in Table 8.27.

Sludge Retention Time Sludge retention time is the length of time the sludge remains in the digester:

$$\text{Sludge retention time (days)} = \frac{\text{Digester volume (gal)}}{\text{Sludge volume added per day (gpd)}} \tag{8.82}$$

■ EXAMPLE 8.65

Problem: Sludge is added to a 525,000-gal digester at the rate of 12,250 gal per day. What is the sludge retention time?

Solution:

$$\text{Sludge retention time} = 525{,}000\text{ gal} \div 12{,}250\text{ gpd} = 42.9\text{ days}$$

Estimated Gas Production in Cubic Feet/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

$$\text{Gas Production (ft}^3\text{)} = \text{VM}_{\text{in}}\text{ (lb/day)} \times \text{\%VM reduction} \times \text{Production rate (ft}^3\text{/lb)} \tag{8.83}$$

■ EXAMPLE 8.66

Problem: The digester receives 11,450 lb of volatile matter per day. Currently, the volatile matter reduction achieved by the digester is 52%. The rate of gas production is 11.2 ft^3 of gas per pound of volatile matter destroyed. What is the gas production in cubic feet per day?

Solution:

$$\text{Gas production} = 11{,}450\text{ lb/day} \times 0.52 \times 11.2\text{ ft}^3\text{/lb} = 66{,}685\text{ ft}^3\text{/day}$$

Percent Volatile Matter Reduction Because of the changes occurring during sludge digestion, the calculation used to determine percent volatile matter reduction is more complicated.

$$\%\text{VM reduction} = \frac{\left(\%\text{VM}_{\text{in}} - \%\text{VM}_{\text{out}}\right) \times 100}{\%\text{VM}_{\text{in}} - \left(\%\text{VM}_{\text{in}} \times \%\text{VM}_{\text{out}}\right)} \tag{8.84}$$

■ EXAMPLE 8.67

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:

$$\%\text{VM reduction} = \frac{(0.74 - 0.55) \times 100}{0.74 - (0.74 \times 0.55)} = 57\%$$

Percent Moisture Reduction in Digested Sludge

$$\%\text{ Moisture reduction} = \frac{\left(\%\text{ Moisture}_{\text{in}} - \%\text{ Moisture}_{\text{out}}\right) \times 100}{\%\text{ Moisture}_{\text{in}} - \left(\%\text{ Moisture}_{\text{in}} \times \%\text{ Moisture}_{\text{out}}\right)} \tag{8.85}$$

■ EXAMPLE 8.68

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%

Solution:

Note: Percent moisture = 100% – Percent solids.

$$\%\text{ Moisture reduction} = \frac{(0.94 - 0.86) \times 100}{0.94 - (0.94 \times 0.86)} = 61\%$$

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%.

Three methods of composting wastewater biosolids are common. Each method involves mixing dewatered wastewater solids with a bulking agent to provide carbon and increase porosity. The resulting mixture is piled or placed in a vessel where microbial activity causes the temperatures of the mixture to rise during the active composting period. The specific temperatures that must be achieved and maintained for successful composting vary based on the method and use of the end product. After active composting the material is cured and distributed. Again, there are three commonly employed composting methods but we only describe the aerated static pile (ASP) method because it is commonly used.

In the aerated static pile type of composting facility, the homogenized mixture of bulking agent (coarse hardwood wood chips) and dewatered biosolids is piled by front-end loaders onto a large concrete composting pad where it is mechanically aerated via PVC plastic pipe embedded within the concrete slab. This ventilation procedure is part of the 26-day period of active composting when adequate air and oxygen are necessary to support aerobic biological activity in the compost mass and to reduce the heat and moisture content of the compost mixture. Keep in mind that a compost pile without a properly sized air distribution system can lead to the onset of anaerobic conditions and can give rise to putrefactive odors.

For illustration and discussion purposes, we assume that a typical overall composting pad area is approximately 200 feet by 240 feet and consists of 11 blowers and 24 pipe troughs. Three blowers are 20-hp, 2400-cfm, variable-speed-drive units capable of operating in either the positive or negative aeration mode. Blowers A, B, and C are each connected to two piping troughs that run the full length of the pad. The two troughs are connected at the opposite end of the composting pad to create an *aeration pipe loop*. The other eight blowers are rated at 3 hp and 1200 cfm and are arranged with one blower per six troughs at half length feeding 200 cfm per trough. These blowers can be operated in the positive or negative aeration mode. Aeration piping within the six pipe troughs is perforated PVC plastic pipe (6-inch inside diameter and 1/4-inch wall thickness). Perforation holes or orifices vary in size from 7/32 inch to 1/2 inch, increasing in diameter as the distance from the blower increases.

The variable-speed motor drives installed with blowers A, B, and C are controlled by five thermal probes mounted at various depths in the compost pile, and various parameters are fed back to the recorder; the other eight blowers are constant speed, controlled by a timer that cycles them on and off. To ensure optimum composting operations it is important to verify that these thermal probes are calibrated on a regular basis. In the constant speed system, thermal probes are installed but all readings are taken and recorded manually. For water and leachate drainage purposes, all aeration piping within the troughs slopes downward with the highest point at the center of the composting pad. Drain caps located at each end of the pipe length are manually removed on a regular basis so that any buildup of debris or moisture will not interfere with the airflow.

The actual construction process involved in building the compost pile will be covered in detail later but for now a few key points should be made. Prior to piling the mixture onto the composting pad, an 18-inch layer of wood chips is laid down and serves as a base material. The primary purpose of the wood chips base is to keep the composting mixture clear of the aeration pipes, thus reducing clogging of the air distribution openings in the pipes and allowing free air circulation. A secondary benefit is that the wood chips insulate the composting mixture from the pad. The compost pad is like a heat sink, and this insulating barrier improves the uniformity of heat distribution within the composting mixture.

Lime or alkaline stabilization can achieve the minimum requirements for both Class A (no detectable pathogens) and Class B (a reduced level of pathogens) biosolids with respect to pathogens, depending on the amount of alkaline material added and other processes employed. Generally, alkaline stabilization meets the Class B requirements when the pH of the mixture of wastewater solids and alkaline material is at 12 or above after 2 hours of contact.

Class A requirements can be achieved when the pH of the mixture is maintained at or above 12 for at least 72 hours, with a temperature of 52°C being maintained for at least 12 hours during this time. In one process, the mixture is air dried to over 50% solids after the 72-hour period of elevated pH. Alternatively, the process may be manipulated to maintain temperatures at or above 70°F for 30 or more minutes, while maintaining the pH requirement of 12. This higher temperature can be achieved by overdosing with lime (that is, by adding more than is needed to reach a pH of 12), by using a supplemental heat source, or by using a combination of the two. Monitoring for fecal coliforms or *Salmonella* sp. is required prior to release by the generator for use.

Materials that may be used for alkaline stabilization include hydrated lime, quicklime (calcium oxide), fly ash, lime and cement kiln dust, and carbide lime. Quicklime is commonly used because it has a high heat of hydrolysis (491 British thermal units) and can significantly enhance pathogen destruction. Fly ash, lime kiln dust, or cement kiln dust are often used for alkaline stabilization because of their availability and relatively low cost.

The alkaline stabilized product is suitable for application in many situations, such as landscaping, agriculture, and mine reclamation. The product serves as a lime substitute, source of organic matter, and a specialty fertilizer. The addition of alkaline stabilized biosolids results in more favorable conditions for vegetative growth by improving soil properties such as pH, texture, and water holding capacity. Appropriate applications depend on the needs of the soil and crops that will be grown and the pathogen classification. For example, a Class B material would not be suitable for blending in a top soil mix intended for use in home landscaping but is suitable for agriculture, mine reclamation, and landfill cover where the potential for contact with the pulse is lower and access can be restricted. Class A alkaline stabilized biosolids are useful in agriculture and as a topsoil blend ingredient. Alkaline stabilized biosolids provide pH adjustment, nutrients, and organic matter, reducing reliance on other fertilizers.

Alkaline stabilized biosolids are also useful as daily landfill cover. They satisfy the federal requirement that landfills must be covered with soil or soil-like material at the end of each day (40 CFR 258). In most cases, lime stabilized biosolids are blended with other soil to achieve the proper consistency for daily cover. As previously mentioned, alkaline stabilized biosolids are excellent for land reclamation in degraded areas, including acid mine spills or mine tailings. Soil conditions at such sites are very unfavorable for vegetative growth often due to acid content, lack of nutrients, elevated levels of heavy metals, and poor soil texture. Alkaline stabilized biosolids help to remedy these problems, making conditions more favorable for plant growth and reducing erosion potential. In addition, once a vegetative cover is established, the quality of mine drainage improves.

Thermal treatment (or wet air oxidation) subjects sludge to 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 and causes chemical oxidation of the organic matter. This process substantially improves dewatering and reduces the volume of material for disposal. It also produces a very high-strength waste, which must be returned to the wastewater treatment system for further treatment.

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.

Sludge Dewatering

Digested sludge removed from the digester is still mostly liquid. The primary objective of dewatering biosolids is to reduce moisture and consequently volume to a degree that will allow for economical disposal or reuse. Probably one of the best summarizations of the various reasons why it is important to dewater biosolids was given by Metcalf & Eddy (1991): (1) the costs of transporting biosolids to the ultimate disposal site are greatly reduced when biosolids volume is reduced; (2) dewatered biosolids allow for easier handling; (3) dewatering biosolids allows for more efficient incineration; (4) if composting is the beneficial reuse choice, dewatered biosolids decrease the amount and therefore the cost of bulking agents; (5) with the USEPA's 503 Rule, dewatering

TABLE 8.28
Solids Content of Dewatered Biosolids

Dewatering Method	Approximate Solids Content (%)
Lagoons/ponds	30
Drying beds	40
Filter press	35–45
Vacuum filtration	25
Standard centrifuge	20–25
High G-force/high solids centrifuge	25–40

biosolids may be required to render the biosolids less offensive; and (6) when landfilling is the ultimate disposal option, dewatering biosolids is required to reduce leachate production. Again, the importance of adequately dewatering biosolids for proper disposal or reuse cannot be overstated.

The unit processes that are most often used for dewatering biosolids are (1) vacuum filtration, (2) pressure filtration, (3) centrifugation, and (4) drying beds. Solids contents achievable by various dewatering techniques are shown in Table 8.28. The biosolids cake produced by common dewatering processes has a consistency similar to dry, crumbly, bread pudding (Spellman, 1996). This dry, non-fluid, dewatered, crumbly cake product is easily handled and non-offensive, and it can be land applied manually and by conventional agricultural spreaders (Outwater, 1994).

Dewatering processes are usually divided into natural air drying and mechanical methods. Natural dewatering methods include removing moisture by evaporation and gravity or induced drainage such as sand beds, biosolids lagoons, paved beds, *Phragmites* reed beds, vacuum-assisted beds, Wedgewater™ beds, and dewatering via freezing. These natural dewatering methods are less controllable than mechanical dewatering methods but are typically less expensive. Moreover, these natural dewatering methods require less power because they rely on solar energy, gravity, and biological processes as the source of energy for dewatering. Mechanical dewatering processes include pressure filters, vacuum filters, belt filters, and centrifuges. The aforementioned air drying and mechanical dewatering processes will be discussed in greater detail later in this text.

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.

Four types of drying beds are commonly used to dewater biosolids: (1) sand, (2) paved, (3) artificial media, and (4) vacuum-assisted (Metcalf & Eddy, 1991). In addition to these commonly used dewatering methods, a few of the innovative methods of natural dewatering will also be discussed in this section. The innovative natural dewatering methods to be discussed include experimental work on biosolids dewatering via freezing. Moreover, dewatering biosolids with aquatic plants, which has been tested and installed in several sites throughout the United States, is also discussed.

Drying beds are generally used for dewatering well-digested biosolids. Attempting to air dry raw biosolids is generally unsuccessful and may result in odor and vector control problems. Biosolids drying beds consist of a perforated or open-joint drainage system in support media (usually gravel), covered with a filter media (usually sand but can consist of extruded plastic or wire mesh). Drying beds are usually separated into workable sections by wood, concrete, or other materials. Drying beds may be enclosed or open to the weather. They may rely entirely on natural drainage and evaporation processes or may use a vacuum to assist the operation (both types are discussed in the following sections).

Traditional Sand Drying Beds

This is the oldest biosolids dewatering technique and consists of 6 to 12 inches of coarse sand underlain by layers of graded gravel ranging from 1/8 to 1/4 inches at the top and 3/4 to 1-1/2 inches at the bottom. The total gravel thickness is typically about 1 foot. Graded natural earth (4 to 6 inches) usually makes up the bottom with a web of drain tile placed on 20- to 30-foot centers. Sidewalls and partitions between bed sections are usually made of wooden planks or concrete and extend about 14 inches above the sand surface (McGhee, 1991). Large open areas of land are required for sand drying biosolids. It is not unusual to have drying beds that are over 125 feet long and from 20 to 35 feet in width. Even at the smallest wastewater treatment plants it is normal practice to provide at least two drying beds.

The actual dewatering process occurs as a result of two different physical processes: evaporation and drainage. The liquor that drains off the biosolids goes to a central sump, which pumps it back to the treatment process to undergo further treatment. The operation is very much affected by climate. In wet climates it may be necessary to cover the beds with a translucent material that will allow at least 85% of the sun's ultraviolet radiation to pass through. Typical loading rates for primary biosolids in dry climates ranges up to 200 kg/(square meter × year) and from 60 to 125 kg/(square meter × year) for mixtures of primary and waste activated biosolids.

When a drying bed is put into operation, it is generally filled with digested biosolids to a depth ranging from 8 to 12 inches. The actual drying time is climate sensitive; that is, drying can take from a few weeks to a few months, depending on the climate and the season. After dewatering, the biosolids solids content will range from about 20 to 35% and, more importantly, the volume will have been reduced up to 85%. Upon completion of the drying process, the dried biosolids are generally removed from the bed with handheld forks or front-end loaders. It is important to note that in the dried biosolids removal process a small amount of sand is lost and the bed must be refilled and graded periodically. Dried solids removed from a biosolids drying bed can be either incinerated or landfilled.

Paved Drying Beds

The main reason for using paved drying beds is that they alleviate the problem of mechanical biosolids removal equipment damaging the underlain piping networks. The beds are paved with concrete or asphalt and are generally sloped toward the center where a sump-like area with underlain pipes is arranged. These dewatering beds, like biosolids lagoons, depend on evaporation for dewatering of the applied solids. Paved drying beds are usually rectangular in shape with a center drainage strip. They can be heated via buried pipes in the paved section, and they are generally covered to prevent rain incursion.

In this type of natural dewatering, solids contents of 45 to 50% can be achieved within 35 days in dry climates under normal conditions (McGhee, 1991). The operation of paved drying beds involves applying the biosolids to a depth of about 12 inches. The settled surface area is routinely mixed by a vehicle-mounted machine that is driven through the bed. Mixing is important because it breaks up the crust and exposes wet surfaces to the environment. Supernatant is decanted in a manner similar to biosolids lagoons. Biosolids loadings in relatively dry climates range from about 120 to 260 kg/(m^2/yr). The two major disadvantages of paved drying beds are that they have a larger land requirement than that of sand beds, and they have high capital costs.

When attempting to determine the bottom area dimensions of a paved drying bed, computation by trial-and-error using the following equation becomes necessary (Metcalf & Eddy, 1991):

$$A = \frac{1.04S\left[(1-S_d)/S_d - (1-S_e)/S_e\right] + 62.4(P)(A)}{62.4(K_e)(E_p)} \tag{8.86}$$

where

A = Bottom area of paved bed (ft^2).

S = Annual biosolids production, dry solids (lb).

S_d = Percent dry solids in the biosolids after decanting (as a decimal).

S_e = Percent dry solids required from final disposal (as a decimal).

P = Annual precipitation (ft).

K_e = Reduction factor for evaporation from biosolids vs. a free water surface (use 0.6 for a preliminary estimate; pilot test to determine factor for final design).

E_p = Free water pan evaporation rate for the area (ft/yr).

Although the construction and operation methodologies for biosolids drying beds are well known and have been widely accepted, this is not to say that the wastewater industry has not attempted to incorporate further advances into their construction and operation. For example, in order to reduce the amount of dewatered biosolids that must be manually removed from drying beds, attempts have been made to construct drying beds in such a way that they can be planted with reeds—namely, the *Phragmites communis* variety (to be covered in greater detail later). The intent of augmenting the biosolids drying bed with reeds is to achieve further desiccation. Moreover, tests have shown that the plants extend their root systems into the biosolids mass. This extended root system has the added benefit of helping to establish a rich microflora that eventually feeds upon the organic content of the biosolids. It is interesting to note that normal plant activity works to keep the system aerobic.

Artificial Media Drying Beds

The first artificial media drying beds, developed in England in 1970, used a stainless-steel medium called *wedge wire*. Later, as the technology advanced, the stainless steel fine wire screen mesh was replaced with a high-density polyurethane medium named Wedgewater™. The polyurethane is less expensive than the stainless-steel medium but has a shorter life expectancy. Wedge wire beds are similar in concept to vacuum-assisted drying beds (to be described later). The medium used in wedge wire beds consists of a septum with wedge-shaped slots about 0.01 inch wide. Initially, the bed is filled with water to a level above the wire screen. Chemically conditioned biosolids are then added and, after a brief holding period, are allowed to drain through the screen; because excess water cannot return to the biosolids through capillary action, the biosolids dewater faster with this process (Corbitt, 1989; McGhee, 1991).

Vacuum-Assisted Drying Beds

For small plants that process small quantities of biosolids and have limited land area, vacuum-assisted drying beds may be the preferred method of dewatering biosolids. Vacuum-assisted drying beds normally employ the use of a small vacuum to accelerate dewatering of biosolids applied to a porous medium plate. This porous medium is set above an aggregate-filled support underdrain which, as the name implies, drains to a sump. The small vacuum is applied to this underdrain, which works to extract free water from the biosolids; with biosolids loadings on the order of less than 10 kg/m^2 per cycle, the time required to dewater conditioned biosolids is about 1 day (McGhee, 1991). Using this method of dewatering it is possible to achieve a solids content of >30%, although 20% solids is a more normal expectation.

Removal of dewatered biosolids is usually accomplished with mechanized machinery such as front-end loaders. Once the solids have been removed it is important to wash the surface of the bed with high-pressure hoses to ensure that residuals are removed. The main advantage cited for this dewatering method is the reduced amount of time necessary for dewatering, which reduces the effects of inclement climatic conditions on biosolids drying. The main disadvantage of this type of dewatering may be its dependence on adequate chemical conditioning for successful operation (Metcalf & Eddy, 1991).

Natural Methods of Dewatering Biosolids

Two innovative methods for natural biosolids dewatering are discussed in this section: dewatering via freezing and dewatering using aquatic plants. In freeze-assisted drying, low winter temperatures accelerate the dewatering process. Freezing biosolids works to separate the water from the solids. The free water drains quickly when the granular mass is thawed (Haug, 1986). It is not unusual to attain a solids concentration greater than 25% when the mass thaws and drains. Determining the feasibility of freezing biosolids in a particular area is dependent on the depth of frost penetration. The maximum depth of frost penetration for an area can be found in published sources or local records. When attempting to calculate the depth of frost penetration it may be helpful to use the following equation for 3-inch (75-mm) layers (McGhee, 1991):

$$Y = 1.76\, F_p - 101$$

where

Y = Total depth of biosolids (cm).

F_p = Maximum depth of frost penetration (cm).

In this example, the biosolids is applied in 75-mm layers. As soon as the first layer is frozen, another layer is applied. The goal is to fill the bed with biosolids by the end of winter. It must be pointed out that in using this layered method of freeze-dewatering biosolids it is important to ensure that each layer is frozen before the next is applied. Moreover, any snow or debris that falls should be removed from the surface; otherwise, it will serve to insulate the biosolids. Outwater (1994) observed that, “To ensure successful performance at all times, the design should be based on the warmest winter in the past 20 years and on a layer thickness which will freeze in a reasonable amount of time if freeze–thaw cycles occur during the winter” (p. 86). Another rule of thumb to use in making a determination of whether or not biosolids freezing is a viable dewatering option is that biosolids freezing is unlikely to be a practical concept unless more than 100 cm frost penetration is assured (Reed, 1987).

> ***Note:*** Dewatering via freezing is primarily in the pilot study stage. Experimental work in this area has led to pilot plants and has yielded various mathematical models, but no full-scale operations (Outwater, 1994).

Using aquatic plants to dewater biosolids was developed in Germany in the 1960s. In this first project reed beds were constructed in submerged wetlands. To date, although considered to be an innovative dewatering technology without specific design criteria, there are several hundred systems operating in Europe, United States, and Australia. In the reed bed system, a typical sand drying bed for biosolids is modified. Instead of removing the dewatered biosolids from the beds after each application, reeds (*Phragmites communis*) are planted in the sand. For the next several years (5 to 10 years), biosolids are added and then the beds are emptied. In the reed bed operation, biosolids are spread on the surface of the bed via troughs or gravity-fed pipes. When the bed is filled to capacity, about 4 inches of standing liquid will remain on the surface until it evaporates or drains down through the bed, where tile drains return it to the treatment process. In an aquatic reed bed, the reeds perform the important function of developing, near the root zone, a rich microflora that feeds on the organic material in biosolids. *Phragmites* reeds are particularly suitable for this application because they are resistant to biosolids contaminants. Although the roots penetrate into the finer gravel and sand, they do not penetrate through lower areas where the larger stones or fragments are located. This is important because root penetration to the lower bed levels could interfere with free drainage.

Another advantage of using *Phragmites* reeds in the aquatic plant drying bed is their growing pattern. *Phragmites* roots grow and extend themselves through rhizomes (underground horizontal stems, often thickened and tuber shaped, that have buds, nodes, and scale-like leaves). From each rhizome, several plants branch off and grow vertically through the biosolids. This vertical growth aids in dewatering by providing channels through which the water drains. The reeds also absorb some of this water, which is then given off to the atmosphere through evapotranspiration. The biosolids will be reduced to about 97% solids. Along with desiccating the biosolids deposits, the reeds work to cause extensive mineralization (Epstein and Alpert, 1984).

Phragmites reed beds are operated year-round. In the fall the reeds are harvested, leaving their root systems intact. The harvested reeds, depending on contaminant concentrations, can be incinerated, landfilled, or composted. It takes about 8 years to fill an average reed bed to capacity. When this occurs, it must be taken out of service and allowed to stand fallow for 6 months to a year. This fallow period allows for stabilization of the top surface layer. The resulting biosolids product is dry and crumbles in the hands (it is friable). If contamination levels are within acceptable limits as per the USEPA's 503 Rule, the dewatered biosolids product can be land-applied.

Operation of a *Phragmites* reed bed has limitations. For example, to ensure a successful dewatering operation it is prudent to hire the services of an agronomist who is familiar with plant growth, care, and control of plant pests such as aphids. Moreover, this dewatering system is designed for regions that are subject to four distinct seasons because *Phragmites* requires a dormancy, wintering-over, period for proper root growth. Additionally, reed beds are not suitable for large-scale operations for operational reasons and also may be cost prohibitive due to the cost of land. The jury is still out on how effective reed bed dewatering systems are, because the technology is relatively new and none of the beds has been emptied yet; thus, it is difficult to predict the quality of the end-product.

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. In operation, 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.

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 in 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.

Filter Media Drum and belt vacuum filters use natural or synthetic fiber materials. On the drum filter, the cloth is stretched and secured to the surface of the drum. In the belt filter, the cloth is stretched over the drum and through the pulley system. The installation of a blanket requires several days. The cloth will (with proper care) last several hundred to several thousand hours. The life of the blanket depends on the cloth selected, the conditioning chemical, backwash frequency, and cleaning (e.g., acid bath) frequency.

Filter Drum The filter drum is a maze of pipe work running from a metal screen and wooden skeleton which connects 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. Normally, submergence is limited to 1/5 or less of the filter surface at a time.

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.

Vacuum Filter Yield (lb/hr/ft^2) Calculation Probably the most frequent calculation that vacuum filter operators have to make is determining filter yield. Example 8.69 illustrates how this calculation is made.

■ EXAMPLE 8.69

Problem: Thickened thermally condition 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:

$$\text{Area of a cylinder side} = 3.14 \times \text{Diameter} \times \text{Length} = 3.14 \times 9.8\text{ ft} \times 12\text{ ft} = 369.3\text{ ft}^2$$

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:

$$\frac{3002.4\text{ lb/hr}}{369.3\text{ ft}^2} = 8.13\text{ lb/hr/ft}^2$$

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 presses are available, but the most commonly used types are plate and frame presses and belt presses. Filter presses include the belt or plate-and-frame types. The belt filter includes two or more porous belts, rollers, and related handling systems for chemical makeup and feed, as well as supernatant and solids collection and transport.

The plate-and-frame filter consists of a support frame, filter plates covered with porous material, a hydraulic or mechanical mechanism for pressing plates together, and related handling systems for chemical makeup and feed, as well as supernatant and solids collection and transport. 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 (O&M) costs than those of 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.

Filter Press Process Control Calculations As part of the operating routine for filter presses, operators are often called upon to make certain process control calculations. The process control calculation most commonly used in the operation of a belt filter press is one that determines the hydraulic loading rate on the filter press unit. The process control calculation most commonly used in the operation of plate and filter presses is one that determines the pounds of solids pressed per hour. Both of these calculations are demonstrated below.

■ EXAMPLE 8.70. HYDRAULIC LOADING RATE FOR BELT FILTER PRESSES

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:

$$\frac{0.30\text{ MG}}{1\text{ day}} \times \frac{1{,}000{,}000\text{ gal}}{1\text{ MG}} \times \frac{1\text{ day}}{1440\text{ min}} = \frac{208.3\text{ gal}}{1\text{ min}}$$

$$60\text{ in.} \times \frac{1\text{ ft}}{12\text{ in.}} = 5\text{ ft}$$

$$\frac{208.3\text{ gal}}{5\text{ ft}} = 41.7\text{ gpm/ft}$$

■ EXAMPLE 8.71. POUNDS OF SOLIDS PER HOUR FOR PLATE-AND-FRAME PRESSES

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:

$$850\text{ gal} \times \frac{3.7\%}{100\%} \times \frac{8.34\text{ lb}}{1\text{ gal}} = 262.3\text{ lb}$$

$$\frac{262.3\text{ lb}}{120\text{ min}} \times \frac{60\text{ min}}{1\text{ hr}} = 131.2\text{ lb/hr}$$

$$\frac{131.2\text{ lb/hr}}{140\text{ ft}^2} = 0.94\text{ lb/hr/ft}^2$$

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, chemical makeup and feed equipment and support systems for removal of dewatered solids are required, in addition to centrifuge pumping equipment for solids feed and centrate removal. Centrifuge operation is dependent upon various performance factors:

- Bowl design—length/diameter ratio; flow pattern
- Bowl speed
- Pool volume
- 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 the treatment system, and to perform required maintenance as outlined in the manufacturer's technical manual.

Sludge Incineration

Not surprisingly, incinerators produce the maximum solids and moisture reductions. The equipment required for incinceration depends on whether the unit is a multiple hearth or fluidized 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 or disposal.

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 four 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.

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 along with exhaust gases. Ash particles are removed using common air pollution control processes. Oxygen analyzers in the exhaust gas stack control the airflow rate.

> ***Note:*** Because these systems retain a high amount of heat in the sand, the system can be operated as little as 4 hr per day with little or no reheating.

LAND APPLICATION OF BIOSOLIDS

The purpose of land application of biosolids is to dispose of the treated biosolids in an environmentally sound manner by recycling nutrients and soil conditioners. To be land applied, wastewater biosolids must comply with state and federal biosolids management and disposal regulations. Biosolids must not contain materials that are dangerous to human health (e.g., toxicity, pathogenic organisms) or dangerous to the environment (e.g., toxicity, pesticides, heavy metals). Treated biosolids are land applied by either direct injection or application and plowing in (incorporation). 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/testing functions. Biosolids sampling and testing includes determination of percent solids, heavy metals, organic pesticides and herbicides, alkalinity, total organic carbon (TOC), organic nitrogen, and ammonia nitrogen.

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.

Disposal Cost

The cost of disposal of biosolids can be determined by

$$\text{Cost} = \text{Wet tons/yr} \times \%\ \text{Solids} \times \text{Cost/dry ton} \tag{8.87}$$

■ EXAMPLE 8.72

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:

$$\text{Cost} = 1925\ \text{wet tons/yr} \times 0.18 \times \$28\text{/dry ton} = \$9702$$

Plant Available Nitrogen (PAN)

One factor considered when land applying biosolids is the amount of nitrogen in the biosolids available to the plants grown on the site. This includes ammonia nitrogen and organic nitrogen. The organic nitrogen must be mineralized for plant consumption. Only a portion of the organic nitrogen is mineralized per year. The mineralization factor (f_1) is assumed to be 0.20. The amount of ammonia nitrogen available is directly related to the time elapsed between applying the biosolids and incorporating (plowing) the sludge into the soil. We provide volatilization rates based on this example below:

$$\text{PAN (lb/dry ton)} = \left[\left(\text{Organic nitrogen (mg/kg)} \times f_1\right) + \left(\text{Ammonia nitrogen (mg/kg)} \times V_1\right)\right] \times 0.002 \text{ lb/dry ton} \tag{8.88}$$

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 hr.
V_1 = 0.70 if biosolids are plowed in within 7 days.

■ EXAMPLE 8.73

Problem: The biosolids contain 21,000 mg/kg of organic nitrogen and 10,500 mg/kg of ammonia nitrogen. The biosolids are incorporated into the soil within 24 hr after application. What is the plant available nitrogen (PAN) per dry ton of solids?

Solution:

$$\text{PAN} = [(21{,}000 \text{ mg/kg} \times 0.20) + (10{,}500 \text{ mg/kg} \times 0.85)] \times 0.002 = 25.4 \text{ lb/dry ton}$$

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. The biosolids application rate based on the nitrogen requirement is determined by the following:

1. Use an agriculture handbook to determine the nitrogen requirement of the crop to be grown.
2. Determine the amount of sludge in dry tons required to provide this much nitrogen:

$$\text{Dry tons/ac} = \frac{\text{Plant nitrogen requirement (lb/ac)}}{\text{Plant available nitrogen (lb/dry ton)}} \tag{8.89}$$

■ EXAMPLE 8.74

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:

$$\text{Application rate} = \frac{150 \text{ lb/ac}}{30 \text{ lb/dry ton}} = 5 \text{ dry tons/ac}$$

Metals Loading

When biosolids are land applied, metals concentrations are closely monitored and their loading on land application sites is calculated:

$$\text{Loading (lb/ac)} = \text{Metal conc. (mg/kg)} \times 0.002 \text{ lb/dry ton} \times \text{Application rate (dry tons/ac)} \tag{8.90}$$

■ EXAMPLE 8.75

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:

$$\text{Loading rate} = 14\ \text{mg/kg} \times 0.002\ \text{lb/dry ton} \times 11\ \text{dry tons} = 0.31\ \text{lb/ac}$$

Maximum Allowable Applications Based upon 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:

$$\text{Applications} = \frac{\text{Maximum allowable cumulative load for the metal (lb/ac)}}{\text{Metal loading (lb/ac/application)}} \tag{8.91}$$

■ EXAMPLE 8.76

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:

$$\text{Applications} = \frac{48.0\ \text{lb/ac}}{0.35\ \text{lb/ac}} = 137$$

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:

$$\text{Site life (yr)} = \frac{\text{Maximum allowable applications}}{\text{Number of applications planned per year}} \tag{8.92}$$

■ EXAMPLE 8.77

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 120 applications. Based on the lead loading and the application rate, how many years can this site be used?

Solution:

$$\text{Site life} = 120\ \text{applications} \div 2\ \text{applications per year} = 60\ \text{years}$$

> ***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.

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9 Soil Quality

One can make a day of any size, and regulate the rising and setting of his own sun and the brightness of its shining.

—John Muir, naturalist and author

The sediments are a sort of epic poem of the Earth. When we are wise enough, perhaps we can read in them all of past history.

Carson (1951)

INTRODUCTION

When we talk about learning something from practical experience, we say we need to get in there and get our hands dirty. Increasing urbanization means increasing separation from practical knowledge in many areas of land use—separation from getting our hands dirty. American society has reached the point where "fresh air kids" are sent from New York to what amounts to smaller cities for a week in the "country." Many members of our society have never grown anything but houseplants potted in soil that comes packaged in plastic from a store—a packaged, sterile experience of what soil is and does. But, soil doesn't begin wrapped in plastic, any more than do the meat and produce people buy at the supermarket. When we forget that we are reliant on what our earth produces out of the fertility of that thin, fine layer of topsoil, we become wasteful, and we put ourselves at risk. We underestimate the value of our soil. We clear-cut it, we pave over it, we expand our communities needlessly on it, and, through carelessness and unconcern, we poison it. In short, we waste it.

As awareness of the serious soil pollution problems we must now mitigate and remediate grows, as we work to develop effective methods to reuse and recycle contaminated soil, we still have a tendency to think of soil pollution only as it affects our water supply. Again, we undervalue the worth of soil. We should not lose sight of the mountains of stone and eternity of time that went into making the soil under our feet.

In many respects, soil pollution is to environmental science in the 1990s what water and air pollution were to earlier decades—the pressing environmental problem at hand. Although developing methods to control air and water pollution was difficult, both socially and politically, once the regulations were in place and working effectively, the problems confronting the environmentalists were relatively simple to identify. Soil pollution, however, presents us with a new problem. Soil contamination sites, especially those from old underground sources (such as underground storage tanks, or USTs), create a difficult game of contamination "hide and seek." New techniques for handling the contamination show signs of promise and we have no shortage of sites in need of remediation, but we must also remember that hidden sites are still affecting us beneath our feet. Soil pollution has come to our attention at a time when regulations to begin remediation are being put in place, and the public is beginning to understand the importance of mitigating contaminated areas; however, political attacks have weakened the regulatory agencies' ability to clean up contaminated sites.

EVOLUTION OF SOIL[*]

If a man from today were transported back in time to a particular location, he would instantly recognize the massive structure before him, even though he might be taken aback at what he was seeing: a youthful mountain range with considerable mass, steep sides, and a height that certainly reached beyond any cloud. He would instantly relate to one particular peak—the tallest, most massive one. The polyhedron-shaped object, with its polygonal base and triangular faces culminating in a single sharp-tipped apex, would look familiar—comparable in shape, but larger in size, to the largest of the Great Egyptian Pyramids, although the Pyramids were originally covered in a sheet of limestone, not the thick, perpetual sheet of solid ice and snow covering this mountain peak.

If that same man were to walk this same site today, if he knew what had once stood upon this site, the changes would be obvious and startling—and entirely relative to time. Otherwise, he wouldn't give a second thought while walking across its remnants and through the vegetation growing from its pulverized and amended remains. Over 300 million years ago, the pyramid-shaped mountain peak stood in full, unchallenged splendor above the clouds, wrapped in a cloak of ice, a mighty fortress of stone, seemingly vulnerable to nothing, standing tallest of all—higher than any mountain ever stood—or will ever stand—on Earth.

And so it stood, for millions upon millions of passings of the Earth around the sun. Born when Mother Earth took a deep breath, the pyramid-shaped peak stood tall and undisturbed until millions of years later, when Mother Earth stretched. Today we would call this stretch a massive earthquake, although humans have never witnessed one of such magnitude. Rather than registering on the Richter scale, it would have destroyed it. When this massive earthquake shattered the Earth's surface, nothing we would call intelligent life lived on Earth—and it's a good thing. During this massive upheaval, the peak shook to its very foundations, and after the initial shockwave and hundreds of aftershocks, the solid granite structure was fractured. This immense fracture was so massive that each aftershock widened it and loosened the base foundation of the pyramid-shaped peak itself. Only 10,000 years later (a few seconds relative to geologic time), the fracture's effects totally altered the shape of the peak forever. During a horrendous windstorm, one of an intensity known only in Earth's earliest days, a sharp tremor (emanating from deep within the Earth and shooting up the spine of the mountain itself, up to the very peak) widened the gaping wound still more.

Decades of continued tremors and terrible windstorms passed (no present-day structure could withstand such a blasting), and, finally, the highest peak of that time, of all time, fell. It broke off completely at its base, and, following the laws of gravity (as effective and powerful a force then as today, of course), it tumbled from its pinnacle position and fell more than 20,000 feet, straight down. It collided with the expanding base of the mountain range, the earth-shattering impact destroying several thousand acres. What remained intact finally came to rest on a precipitous ledge, 15,000 feet in elevation. The pyramid-shaped peak, much smaller now, sat precariously perched on the precipitous ledge for about 5 million years.

Nothing, absolutely nothing, is safe from time. The most inexorable natural law is that of entropy. Time and entropy mean change and decay—harsh, sometimes brutal, but always inevitable. The bruised, scarred, truncated, but still massive rock form, once a majestic peak, was now a victim of Nature's way. Nature, with its chief ally, time, at its side works to degrade anything and everything that has substance and form. For better or for worse, in doing so Nature is ruthless, sometimes brutal, and always inevitable—but never without purpose. While resting on the ledge, the giant rock, over the course of that 5 million years, was exposed to constantly changing conditions. For several thousand years, Earth's climate was unusually warm—almost tropical—everywhere. Throughout this warm era, the rock was not covered with ice and snow, but instead baked in intense heat, steamed in hot rain, and endured gritty, violent windstorms that arose and released their abrasive fury, sculpting the rock's surface each day for more than 10,000 years.

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[*] Adapted from Spellman, F.R. and Stoudt, M.L., *Environmental Science*, Scarecrow Press, Lanham, MD, 2013.

Then came a pause in the endless windstorms and upheavals of the young planet, a span of time when the weather wasn't furnace-hot or arctic-cold, but moderate. The rock was still exposed to sunlight but at lower temperatures, to rainfall at increased levels, and to fewer windstorms of increased fury. The climate remained so for some years—then the cycle repeated itself—arctic cold, moderately warm, furnace hot—and repeated itself and again.

During the last of these cycles, the rock, considerably affected by physical and chemical exposure, was reduced in size even more. Considerably smaller now than when it landed on the ledge, and a mere pebble compared to its former size, it fell again, 8000 feet to the base of the mountain range, coming to rest on a bed of talus. Reduced in size still more, it remained on its sloping talus bed for many more thousands of years.

Somewhere around 15,000 BC, the rock form, continuously exposed to chemical and mechanical weathering, its physical structure weakened by its long-ago falls, fractured, split, and broke into ever-decreasing-sized rocks, until the largest intact fragment left from the original rock was no bigger than a four-bedroom house. But change did not stop, and neither did time, rolling on until about the time when the Egyptians were building their pyramids. By now, the rock had been reduced, by this long, slow decaying process, to roughly ten feet square. Over the next thousand years, the rock continued to decrease in size, wearing, crumbling, flaking away, surrounded by fragments of its former self, until it was about the size of a beach ball. Covered with moss and lichen, a web of fissures, tiny crevices, and fractures was now woven through the entire mass. Over the next thousand or so years, via *bare rock succession*, what had once been the mother of all mountain peaks, the highest point on Earth, had been reduced to nothing more than a handful of soil.

How did this happen? What is bare rock succession? If a layer of soil is completely stripped off land by natural means (e.g., water, wind), by anthropogenic means (tillage plus erosion), or by cataclysmic occurrence (a massive landslide or earthquake), only after many years can a soil-denuded area return to something approaching its original state, or can a bare rock be converted to soil. But, given enough time—perhaps a millennium—the scars heal over, and a new, virgin layer of soil forms where only bare rock once existed. The series of events taking place in this restoration process is known as bare rock succession. It is indeed a true "succession"—with identifiable stages. Each stage in the pattern dooms the existing community as it succeeds the state that existed before.

Bare rock, however it is laid open to view, is exposed to the atmosphere. The geologic processes that cause weathering begin breaking down the surface into smaller and smaller fragments. Many forms of weathering exist, and all effectively reduce the bare rock surface to smaller particles or chemicals in solution. Lichens appear to cover the bare rock first. These hardy plants grow on the rock itself. They produce weak acids that assist in the slow weathering of the rock surface. The lichens also trap wind-carried soil particles, which eventually produce a very thin soil layer—a change in environmental conditions that gives rise to the next stage in bare rock succession.

Mosses replace lichens, growing in the meager soil the lichens and weathering provide. They produce a larger growing area and trap even more soil particles, providing a more moist bare rock surface. The combination of more soil and moisture establishes abiotic conditions that favor the next succession stage. Now the seeds of herbaceous plants invade what was once bare rock. Grasses and other flowering plants take hold. Organic matter provided by the dead plant tissue is added to the thin soil, while the rock still weathers from below. More and more organisms join the community as it becomes larger and more complex.

By this time, the plant and animal community is fairly complicated. The next major invasion is by weedy shrubs that can survive in the amount of soil and moisture present. As time passes, the process of building soil speeds up as more and more plants and animals invade the area. Soon trees take root and forest succession is evident. Many years are required, of course, before a climax forest will grow here, but the scene is set for that to occur (Tomera, 1989).

Today, only the remnants of the former, incomparable pyramid-shaped peak are left in the form of soil—soil packed full of organic humus, soil that looks like mud when wet and that, when dry, most people would think was just a handful of dirt.

WHAT IS SOIL?

In any discussion about soil (after air and water, the third environmental medium), we must initially define exactly what soil is and explain why soil is so important to us. Having said the obvious, we must also clear up a major misconception about soil. As the chapter's introduction indicates, people often confuse soil with dirt. Soil is not dirt. Dirt is misplaced soil—soil where we don't want it, contaminating our hands or clothes, tracked in on the floor. Dirt we try to clean up and keep out of our environment. But *soil* is special—mysterious, critical to our survival, and, whether we realize it or not, essential to our existence. We have relegated soil to an ignoble position. We commonly degrade it—we consider only feces to be a worse substance, but soil deserves better. Before moving on, let's take another look at that handful of "dirt" that our modern man is holding after the mountain peak was crafted into soil by the sure hand of Nature over millions and millions of years.

What is soil, really? Perhaps no word causes more confusion in communications among various groups of laypersons and professionals—environmental scientists, environmental engineers, specialized groups of earth scientists, and engineers in general—than the word "soil." Why? From the professional's perspective, the problem lies in the reasons why different groups study soils.

Pedologists (soil scientists) are interested in soils as a medium for plant growth. Representing a corresponding branch of engineering soils specialists, *soil engineers* look at soil as a medium that can be excavated with tools. A *geologist*'s view of soil falls somewhere between that of pedologists and soil engineers—they are interested in soils and the weathering processes as past indicators of climatic conditions and in relation to the geologic formation of useful materials ranging from clay deposits to metallic ores.

To clear up this confusion, let's view that handful of soil from a different—but much more basic and revealing—perspective. Consider the following descriptions of soil to better understand what soil is and why it is critically important to us all:

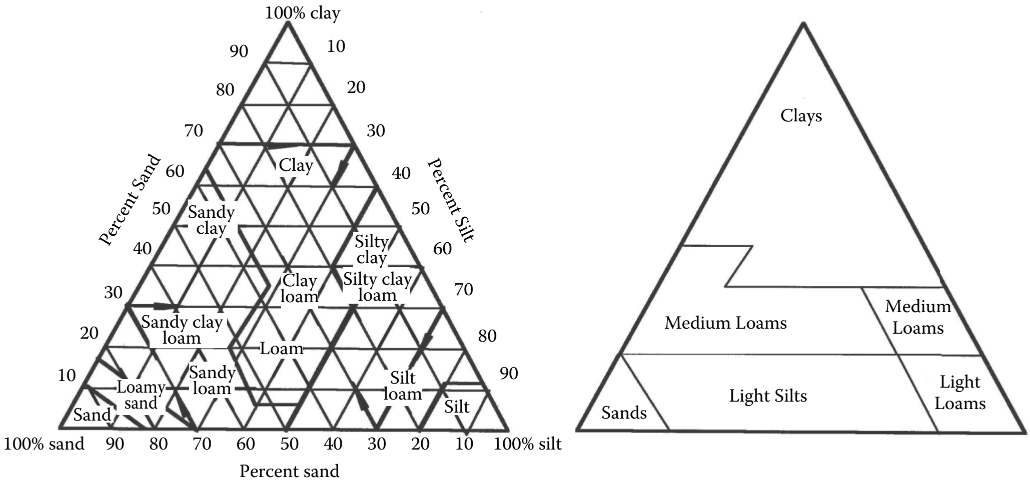
1. A handful of soil is alive, a delicate living organism—as lively as an army of migrating caribou and as fascinating as a flock of egrets. Literally teeming with life of incomparable forms, soil deserves to be classified as an independent ecosystem or, more correctly stated, as many ecosystems.
2. When we reach down and pick up an handful of soil, exposing the stark bedrock surface, it should remind us, maybe startle some of us, that without its thin living soil layer Earth is a planet as lifeless as our own moon.

If you still prefer to call soil dirt, that's okay. Maybe you view dirt in the same way as E.L. Konigsburg's character Ethan does:

> The way I see it, the difference between farmers and suburbanites is the difference in the way we feel about dirt. To them, the earth is something to be respected and preserved, but dirt gets no respect. A farmer likes dirt. Suburbanites like to get rid of it. Dirt is the working layer of the earth, and dealing with dirt is as much a part of farm life as dealing with manure: neither is user-friendly, but both are necessary (Konigsburg, 1996, p. 64).

SOIL BASICS

Soil is the layer of bonded particles of sand, silt, and clay that covers the land surface of the Earth. Most soils develop multiple layers. The topmost layer (*topsoil*) is the layer in which plants grow. This topmost layer is actually an ecosystem composed of both biotic and abiotic components—inorganic chemicals, air, water, decaying organic material that provides vital nutrients for plant photosynthesis, and living organisms. Below the topmost layer (usually no more than a meter in thickness), is the *subsoil*, which is much less productive, partly because it contains much less organic matter. Below that is the *parent material*, the bedrock or other geologic material from which the soil is ultimately



(A) (B)

FIGURE 9.1 (A) Textural triangle similar to U.S. Department of Agriculture model; (B) broad groups of textural classes. (Adapted from Briggs, D. et al., *Fundamentals of the Physical Environment*, Routledge, London, 1997, p. 323.)

formed. The general rule of thumb is that it takes about 30 years to form one inch of topsoil from subsoil; it takes much longer than that for subsoil to be formed from parent material, the length of time depending on the nature of the underlying matter (Franck and Brownstone, 1992).

Soil Properties

From the environmental scientist's view (with regard to land conservation and remediation methodologies for contaminated soil remediation through reuse and recycling), four major properties of soil are of interest: soil texture, slope, structure, and organic matter. Soil texture (see Figure 9.1), or the relative proportions of the various soil separates in a soil, is a given and cannot be easily or practically changed significantly. It is determined by the size of the rock particles (sand, silt, and clay particles) or the soil separates within the soil. The largest soil particles are gravel, which consists of fragments larger than 2.0 mm in diameter. Particles between 0.05 and 2.0 mm are classified as sand. Silt particles range from 0.002 to 0.05 mm in diameter, and the smallest particles (clay particles) are less than 0.002 mm in diameter. Clays are composed of the smallest particles, but these particles have stronger bonds than silt or sand; once broken apart, though, they erode more readily. Particle size has a direct impact on erosion. Rarely does a soil consist of only one single size of particle; most are a mixture of various sizes.

The slope (or steepness of the soil layer) is another given, important because the erosive power of runoff increases with the steepness of the slope. Slope also allows runoff to exert increased force on soil particles, which breaks them apart more readily and carries them farther away.

Soil structure (tilth) should not be confused with soil texture—they are different. In fact, in the field, the properties determined by soil texture may be considerably modified by soil structure. Soil structure refers to the combination or arrangement of primary soil particles into secondary particles (units or peds). Simply stated, soil structure refers to the way various soil particles clump together. Clusters of soil particles, called *aggregates*, can vary in size, shape, and arrangement; they combine naturally to form larger clumps called *peds*. Sand particles do not clump because sandy soils lack structure. Clay soils tend to stick together in large clumps. Good soil develops small friable (easily crumbled) clumps. Soil develops a unique, fairly stable structure in undisturbed landscapes, but agricultural practices break down the aggregates and peds, lessening erosion resistance.

The presence of decomposed or decomposing remains of plants and animals (organic matter) in soil helps not only fertility but also soil structure—especially the ability of soil to store water. Live organisms such as protozoa, nematodes, earthworms, insects, fungi, and bacteria are typical inhabitants of soil. These organisms work to either control the population of organisms in the soil or to aid in the recycling of dead organic matter. All soil organisms, in one way or another, work to release nutrients from the organic matter, changing complex organic materials into products that can be used by plants.

SOIL FORMATION

Soil is formed as a result of physical, chemical, and biological interactions in specific locations. Just as vegetation varies among biomes, so do the soil types that support that vegetation. The vegetation of the tundra and that of the rain forest differ vastly from each other and from vegetation of the prairie and coniferous forest; soils differ in similar ways. In the soil-forming process, two related, but fundamentally different, processes are occurring simultaneously. The first is the formation of soil parent materials by weathering of rocks, rock fragments, and sediments. This set of processes is carried out in the zone of weathering. The end point is producing parent material for the soil to develop in and is referred to as C horizon material. It applies in the same way for glacial deposits as for rocks. The second set of processes is the formation of the soil profile by soil-forming processes, which gradually change the C horizon material into A, E, and B horizons. Figure 9.2 illustrates two soil profiles, one on hard granite and one on a glacial deposit.

Soil development takes time and is the result of two major processes: weathering and morphogenesis. Weathering (the breaking down of bedrock and other sediments that have been deposited on the bedrock by wind, water, volcanic eruptions, or melting glaciers) happens physically, chemically,

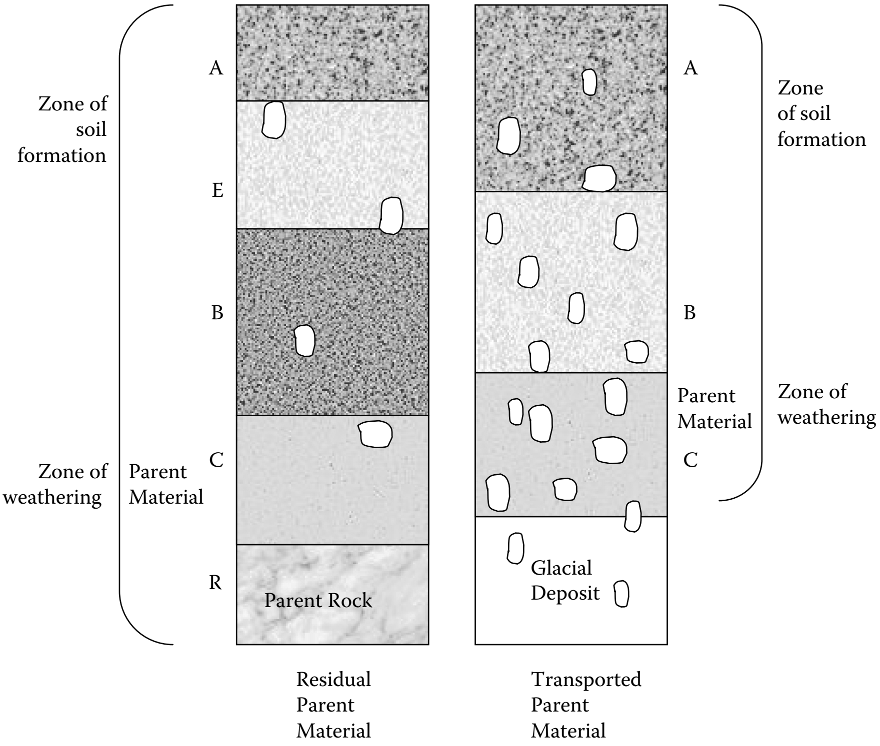


FIGURE 9.2 Soil profiles on residual and transported parent materials.

or a combination of both. Physical weathering involves the breaking down of rock primarily by temperature changes and the physical action of water, ice, and wind. When a geographical location is characterized as having an arid desert biome, the repeated exposure to very high temperatures during the day followed by low temperatures at night causes rocks to expand and contract and eventually to crack and shatter. At the other extreme, in cold climates rock can crack and break as a result of repeated cycles of expansion of water in cracks and pores during freezing and contraction during thawing. Another type of physical weathering occurs when various vegetation types spread their roots and grow, and the roots can exert enough pressure to enlarge cracks in solid rock, eventually splitting and breaking the rock. Plants such as mosses and lichens also penetrate rock and loosen particles.

Bare rocks are also subjected to chemical weathering, which involves chemical attack and dissolution of rock. Accomplished primarily through oxidation via exposure to oxygen gas in the atmosphere, acidic precipitation (after having dissolved small amounts of carbon dioxide gas from the atmosphere), and acidic secretions of microorganisms (bacteria, fungi, and lichens), chemical weathering speeds up in warm climates and slows down in cold ones. Physical weathering and chemical weathering do not always (if ever) occur independently of each other; instead, they normally work in combination, and the results can be striking.

A classic example of the effect and power of their simultaneous actions can be seen in the ecological process known as *bare rock succession*. The final stages of soil formation consist of the processes of *morphogenesis*, or the production of a distinctive *soil profile* with its constituent layers or *horizons* (see Figure 9.2). The soil profile (the vertical section of the soil from the surface through all its horizons, including C horizons) gives the environmental scientist critical information. When properly interpreted, soil horizons can warn of potential problems in using the land and tell much about the environment and history of a region. The soil profile allows us to describe, sample, and map soils.

Soil horizons are distinct layers, roughly parallel to the surface, which differ in color, texture, structure, and content of organic matter. The clarity with which horizons can be recognized depends upon the relative balance of the migration, stratification, aggregation, and mixing processes that take place in the soil during morphogenesis. In podzol-type soils (formed mainly in cool, humid climates), striking horizonation is quite apparent; in vertisol-type soils (soils high in swelling clays), the horizons are less distinct. When horizons are studied, they are given a letter symbol to reflect the genesis of the horizon (see Figure 9.2).

Certain processes work to create or destroy clear soil horizons. Processes that tend to create clear horizons by vertical redistribution of soil materials include the leaching of ions in soil solutions, movement of clay-sized particles, upward movement of water by capillary action, and surface deposition of dust and aerosols. Clear soil horizons are destroyed by mixing processes that occur because of organisms, cultivation practices, creep processes on slopes, frost heave, and swelling and shrinkage of clays—all part of the natural soil formation process.

SOIL FERTILITY

Soil fertility is a major concern, not only throughout the United States but also worldwide. The impacts on soil fertility from agricultural practices (such as erosion, salination, and waterlogging) are well known, well studied, and well documented. Remediation practices are also known and actually in place in many locations throughout the globe. Indeed, solving problems related to soil fertility has received considerable attention, driven not only by a growing and hungry worldwide population but also by pocketbook issues—economics. However, a major problem related to soil fertility that has only recently become apparent in the human population's continuing fight to maintain soil for its primary purpose (or, as pointedly and correctly stated by the World Resource Institute, "its ability to process nutrients into a form usable by plants") is soil contamination or soil pollution.

SOIL POLLUTION

Soil pollution generated by industrial contamination, management of Superfund sites, exploration and production, mining, and nuclear industrial practices, among others, is impacting soil quality in ways we have only recently begun to comprehend. Complicating the problem is that soil pollution remains difficult to assess. Some evidence, however, clearly indicates the impact of a few industrial practices related to soil pollution. For example, we know that petroleum-contaminated soil affects the largest number of sites and represents the largest total volume of contaminated material. However, the volume of petroleum-contaminated soil that is either discovered or is generated each year is not consistently tracked on a local basis, so the actual total is unknown. We also know, from the evidence—for example, in Oklahoma, contaminated soil accounts for about 90% of the waste generated as a one-time occurrence—that the overall amount of contaminated soil generated can be staggering (Testa, 1997).

Pollution of soil and water is a problem common to all human societies. Throughout the history of civilization, humans have probably had little problem recognizing surface water contamination. Treatment of surface water for drinking became common in the late 19th century, and health problems linked to drinking impure water in developed countries are now rare. Underdeveloped countries, however, are still faced with a lack of safe drinking water.

Only in the past several decades has a new problem come to light, literally and figuratively: contamination of the soil and its underground environment. In developed countries, this problem is much more serious because of their history of industrialization and the wide range of hazardous materials and other chemicals that have been introduced, either by design or accident, to the underground environment. Ignorance—more than intent—is the culprit. We were ignorant in the sense that we did not comprehend the degree to which contaminants could migrate through the soil or the damage they could do to the soil medium and the groundwater under its protective surface—or the difficulty we would encounter in tracing and removing most contaminants after discovery.

Beginning with the most contaminated sites, the response (in developed countries) to underground contamination has been a massive effort to define the extent of contamination and to remediate the subsurface. This response has been driven by governmental regulations dealing with waste handling and disposal, as well as many other potentially contaminating activities. The range of activities that cause underground contamination is much larger than most environmental scientists would have guessed even a few years ago. We briefly discuss these activities in the sections that follow.

Soil quality problems originating on the surface include natural atmospheric deposition of gaseous and airborne particulate pollutants; infiltration of contaminated surface water; land disposal of solid and liquid waste materials; stockpiles, tailings, and spoil; dumps; salt spreading on roads; animal feedlots; fertilizers and pesticides; accidental spills; and composting of leaves and other yard wastes. Although we do not discuss them in detail in this text, other sources of soil contamination are related to petroleum products. These other sources include direct disposal of used oils on the ground by individuals or industries; seepage from landfills, illegal dumps, unlined pits, ponds, and lagoons; and spills from transport accidents. Even automobile accidents contribute to the soil burden (Tucker, 1989). This section focuses on both the *surface origins* of soil contaminants and the *industrial practices* that can contaminate soil, and the next section addresses the concepts of remediation and resource recovery.

> ***Note:*** The following discussion focuses on contamination originating on land surfaces; however, be aware that soil and subsurface contamination may also originate below ground (but above the water table) due to septic tanks, landfills, sumps and dry wells, graveyards, underground storage tanks, and underground pipelines, among other sources. In addition, soil, subsurface, and groundwater contamination may also originate below the water table due to mines, test holes, agricultural drainage wells, and canals.

GASEOUS AND AIRBORNE POLLUTANTS

Soil figures prominently in the function of the carbon, nitrogen, and sulfur cycles—the biogeochemical cycles. While prominent in the normal operation of these cycles, soil interfaces in powerful and essential ways with the atmosphere. Consider the nitrogen cycle, where nitrates and ammonium ions in rainwater are absorbed by plant roots and soil microorganisms and converted to amino acids or to gaseous N_2 and N_2O, which diffuse back to the atmosphere. The N_2 uptake and conversion to amino acids (nitrogen fixation) by symbiotic and free-living soil microorganisms balances this loss of gaseous nitrogen. NO, NO_2, and NH_3 (other nitrogen gases) are also emitted and absorbed by soils. Soil reactions are major determinants of trace gas concentrations in the atmosphere. Air pollutants—sulfur dioxide, hydrogen sulfide, hydrocarbons, carbon monoxide, ozone, and atmospheric nitrogen gases—are absorbed by soil. Because soil reactions are subtle, they are often ignored in tracing the effects of air pollution; however, two classic examples of airborne particulate soil contamination are the accumulation of heavy metals around smelters and soils in urban areas contaminated by exhaust fumes associated with vehicle emissions. Although these two soil polluters can be serious in localized areas, long-range effects of such contamination are considered minor.

INFILTRATION OF CONTAMINATED SURFACE WATER

When wells are installed near streams and rivers, the well induces recharge from the water body, providing high yield with low drawdowns; however, if the water body that the well draws from is polluted, soil-water well field contamination can result. This most commonly occurs from a shallow water supply well drawing water from the alluvial aquifer adjacent to the stream. The cone of depression imposed by pumping the well or well field creates a gradient on the water table directed toward the well. This pulls the polluted water through the soil and contaminates both the well field and well.

LAND DISPOSAL OF SOLID AND LIQUID WASTE MATERIALS

Land disposal, stockpiling, and land-applying wastes or materials, including liquid and sludge (biosolids) wastes from sewage treatment plants (nearly half of the municipal sewage biosolids produced in the United States are applied to the soil, either for agricultural purposes or to remediate land disturbed by mining and other industrial activities), food processing companies, and other sources, have become common practices. The purpose of such practices is twofold: They serve as a means of disposal and provide beneficial use of such materials as fertilizers for agricultural lands, golf courses, city parks, and other areas. The objective is to allow biological and chemical processes in the soil, along with plant uptake, to break down the waste products into harmless substances. In many cases, such practices are successful; however, a contamination problem may arise if any of the wastes are water soluble and mobile, which could allow them to be carried deep into the subsurface. If the drainage or seepage area is underlain by shallow aquifers, a groundwater contamination problem may arise.

STOCKPILES, TAILINGS, AND SPOILS

The practice of stockpiling chemical products, if not properly managed, contributes to soil and subsurface pollution. Road-salt stockpiles are maintained by many local highway departments and some large industries for snow and ice removal in winter, but the salt can leach into the soil. Tailings produced in mining activities commonly contain materials (e.g., asbestos, arsenic, lead, radioactive substances) that are a health threat to humans and other living organisms. Tailings may also contain contaminants, including sulfide, which forms sulfuric acid upon contact with precipitation. The precipitation runs off or is leached from tailing piles, infiltrating the surface layer and contaminating soil. It may ultimately reach groundwater. Spoil (a common result of excavations where huge amounts of surface cover are removed, piled, and then moved somewhere else) causes problems similar to tailing problems, in that precipitation removes materials in solution in percolating waters (leaching). Pollutants migrate from the spoil, finding their way into the soil and into shallow aquifers.

Dumps

Until recently, a common waste disposal practice was to take whatever was not wanted and dump it somewhere, anywhere, out of sight. Today, uncontrolled dumping is prohibited in most industrialized countries, but the old dumping sites can contain just about anything and may still represent the threat of subsurface contamination. Another problem that is still with us is "midnight dumping." Because dumping today is controlled and regulated, many disposers attempt to find alternative ways to get rid of junk. Unfortunately, much of this junk consists of hazardous materials and toxins that end up finding their way into and through soil to aquifers. In addition to the midnight dumping problem, another illegal disposal practice has developed in some industries because of the high cost involved with proper disposal. This practice, commonly referred to as "immaculate conception," occurs when workers in industrial facilities discover unmarked drums or other containers of unknown wastes that suddenly appear on loading docks or elsewhere in the facility. Then, of course, these immaculately conceived vessels of toxic junk end up being thrown out with the common trash, and their contents eventually percolate through the soil to an aquifer.

Salt Spreading on Roads

The practice of spreading deicing salts on highways is widespread, especially in urban areas in the north. Not only does this practice contribute to the deterioration of automobiles, bridges, and the roadway itself, but it also adversely affects plants growing alongside a treated highway or sidewalk. More seriously, salt contamination quickly leaches below the land surface. The productivity of the land decreases, because most plants cannot grow in salty soils. Contamination of wells used for drinking water can occur in areas with long-term continued use.

Animal Feedlots

Animal feedlots are a primary source of nonpoint surface water pollution. Animal feedlots are also significant contributors to groundwater pollution. Because animal waste in feedlots literally piles up and is stationary (sometimes for extended periods), runoff containing contaminants not only may enter the nearest surface water body but may also seep into the soil, contaminating it. If the contaminated flow continues unblocked through the subsurface, the flow may eventually make its way into shallow aquifers.

Fertilizers and Pesticides

Fertilizers and pesticides have become the mainstays of high-yield agriculture. They have also had a significant impact on the environment, with each yielding different types of contaminants. When we apply fertilizers and pesticides to our soil, are we treating the soil—or poisoning it? This question is relatively new to us—and one we are still trying to definitively answer. One thing is certain, though. With regard to fertilizer and pesticide applications and the long-term effects of such practices, the real issue is that we do not know what we do not know. We are only now starting to see and understand the impact of using these chemicals. We have a lot to learn. Let's take a look at a few of the known problems with using chemical fertilizers and pesticides.

Nitrogen fertilizers are applied to stimulate plant growth but often in greater quantities than plants can use at the time of application. Nitrate, the most common chemical form of these fertilizers, can easily leach below the plant root zone by rainfall or irrigation. When it has moved below the root zone, it usually continues downward to the water table. When we put total dependency upon chemical fertilizers, they can change the physical, chemical, and biotic properties of the soil—another serious problem.

Pesticides (any chemical used to kill or control populations of unwanted animals, fungi, or plants) are not as mobile as nitrate, but they are toxic at much lower concentrations. The perfect pesticide would be inexpensive, would affect only the target organism, would have a short half-life, and would break down into harmless substances. As of yet, though, we have not developed the perfect pesticide, and herein lies a multifaceted problem. Pesticides used in the past—and some of those being used today—are very stable and persistent and can become long-term problems. They may also be transported from the place of original application to other parts of the world by wind or ocean currents.

Another problem associated with persistence in pesticide use is that they may accumulate in the bodies of organisms in the lower trophic levels. When a lower trophic level animal receives small quantities of pesticides in its food and cannot eliminate them, the concentration within the organism increases. Bioaccumulation occurs when these organisms accumulate higher and higher amounts of materials within their bodies. Eventually, these organisms pass on such accumulation to higher trophic level organisms, and the bioaccumulated toxins move on up the food chain to the highest levels.

ACCIDENTAL SPILLS

Disturbingly common, accidental spills of chemical products can be extremely damaging to any of the three environmental media—air, water, and soil. When chemical spills in the soil media are not discovered right away, the contaminant may migrate into and through the soil to the water table. As a general rule of thumb, we may assume that the impact of a chemical spill in soil (or any other medium) is directly related to the concentration present at the point and time of release, the extent to which the concentration increases or decreases during exposure, and the time over which the exposure continues.

COMPOSTING OF LEAVES AND OTHER WASTES

Composting is a common practice for many homeowners (especially gardeners), who use the contained and controlled decay of yard and vegetable wastes as an environmentally friendly way to dispose of or beneficially reuse them. When the feed materials (leaves, twigs, and other organics) have been treated with chemical pesticides and some fertilizers, however, composting this material may be harmful to the soil.

INDUSTRIAL PRACTICES AND SOIL CONTAMINATION

Contamination sources from industrial practices include spillage and leakage from underground storage tanks (USTs), oil field sites, chemical sites, geothermal sites, manufactured gas plants, mining sites, and many other industrial activities. As a result of the Persian Gulf and Iraq wars, we have also experienced contamination from environmental terrorism on an alarmingly large scale.

Contamination from Oil Field Sites

People often repeat two clichés: “The past has a way of catching up with us” and “If we don’t learn from our past mistakes we are doomed to repeat them.” Keep in mind that clichés become clichés by being true. And these two are certainly true when we consider the problems with soil contamination from oil field sites, a source of large volumes of hydrocarbon-contaminated soil resulting from past and existing oil fields. The extent of the impact of this problem is location specific. For example, past and present-day oil exploration and production activities located in remote parts of Oklahoma and Texas are not highly visible and thus not subject to public scrutiny. In these remote locations, disposing of hydrocarbon-contaminated soil is easy and inexpensive.

In highly urbanized locations (e.g., Los Angeles County, where more than 3000 acres of prime real estate are being or have been exploited for petroleum), developers sit back and eagerly wait until existing fields reach their productive ends, at which point the developers move right in and redevelop the prime real estate (prime in the sense of location and shortage of available real estate). The ill-informed developer quickly finds out, however, that just because the well runs dry does not mean that the land can immediately be marketed and developed. In these areas, the disposal of contaminated soils has emerged as a serious and expensive undertaking.

On or near petroleum-producing properties, the primary sources of soil contamination include oil wells, sumps, pits, dumps leakage from aboveground storage tanks, and leakage and/or spillage. Secondary sources include USTs, transformers, piping ratholes, well cellars, and pumping stations. In addition, the large stationary facilities used for the refining of petroleum have the potential to cause chronic pollution by the discharge of hydrocarbon-laden wastewaters, and by frequent small spills. The primary hazardous constituents associated with oil field properties include drilling mud and constituents, methane, and crude oil. When crude contains certain constituents above maximum contaminant levels—arsenic, chloride, chromium, lead, polychlorinated biphenyls (PCBs)—and has a flash point less than the minimum standard as set by the American Society for Testing and Materials (ASTM) for recycled products, it may be considered a hazardous waste. Close to many oil fields there exist complete handling and processing ancillaries—refineries, terminals, and pipelines—which also contribute to the overall volume of contaminated soil generated. Of primary concern are contaminants such as crude oil, refined products, and volatile organic compounds.

Contamination from Chemical Sites

The 1979 PEDCO–Eckhardt Survey (commonly referred to as the Eckhardt Survey) of more than 50 of the largest manufacturing companies in the United States reported that almost 17 million tons of organic generated wastes were disposed of. Of this total, more than 10 million tons were untreated (residing in landfills, ponds, lagoons, and injection wells). Approximately 0.5 million tons were incinerated, and approximately 0.5 million tons were either recycled or reused. The volume of contaminated soil as a result of one-time occurrence was not addressed in this survey. Soil contamination from organic chemicals is a serious matter. Some of these organic compounds are biologically damaging even in small concentrations. When they do find their way into the soil, certain organic chemicals may kill or inhibit sensitive soil organisms, which can undermine the balance of the soil community. Once in the soil, the contaminant may be transported from the soil to the air, water, or vegetation, where it may be inhaled, ingested, or contacted over a wide area by a number of organisms. Because of their potential harm, controlling the release of organic chemicals and understanding their fate and effects in the soil are imperative.

Contamination from Geothermal Sites

Geothermal energy is natural heat generated beneath the surface of the Earth. The mantle, 15 to 30 miles below the Earth's crust, is composed of a semi-molten rock layer. Beneath the mantle, intense pressure caused by molten rock of iron and nickel and decaying radioactive elements helps warm the Earth's surface. Geothermal energy generally lies too deep to be harnessed, but in certain areas where the molten rock has risen closer to the surface through massive fractures in the crust, underground reservoirs of dry steam, wet steam, and hot water are formed. As with oil deposits, these deposits can be drilled and their energy used to heat water, drive industrial processes, and generate electricity.

Generally, geothermal resources are more environmentally friendly than nuclear energy or fossil fuels; however, several drawbacks to geothermal energy use adversely impact the environment. As with oil field operations, geothermal operations provide another example of the close relationship between site usage and the potential for adverse environmental impact. The two constituents associated with geothermal plants that may be considered hazardous are brine and lead-mine scale (Testa, 1997).

A major problem is the disposal of wastewater from geothermal wells containing brine—geothermal mineralizing fluids composed of warm to hot saline waters containing sodium, potassium, chloride, calcium, and minor amounts of other elements that may be harmful to plants and animals. The problem with lead-mine scale is more directly related to process equipment failures than environmental problems, as it is a result of scale buildup in pipes and other process equipment which may lead to equipment failure (pipe rupture, for example), which, in turn, may lead to geothermal fluid spills and soil, air, or water contamination.

Contamination from Manufactured Gas Plants

The manufacture of gas is not a new process. Since the late 1890s, manufactured gas plants (approximately 3000 of them located in the United States) have been in operation, have been upgraded, or have been completely redeveloped in one way or another. The environmental soil pollution problem associated with manufactured gas plants is the production and disposal of tarry substances, primarily produced in the coal gasification processes of coal carbonization, carburetted waste gas, natural gas, or combination processes. Other than the obvious mess that the production of any tar-like substance can produce, the main environmental problem with tars is that they contain organic and inorganic compounds that are known or suspected carcinogens. The average volume of tar-contaminated soil averages 10,000 cubic yard per site (Testa, 1997).

Contamination from Mining Sites

According to the U.S. Departments of Interior and Agriculture, since the mid-1860s more than 3 million acres of land in the United States have been surface-mined for various commodities. Leading the list of commodities being mined is coal, followed by sand and gravel, stone, gold, phosphate rock, iron ore, and clay, respectively. Mining operations can give rise to land and water pollution. Sediment pollution via erosion is the most obvious problem associated with surface mining. Sediment pollution to natural surface water bodies is well documented. The Chesapeake Bay, for example, is not the fertile oyster-producing environment it was in the past. Many environmentalists initially blamed the Bay's decline on nutrient-rich substances and chemical pollutants. Recent studies of the Bay's tributaries and the Bay itself, however, indicate that oysters may be suffering (literally suffocating) from sedimentation rather than nutrient contamination. Because the topic has been less studied, the effects that mining sediments and mining wastes (from mining, milling, smelting, and leftovers) are having on soil are not well known. Typical mining wastes include acid produced by oxidation of naturally occurring sulfides in mining waste, asbestos produced in asbestos mining and milling operations, cyanide produced in precious metal heap-leaching operations, leach liquors produced during copper-dump leaching operations, metals from mining and milling operations, and radionuclides (radium) from uranium and phosphate mining operations.

One soil contaminant source is well known and well documented: acid mine drainage. Acid formations occur when oxygen from the air and water react with sulfur-bearing minerals to form sulfuric acid and iron compounds. These compounds may directly affect the plant life that absorbs them or have an indirect effect on the flora of a region by affecting the soil minerals and microorganisms. Another problem with mining is solid wastes. Metals are always mixed with material removed from a mine. These materials usually have little commercial value and thus must be disposed somewhere. The piles of rock and rubble are not only unsightly but are also prone to erosion, and leaching releases environmental poisons into the soil.

Contamination from Environmental Terrorism

Many human activities that have resulted in environmental contamination have been the result of accidents or poor planning, poor decision making, inferior design, shoddy workmanship, ignorance, or faulty equipment. Whenever the public becomes aware of environmental contamination, they could assume that such factors were behind the contamination, at least prior to 1991. Certainly the first Persian Gulf War changed this perception. After the Gulf War, almost half of Kuwait's 1500 oil wells were releasing oil into the environment. An estimated 11 million barrels of oil were either being burned or spilled each day, in 600 wells. After the well capping operation got underway, and after more than 200 wells had been capped, this amount was reduced to approximately 6 million barrels by the end of summer. The harmful effects to the atmosphere and Persian Gulf were only part of the problem, however. Numerous pools of oil formed, some of them up to 4 ft deep, collectively containing an estimated 20 million barrels of oil (Andrews, 1992). The larger long-term problem of this blatant act of terrorism is twofold: the presence of the oil pools and huge volumes of petroleum-contaminated soil.

UNDERGROUND STORAGE TANKS: THE PROBLEM

Soil or *subsurface remediation* is a still-developing branch of environmental science and engineering. Because of the regulatory programs of the 1980 Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), better known as Superfund, and the 1976 Resource Conservation and Recovery Act (RCRA), better known as the Cradle-to-Grave Act, remediation is an accepted entry in the environmental vocabulary. How commonly is remediation known? To best answer this question, follow the response of venture capitalists in their attempts to gain a foothold in this relatively new technological field. MacDonald (1997, p. 560) pointed out:

> In the early 1990s, venture capitalists began to flock to the market for groundwater and soil cleanup technologies, seeing it as offering significant new profit potential. The market appeared large; not only was $9 billion per year being spent on contaminated site cleanup, but existing technologies were incapable of remediating many serious contamination problems.

Numerous remediation technologies (also commonly known as *innovative cleanup technologies*) were developed and became commercially available since CERCLA and RCRA were put into place. We briefly discuss these technologies in this chapter, especially those designed and intended to cleanup sources of subsurface contamination caused by underground storage tanks (USTs). We focus on technology used in contamination from failed USTs primarily because these units have been the cause of the majority of contamination events and remediation efforts to date. As a result, enormous volumes of information have been recorded on this remediation practice, both from the regulators and the private industries involved with their cleanup. Keep in mind that, no matter what the contaminant, removing every molecule of contamination and restoring the landscape to its natural condition is highly unlikely (although it likely is the goal of the regulatory agency monitoring a particular UST cleanup effort). No one knows for sure the exact number of underground storage tank systems installed in the United States; however, most estimates range in the millions. Several thousands of these tanks, including ancillaries such as piping, are currently leaking. Why are so many USTs leaking? They leak for several reasons: (1) corrosion, (2) faulty tank construction, (3) faulty installation, (4) piping failure, (5) overfills and spills, or (6) incompatibility of UST contents.

CORROSION PROBLEMS

Corrosion is the most common cause of tank failure. Most older tanks are single-shell construction, made of unprotected bare steel. Many leaked in the past (and have been removed, we hope), are leaking at present, or (if not removed or rehabilitated) will certainly leak in the future. Even a small leak, if undetected or ignored, causes large amounts of petroleum product to enter the subsurface.

Faulty Construction

As with any material item, USTs are only as good as their construction, workmanship, and the materials used in their construction. If a new washing machine is improperly assembled, it will likely fail, sooner than later. If a ladder is made of a material not suited to handle the load bearing, it may fail, and the consequences may result in injury. You can probably devise your own list of possible failures resulting from poor or substandard construction or poor workmanship. We all have such a list—some lengthier than others. USTs are no different than any other manufactured item. If they are not constructed properly, and if workmanship is poor, they will fail. It's that simple—although the results of such failure are not so simple.

Faulty Installation

Probably the most important step in tank installation is to ensure that adequate backfilling is provided to ensure that no possible movement of the tank can occur after it is placed in the ground. Any such movement not only might damage the tank (especially fiberglass-reinforced plastic tanks) but could also jar loose pipe connections or cause pipe joints to separate. Failure to use special care in the installation process results in leaks. Care must also be taken to ensure that underground leak detection devices are carefully and correctly installed. Obviously, if a tank is leaking, it is best to discover that as soon as possible so remediation can be initiated quickly, before a minor spill turns into a nasty environmental contamination incident.

Piping Failures

We have mentioned tank-piping failure resulting from improper installation, but piping can fail in other ways as well. Before we discuss them, note that the U.S. Environmental Protection Agency (USEPA) and other investigators clearly indicate that piping failure is one of the most common causes of larger UST spills. If metal piping is used to connect tanks together, to delivery pumps, to fill drops, or for whatever reason, the danger of corrosion from rust or from electrolytic action is always present. Electrolytic action occurs because threaded pipes (or other metal parts made electrically active by threading) have a strong tendency to corrode if not properly coated or otherwise protected. To prevent electrolytic action, *cathodic protection* is usually installed to eliminate electrolytic action. Piping failures are caused equally by poor workmanship, which usually appears around improperly fitted piping joints (both threaded and PVC types), by incomplete tightening of joints, by construction accidents, and by improper installation of cover pads.

Spills and Overfills

Any UST facility can be the site of environmental pollution as the result of spills and overfills, usually caused by human error. The USEPA has promulgated tank filling procedures in its 40 CFR 280 regulations and the National Fire Protection Association (NFPA) has issued tank filling guidelines (NFPA-385), but spills from overfilling still occur frequently. UST overfilling is bad enough in itself, but environmental contamination problems are compounded by repeated spills or unreported spills. Petroleum products or hazardous wastes can literally saturate the spill area, intensifying soil corrosiveness (Blackman, 2001).

Compatibility of Contents and UST

Placing highly corrosive materials into containers not rated to contain them is asking for trouble. New chemicals (including fuels) are constantly under development and entering the marketplace. Developing such fuels is usually meant to achieve improved air quality, but improving air quality at the expense of water and soil makes no sense. Many USTs currently in use are fiberglass-reinforced plastic (FRP) tanks, installed to replace unprotected, bare steel tanks. FRPs are rated or modified by using a different liner to safely store the fuel products now commonly used. When a new, exotic blend of fuel is developed and placed in a FRP-type tank that proves incompatible, problems occur. Incompatibility problems include blistering, internal stress, cracking, and under-film corrosion. The American Petroleum Institute put together a standard to help prevent FRP-constructed or lined tank problems. The standard should be referred to when existing tanks are used for nonstandard fuel products.

CHEMICAL RELEASE RISK ASSESSMENT

Hydrocarbon spillage or disposal problems are complex. The risk assessment process, which enables scientists, regulatory officials, and industrial managers to evaluate the public health risks associated with the hydrocarbon releases (or any other toxic chemical release) to soil and groundwater, can ease the problem complexity. The risk assessment process consists of the following four steps (Blackman, 2001; Ehrhardt et al., 1986; ICAIR, 1985):

1. *Toxicological evaluation* (hazard identification)—This step should answer the question, "Does the chemical have an adverse effect?" The factors to consider during the toxicological evaluation for each contaminant include routes of exposure (ingestion, absorption, and inhalation), types of effects, reliability of data, dose, mixture effects, and the strength of evidence supporting the conclusions of the toxicological evaluation.
2. *Dose–response evaluation*—When a chemical has been toxicologically evaluated and the result indicates that the chemical is likely to cause adverse effects, determining the potency of the chemical is the next step. The dose–response curve describes the relationship between degree of exposure to a chemical (dose) and the magnitude of the effect (response) in the exposed organism.
3. *Exposure assessment*—Estimates are made of the actual or potential human exposure magnitude, the exposure frequency and duration, and the potential exposure pathways.
4. *Risk characterization*—Adverse health effects are estimated under the conditions of exposure found and described in the exposure assessment.

EXPOSURE PATHWAYS

Determining exposure pathways resulting from the performance of the remediation option chosen to mitigate a particular UST leak or spill is as important as assessing the risk and evaluating the findings. Exposure pathways that may be encountered during site excavation, installation, operations, maintenance, and monitoring fall into two categories: (1) direct human exposure pathways, and (2) environmental exposure pathways. These two categories are further divided into primary and secondary exposure pathways. Primary exposure pathways directly affect site operations and personnel (e.g., skin contact during soil sampling) or directly affect cleanup levels to be achieved by remediation technology. For example, when soil impact is the chief issue at a site, soil impact sets the cleanup level and corresponding time frame when cleanup stops. Secondary exposure pathways occur during site operations and exhibit significant decreases with time as treatment progresses (e.g., wind-blown dust) (EPRI–EEI, 1988).

REMEDIATION OF UST-CONTAMINATED SOILS

Preliminary steps must be taken before petroleum-contaminated soil remediation is possible. Soil sampling confirms that a tank is actually leaking and determines the extent of contamination. Upon leak discovery, any petroleum product remaining in the UST should be pumped out into holding tanks or containers because of the potential damage to the tank (and further spillage) during removal. The tank area then is excavated and the tank removed. After sampling and tank removal, what type of remediation technology to employ in the actual cleanup effort must be determined.

Various organizations, environmental industries, and regulatory agencies perform technical investigations and evaluations of the various aspects of remediation methods for petroleum hydrocarbons in soil, fate and behavior of petroleum hydrocarbons in soil, and economic analyses. The electric utility industry is at the forefront of conducting such studies, because it owns and operates many USTs and other facilities for using, storing, or transferring petroleum products, primarily motor and heating fuels. USEPA developed federal regulations for reducing and controlling environmental damage from UST leakage, and many states and localities have developed and implemented strict regulations governing USTs and remedial actions for product releases to soil and groundwater.

The Electric Power Research Institute (EPRI), Edison Electric Institute (EEI), and Utility Solid Waste Activities Group (USWAG) in a cooperative effort conducted a technical investigation. From their findings, they developed a report entitled *Remedial Technologies for Leaking Underground Storage Tanks* (EPRI–EEI, 1988), which focused on one of the major components of the technical investigation. The report described and evaluated available technologies for remediating soil and groundwater that contain petroleum products released from underground storage tank leaks. A general introduction to state-of-the-art cleanup technology, this report still serves as a reference for feasible method determination; it also provides a description of basic elements and discusses selection and implementation factors for a remedial program.

The available technologies for remediating petroleum-product-contaminated soil and groundwater are divided into two categories: *in situ* treatment and non-*in situ* treatment (i.e., the treatment of soil in place and the treatment of soil removed from the site). Each of the remedial technologies is briefly described in the following sections, using information adapted from the 1988 report.

IN SITU TECHNOLOGIES

With *in situ* technologies, because no excavation is required exposure pathways are minimized. Only exposure pathways that could result from the actual streams produced by the technologies are an issue, eliminating those associated with handling and transport.

In Situ Volatilization

In situ volatilization (ISV) (also known as *in situ* air stripping) uses forced or drawn air currents through in-place soil to remove volatile compounds. ISV has a successful track record for both effectiveness and cost efficiency. A common ISV system used to enhance subsurface ventilation and volatilization of volatile organic compounds consists of the following operations:

1. A preinjection air heater warms the influent air to raise subsurface temperatures and increase the volatilization rate.
2. Injection or induced draft forces established air flow through the unsaturated zone.
3. Slotted or screened pipe allows air flow through the system but restricts entrainment of soil particles.
4. A treatment unit (usually activated carbon) is used to recover volatilized hydrocarbon, minimizing air emissions.
5. Miscellaneous air flow meters, bypass and flow control valves, and sampling ports are generally incorporated into the design to facilitate air flow balancing and assess system efficiency.

Four factor categories influence volatilization of hydrocarbon compounds from soils: soil, environment, chemical, and management (Jury, 1986). *Soil factors* include water content, porosity and permeability, clay content, and adsorption site density:

1. *Water content* influences the rate of volatilization by affecting the rates at which chemicals can diffuse through the vadose zone. An increase in soil water content will decrease the rate at which volatile compounds are transported to the surface via vapor diffusion.
2. *Soil porosity* and *permeability* factors relate to the rate at which hydrocarbon compounds volatize and are transported to the surface. A function of the travel distance and cross-sectional area available for flow, diffusion distance increases and cross-sectional flow area decreases with decreasing porosity.
3. *Clay content* affects soil permeability and volatility. Increased clay content decreases soil permeability, which inhibits volatilization.
4. *Adsorption site density* refers to the concentration of sorptive surface available from the mineral and organic contents of soils. An increase in adsorption sites indicates an increase in the ability of soil to immobilize hydrocarbon compounds in the soil matrix.

Environmental factors include temperature, wind, evaporation, and precipitation:

1. *Temperature* increase increases the volatilization of hydrocarbon compounds.
2. *Wind* increase decreases the boundary layer of relatively stagnant air at the ground–air interface, which can assist volatilization.
3. *Evaporation* of water at the soil surface is a factor controlling the upward flow of water through the unsaturated zone, which can assist volatilization.
4. *Precipitation* provides water for infiltration into the vadose zone.

Chemical factors are critical in affecting how various hydrocarbon compounds interact with the soil matrix. The primary chemical properties that affect the susceptibility of chemicals to *in situ* volatilization include solubility, concentration, octanol–water partition coefficient, and vapor pressure. *Management factors* related to soil management techniques (e.g., fertilization, irrigation) decrease leaching, increase soil surface contaminant concentrations, or maximize soil aeration and assist volatilization. Site-specific conditions (e.g., soil porosity, clay content, temperature) drive the effectiveness of *in situ* volatilization techniques. Pilot studies and actual experience confirm the following effects:

- *In situ* volatilization has been successful for remediation in an unsaturated zone containing highly permeable sandy soils with little or no clay.
- Recovery periods are typically on the order of 6 to 12 months.
- Gasoline (which is light and volatile) has the greatest recovery rate.
- *In situ* volatilization can be used in conjunction with product recovery systems.
- Ultimate cleanup levels are site dependent and cannot be predicted; thus, they are usually set by regulatory agencies.

In Situ Biodegradation

The naturally occurring microorganisms in soil degrade contaminants to other forms in *in situ* biodegradation. Most petroleum hydrocarbons degrade to carbon dioxide and water by microbial processes (Grady, 1985). Stimulating microbial growth and activities primarily through the addition of oxygen and nutrients, as well as factors such as temperature and pH, influence the microbial rate of growth in this process. Documentation and significant background information related to successful land treatment of refinery waste indicate that biodegradation has proven to be an efficient and cost-effective method for the reduction of hydrocarbons in soil. Heyse et al. (1986) described the biodegradation process as follows:

1. A submersible pump transports groundwater from a recovery zone to a mixing pump.
2. Nutrients such as nitrogen, phosphorus, and trace metals are added to the water in a mixing tank. These nutrients are then transported by the water to the soil to support microbial activity.

3. Hydrogen peroxide is added to the conditioned groundwater from the mixing tank just prior to reintroduction to the soil. As hydrogen peroxide decomposes, it provides the needed oxygen for microbial activity.
4. Groundwater is pumped to an infiltration gallery or injection well, which reintroduces the conditioned water to the aquifer or soils.
5. Groundwater flows from the infiltration galleries or injection wells through the affected area and then back to the recovery wells. The flow of the water should contact all soils containing degradable petroleum hydrocarbons.
6. The water is drawn to the recovery well and pumped to the mixing tank to complete the treatment loop.
7. Groundwater in which hydrocarbon concentrations have been reduced to very low levels is often sent through a carbon adsorption process for removal of the residual hydrocarbons.

Environmental factors that affect biodegradation in soils include temperature and microbial community:

1. *Temperature* increase (up to 104°F) results in an increase in the biodegradation of petroleum fractions due to increased biological activity (Bossert and Bartha, 1984).
2. *Microbial communities* already present are utilized by most *in situ* biodegradation schemes; however, attempts have been made to supplement these populations with additional organisms or engineered organisms.

Chemical factors affect biodegradation in that biodegradation is impossible if the substrate chemical concentrations are too high; however, a substantial substrate (target compound) presence ensures that microbes metabolize the target compound. The solubility of a compound in water also limits biodegradation, because most microbes need moisture to acquire nutrients and avoid desiccation.

Soil factors include the fact that proper aerobic conditions are required for the degradation of hydrocarbons in soil. Too much moisture (saturation) limits oxygen levels and can hinder biological activity. Bossert and Bartha (1984) reported that a moisture content between 50 and 80% of the water-holding capacity is considered optimal for aerobic activities. Oxygen transfer is a key factor in *in situ* biodegradation processes; soils must be fairly permeable to allow this transfer to occur. Soil pH directly affects the microbial population supported by the soil; biodegradation is usually greater in a soil environment with a pH of 7.8. For optimal biodegradation of petroleum hydrocarbons to occur, nutrients (nitrogen and phosphorus) in the proper amounts are required.

Environmental Effectiveness

Although the historical record for this technology is limited, the effectiveness of *in situ* biodegradation is dependent on the same site-specific factors as other *in situ* technologies. Several case studies suggest that

- *In situ* biodegradation is most effective for situations involving large volumes of subsurface soils.
- Significant degradation of petroleum hydrocarbons normally occurs in the range of 6 to 18 months (Brown et al., 1986).
- *In situ* biodegradation has most often been used for the remediation of groundwaters impacted by gasoline.
- Research suggests that limited biodegradation of benzene or toluene may occur under anaerobic conditions (Wilson et al., 1986).
- In soils, the remedial target level for *in situ* biodegradation could be in the low milligram/liter (parts per million) level for total hydrocarbons (Brown et al., 1986).

In Situ Leaching and Chemical Reaction

The *in situ* leaching and chemical reaction process uses water mixed with a surfactant (a surface-active substance such as soap) to increase the effectiveness of flushing contaminated soils in an effort to leach the contaminants into the groundwater. The groundwater is then collected downstream of the leaching site, through a collection system, for treatment and/or disposal.

Environmental Effectiveness

The *in situ* leaching and chemical reaction process is not commonly practiced. Few performance data on its environmental effectiveness are available.

In Situ Vitrification

The *in situ* vitrification process employs electrical current passed through electrodes (driven into the soil in a square configuration), which produces extreme heat and converts soil into a durable glassy material. The organic constituents are pyrolized in the melt and migrate to the surface, where they combust in the presence of oxygen. Inorganics in the soil are effectively bound in the solidified glass (Johnson and Cosmos, 1989).

Environmental Effectiveness

Organic materials are combusted or destroyed by the high temperatures encountered during the vitrification process. The *in situ* vitrification process is a developing technology, and the jury is still out as far as determining its environmental effectiveness.

In Situ Passive Remediation

The *in situ* passive remediation process is the easiest to implement and the least expensive, mainly because it involves no action at the site; however, it is generally unacceptable to the regulatory agencies. It relies upon several natural processes to destroy the contaminant. These natural processes include biodegradation, volatilization, photolysis, leaching, and adsorption.

Environmental Effectiveness

Passive remediation depends on a variety of site-specific and constituent-specific factors, so its environmental effectiveness must be decided on a case-by-case basis.

In Situ Isolation/Containment

Isolation or containment methods work to prevent the migration of liquid contaminant or leachates containing contaminants further into the soil, which is accomplished by separating the contamination area from the environment by installation of impermeable barriers to retain liquid containments within the site. The effectiveness of these methods is usually contingent upon the presence of impervious layers beneath the contaminant to be contained and attaining a good seal at both the vertical and horizontal surfaces. The containment devices discussed in this section adequately isolate the contamination. In these methods, however, the contaminant is not destroyed, merely contained. Containment methods include

- *Slurry walls*—Fixed underground physical barriers are formed in an excavated trench by pumping slurry, usually a bentonite or cement and water mixture.
- *Grout curtains*—Formed in a similar manner, suspension grouts composed of Portland cement or grout are injected under pressure to form a barrier.
- *Sheet piling*—Construction involves physically driving rigid sheets, pilings of wood, steel, or concrete into the ground to form a barrier.

Environmental Effectiveness

Isolation or containment systems effectively physically prevent or impede migration, but the contaminant is not removed or destroyed.

NON-*IN SITU* TECHNOLOGIES

Non-*in situ* techniques require the removal (usually by excavation) of contaminated soils. These soils can be either treated onsite or hauled away for treatment. Non-*in situ* techniques create additional exposure pathways associated with the handling and transport of contaminated soil. The non-*in situ* technologies for soils include land treatment, thermal treatment, asphalt incorporation, solidification and stabilization, chemical extraction, and excavation.

Land Treatment

Affected soils are removed and spread over an area to enhance naturally occurring processes, including volatilization, aeration, biodegradation, and photolysis. Through tilling and cultivating of soils, biological degradation of hydrocarbon compounds can be speeded up. Basic land treatment operation includes these steps:

- The area to be used for land treatment is prepared by removing surface debris, large rocks, and brush.
- The area is graded to provide positive drainage and is surrounded by a soil berm to contain runoff within the land treatment area.
- The pH is adjusted (e.g., by the use of lime) to create a neutral pH.
- If the site is deficient in nutrients, fertilizer is added.
- The petroleum-contaminated soil is spread uniformly over the surface of the prepared area.
- The contaminated material is incorporated into the top 6 to 8 inches of soil (to increase contact with microbes) with a tiller, disc harrow, or other plowing device.
- Reapplication of soils that contain petroleum products is carried out at proper intervals to replenish the hydrocarbon supply.
- Hydrocarbon levels, nutrient levels, and soil pH are monitored to ensure that the hydrocarbons are properly contained and treated in the land treatment area.

Environmental Effectiveness

The effectiveness of land treatment or land farming depends greatly on site-specific conditions. Experience with treating petroleum compounds using this technology confirm that

- Land treatment is effective for degrading hydrocarbon compounds.
- Continuous treatment of petroleum-laden soils can result in the accumulation of metals in the soil matrix.
- Ultimate degradation rates are site dependent and cannot be predicted.

Thermal Treatment

Thermal treatment, a method of treating contaminated soils that requires special equipment, is capable of providing complete destruction of the petroleum contaminant. In thermal treatment, contaminated soils are removed from the ground and exposed to excessive heat in an incinerator. Currently available incinerator types include rotating kilns, fluidized bed incinerators, fixed kilns or hearths, rotating lime or cement kilns, and asphalt plants.

Environmental Effectiveness

The effectiveness of high-temperature incineration for the destruction of petroleum-laden soil is well documented. Destruction and removal efficiencies of 99% can be expected.

Asphalt Incorporation and Other Methods

Asphalt incorporation, a recently developed remedial technology, goes beyond remediation. Asphalt incorporation is actually a reuse or recycling technology. In asphalt incorporation, the containment entrained in soil is used in beneficial reuse (to make asphalt, cement products, and bricks), not simply destroyed or disposed of. Asphalt incorporation and other reuse or recycling technologies involve the assimilation of petroleum-laden soils into hot or cold asphalt processes, wet or dry cement production processes, or brick manufacturing. The petroleum-laden soils are mixed with other constituents to make the final product, while the petroleum contaminants are either volatilized during some treatments or trapped within the substance, thereby limiting contaminant migration. Converting asphalt into asphalt concrete or bituminous concrete involves producing a material that is plastic when being worked and that sets up to a predictable hardness sufficient for its end use. Incorporating contaminated soil into bituminous end products is accomplished by two conventional processes, cold-mix asphalt (CMA) processes and hot-mix asphalt (HMA) processes (Testa, 1997).

Cold-mix asphalt (also called *environmentally processed asphalt*) is produced by a mobile or in-place process. Soils polluted with a variety of contaminants (including petroleum hydrocarbons) serve as the fine-grained component in the mix, along with asphalt emulsion and specific aggregates. A wide range of cold-mix asphaltic products is possible. To enhance the stability of the end product, the mix is usually augmented with lime, Portland cement, or fly ash. Incorporation is accomplished physically by either mixed-in-place methods for large quantities or windrowing for smaller quantities. The CMA process has several advantages, in that it

1. Can process a variety of contaminants
2. Can incorporate large volumes of contaminated soil
3. Offers flexible mix design and specifications
4. Is a mobile process, and processing can occur onsite
5. Is subject to minimal weather restrictions
6. Is cost effective
7. Can be stockpiled and used when needed
8. Can occur onsite

Limitations include the following:

1. Any volatiles present must be controlled.
2. Small volumes of contaminated soil may not be economically viable for mobile plants.

Hot-mix asphalt processes involve incorporating petroleum-laden soils into hot asphalt mixes as a partial substitute for aggregate. This mixture is most often applied to pavement. HMA is produced conventionally using either batch or drum mixing processes. The usual processes entail both mixing and heating to produce pavement material. During the incorporation process, the mixture (which includes the contaminated soils, usually limited to 5% of the total aggregate feed at any one time) is heated. This volatilizes the more volatile hydrocarbon compounds at various temperatures. Compound migration is limited by incorporating the remainder of the compounds into the asphalt matrix during cooling. Advantages to using the HMA process include (1) the time required to dispose of hydrocarbon-laden material is limited only by the size of the batching plant (material may be excavated and stored until it can be used), and (2) it can process small volumes of affected soil easily. Disadvantages include (1) application of the product immediately after processing, (2) the potential for elevated emissions, (3) emission restrictions, and (4) incomplete burning of light-end hydrocarbons that can affect the quality of end product.

Raw materials (including limestone, clay, and sand) are incorporated into the *cement production process* and are then usually fed into a rotary kiln. Contaminated soil is then introduced along with the raw materials or dropped directly into the kiln. The mix is heated to up to 2700°F. Petroleum-laden soil chemically breaks apart during this process, while inorganic compounds recombine with raw materials and form clinkers—dark, hard, golf-ball-sized nodules of rapidly formed Portland cement, which are mixed with gypsum and ground to a fine powder (Testa, 1997). Advantages include the following: (1) the technology is in place and has been tested, (2) raw materials are readily available, (3) water solubility and water permeability are relatively low, and (4) it can accommodate a wide variety of contaminants and material. Disadvantages include (1) odorous material limitations, (2) wide range of volume increase, and (3) both technical and aesthetic material restrictions.

Petroleum-laden soil can be used as an ingredient in *brick production*. The contaminated soil replaces either the shale or firing clay normally used in brick manufacturing processes. The contaminated soil, along with shale or clay, is incorporated into a plasticized mixture, molded into brick, dried, and preheated. Then the brick is fired at 1700 to 2000°F for approximately 12 hours in the kiln. High temperatures and residence times in the kiln destroy organics and incorporate them into the vitrified end product. Advantages of the brick manufacturing process include (1) fine-grained, low permeability soils can be accommodated, (2) the technology is in place and has been tested, and (3) processing can occur onsite. The disadvantage is that this process is restricted primarily to petroleum hydrocarbons and fly ash.

Solidification/Stabilization

Solidification or stabilization of petroleum-laden soils immobilizes contaminants by either encapsulating or converting them but does not physically change the contaminant. This practice is not commonly used for soils because the contaminants are not destroyed. Solidification or stabilization processes can be performed on- or offsite. Various stabilizers and additives are mixed with the contaminated material. A generalized process for the manufacture of pozzolanic material (burned shale or clay resembling volcanic dust that will chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties) using fly ash has been used with some success (Mehta, 1983). Used most frequently to stabilize oily wastes and sludges contained in surface impoundments, solidification or stabilization processes accomplish this in two ways. The stabilizing agent is added directly to sections of *in situ* surface impoundments and thoroughly mixed. As each section solidifies, it forms a base that allows the equipment to reach further into the impoundment.

The second method involves excavation of the sludges in the impoundment, following this procedure (Musser and Smith, 1984):

- Earth-moving machines level piles of kiln dust into 6- to 12-inch-deep layers.
- A machine lifts the sludge from the impoundment and places it on top of the kiln dust.
- Machines mix the two materials together, and a pulverizing mixer is driven over the mixture until homogeneity is achieved.
- The mixture is allowed to dry for about 24 hours and is then compacted and field tested.

The layers are then stacked to build an in-place landfill, or the semisolidified sludge can be trucked to another landfill location.

Chemical Extraction

Excavated contaminated soils are washed to remove the contaminants of concern in the process of chemical extraction. Accomplished in a washing plant, this process uses a water/surfactant or a water/solvent mixture to remove contaminants. Soil is excavated, then washed. This process increases product recovery and is a proven method for the removal of hydrocarbon contaminants from the soil.

Excavation

Excavation, physically removing the contaminated soil for disposal at a hazardous waste or other disposal landfill site, has been the mainstay of site remediation for several decades. Recently, though, the practice has been discouraged by newer regulations that favor alternative onsite waste treatment technologies. Considered a storage process today, not a treatment process, excavation raises issues of future liability for the responsible parties concerning final soil disposal. Landfills are quickly reaching their fill limits, with fewer and fewer new landfilling sites being authorized for construction and operation. This makes onsite treatment a much more attractive prospect. Excavation takes little time to complete and allows for thorough cleanup of the site; however, worker and operator safety considerations, the production of dust and odor, and the relatively high costs associated with the excavation, transportation, and ultimate disposal of the soil make it a less than ideal choice (USEPA, 1985).

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10 Solid and Hazardous Waste

> Unfortunately, man is in the woods, and waste and pure destruction are already making rapid headway.
>
> **—John Muir, naturalist and author**

INTRODUCTION

When we throw waste away, it is not gone. Dealing with the waste has only been postponed. Sometimes this postponement means that when we go back, the wastes are rendered helpful and harmless (as with some biodegradable wastes), but more often it means that the problems we face will be made worse by chemistry and entropy. That 55-gallon drum of toxic waste would have been easier to handle before it rusted out.

Amid the cries of “not in my backyard” and “pick up the trash, but don’t put it down,” we need to hear a more realistic and environmentally kinder truth: *There’s no such thing as a free lunch.* We pay, somehow, for what we get or use, whether we see the charges or not. The price for our solid waste habits will soon be charged to us. In some places, particularly larger cities, an awareness of the size of the bill is beginning to sink in.

Environmentally, what does that mean? In short, if we, as a society, are going to consume as we do, build as we do, grow as we do, then we have to pay the price for our increase. And sometimes that will mean having our waste in our backyard. We will have to increase the amount of solid waste we reuse and recycle, we will have to spend tax dollars to solve the problems with landfills and trash incineration, and we will have to seriously look at how we live, how the goods we buy are packaged, and how our industries deal with their waste, because if we don’t the bill will be more than we can afford to pay.

Advancements in technology have made our lives more comfortable, safer, healthier, and in many cases more enjoyable. Some would say that progress is not without cost. This statement is correct—however, what costs do they refer to? Can we afford the consequences if these costs include more Bhopals, Times Beaches, Love Canals, or another *Exxon Valdez*? If such disasters are “to be included as a cost of progress,” then we must say that the cost outweighs the gain. What we must do to ensure a balance between technological progress and its environmental results is to use technological advances to ensure that “progress” is not too costly—or life threatening—to both our environment and to ourselves.

The *waste management hierarchy* developed by the Resource Conservation and Recovery Act (RCRA) sums up what could, should, would happen with waste—any kind of waste—in the best of all possible worlds. Although it is idealistic to say we should follow these standards, in practical terms we would benefit in the long term by striving to achieve them. Regulating problem wastes, developing safe and environmentally friendly ways to dispose of them, and using the technologies we develop to control the future of such wastes are in the best interests for us all.

When teaching college-level courses dealing with solid and hazardous wastes, the portrayal of American society that I present in my lectures to environmental science, health, and engineering students is not flattering. I describe America as a throwaway society and explain that the American throwaway society displays and underscores a characteristic that might be described as habit, trend, custom, or practice—the tendency we have to discard those objects we no longer want. When we don’t want it anymore, we discard it. When it offends us, we dispose of it. Throughout history, a common attitude has been, “I don’t want it any longer. Take it down to the river and dump it.”

When mile-long caravans of wagon trains crossed the great American prairies, the pioneers often had to resort to discarding anything and everything that overburdened their wagons, such as essential homemaking supplies and furnishings necessary for successful homesteading. Lifelong treasures once so important that they couldn't be left behind now became burdens (and waste) to the American pioneers and were disposed of to make their lives a little easier. This pioneering throwaway tendency has been referred to as a *frontier mentality*. That is, it was all right to throw away anything no longer wanted out in the frontier because there was so much endless space. Trash placed in the vast, endless prairie wouldn't hurt a thing. It was like urinating in the ocean. Wouldn't hurt a thing! Such an attitude, of course, ignores the effect of accumulation, which inexorably clogs up all that apparently empty space eventually.

Again, when something is no longer of value because it is broken, worn out, out of style, or no longer needed for whatever reason, we think that discarding it is not be a big issue. But it is—particularly when the item we throw away is a hazardous substance that is persistent, nonbiodegradable, and poisonous. What is the magnitude of the problem with hazardous substance and waste disposal? Let's take a look at a few facts.

- Hazardous substances, including industrial chemicals, toxic waste, pesticides, and nuclear waste, are entering the marketplace, the workplace, and the environment in unprecedented quantities.
- The United States produces over 300 million metric tons of hazardous waste each year; with a current population of over 320,000,000 people, this amounts to more than one ton for every person in the country.
- Through the pollution of air, soil, and water supplies, hazardous wastes pose both short- and long-term threats to human health and environmental quality.

In this chapter, we discuss a growing and significant problem facing not only all practitioners of pollution science but also of all humanity: *anthropogenically produced wastes*. Specifically, what are we going to do with all the wastes we generate? What are the alternatives? What are the technologies available to us at present to mitigate the waste problem, a problem that grows with each passing day?

Before beginning our discussion, we should focus on an important question: When we throw waste away, is it really gone? Remember, although we are faced today and in the immediate future with growing mountains of wastes (and are running out of places on Earth to dispose of them), we are faced with an even more pressing twofold problem, one related to the waste's toxicity and persistence.

We discuss waste and the toxicity problem later, but for now think about the persistence of the wastes that we dispose of. When we excavate a deep trench and place within it several 55-gallon drums of liquid waste, then bury the entire sordid mess, are we really disposing of the waste in an Earth-friendly way? Are we disposing of it permanently at all? What happens a few years later when the 55-gallon drums corrode and leak? Where does the waste go? What are the consequences of such practices? Are they insignificant to us today because they are tomorrow's problems? We need to ask ourselves these questions and determine the answers now. If we are uncomfortable with the answers we come up with now, shouldn't we feel the same about the answers someone else (our grandchildren) will have to come up with later?

Waste is not easily disposed of. We can hide or mask it. We can move it from place to place. We can take it to the remotest corners of the Earth. But, because of its persistence, waste is not always gone when we think it is. It has a way of coming back, a way of reminding us of its presence, a way of persisting. This chapter defines and discusses solid wastes, particularly focusing on a significant portion of solid wastes referred to as *municipal solid waste* (MSW) because people living in urban areas where many of the problems associated with solid waste occur generate these wastes. In addition, another significant waste problem, *hazardous wastes*, is addressed, as are waste control technologies related to waste minimization, treatment, and disposal.

HISTORY OF SOLID WASTE REGULATION IN THE UNITED STATES

For most of the nation's history, municipal ordinances (rather than federal regulatory control) were the only solid waste regulations in effect. These local urban governments controlled solid waste almost from the beginning of each settlement because of the inherent severe health consequences derived from street disposal. Along with prohibiting dumping of waste in the streets, municipal regulations usually stipulated requirements for proper disposal in designated waste dump sites and mandated owners to remove their waste piles from public property.

The federal government did not begin regulating solid waste dumping until the nation's harbors and rivers were either overwhelmed with raw wastes or headed in that direction. The federal government used its constitutional powers under the Interstate Commerce Clause of the Constitution to enact the Rivers and Harbors Act in 1899. The U.S. Army Corps of Engineers was empowered to regulate and in some cases prohibit private and municipal dumping practices. Not until 1965 did Congress finally get into the picture (as a result of strong public opinion) by adopting the Solid Waste Disposal Act of 1965, which became the responsibility of the U.S. Public Health Service to enforce. The intent of this act was to (Tchobanoglous et al., 1993)

1. Promote the demonstration, construction, and application of solid waste management and resource recovery systems that preserve and enhance the quality of air, water, and land resources.
2. Provide technical and financial assistance to state and local governments and interstate agencies in the planning and development of resource recovery and solid waste disposal programs.
3. Promote a national research and development program for improved management techniques; more effective organizational arrangements; new and improved methods of collection, separation, recovery, and recycling of solid wastes; and the environmentally safe disposal of nonrecoverable residues.
4. Provide for the promulgation of guidelines for solid waste collection, transport, separation, recovery, and disposal systems.
5. Provide for training grants in occupations involving the design, operation, and maintenance of solid waste disposal systems.

After Earth Day 1970, Congress became more sensitive to waste issues. In 1976, Congress passed solid waste controls as part of the Resource Conservation and Recovery Act (RCRA). "Solid waste" was defined as any garbage; refuse; sludge from a waste treatment plant, water supply treatment plant, or air-pollution control facility; and other discarded material.

In 1980, Public Law 96-510, 42 USC Article 9601, the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), was enacted to provide a means of directly responding to and funding the activities of response to problems at uncontrolled hazardous waste disposal sites. Uncontrolled municipal solid waste landfills are facilities that have not operated or are not operating under RCRA (USEPA, 1989). Many other laws that apply to the control of solid waste management problems are now in effect. Federal legislation and associated regulations have encouraged solid waste management programs to be implemented at the state level of government. Apparently, legislation will continue to be an important part of future solid waste management.

SOLID WASTE CHARACTERISTICS

Solid waste, also called *refuse*, *litter*, *rubbish*, *waste*, *trash*, and (incorrectly) *garbage*, refers to any of a variety of materials that are rejected or discarded as being spent, useless, worthless, or in excess. Table 10.1 provides a useful waste classification system. Solid waste is probably more correctly defined as any material thing that is no longer wanted. Defining solid waste is tricky, because solid waste is a series of paradoxes (O'Reilly, 1994):

TABLE 10.1
Classification of Solid Waste

Type	Principal Components
Trash	Highly combustible waste, paper, wood, cardboard cartons (including up to 10% treated papers, plastic, or rubber scraps); commercial and industrial sources
Rubbish	Combustible waste, paper, cartons, rags, wood scraps, combustible floor sweepings; domestic, commercial, and industrial sources
Refuse	Rubbish and garbage; residential sources
Garbage	Animal and vegetable wastes; restaurants, hotels, markets, institutional, commercial, and club sources

Source: Adapted from Davis, M.L. and Cornwell, D.A., *Introduction to Environmental Engineering*, McGraw-Hill, New York, 1991, p. 585.

- It is personal in the kitchen trash can but impersonal in a landfill.
- What one individual may deem worthless (an outgrown or out-of-style coat, for example) and fit only for the trash can another individual may find valuable.
- It is of little cost concern to many Americans yet is very costly to our society in the long term.
- It is an issue of serious federal concern yet a very localized problem from municipality to municipality.

The popular adage is accurate—everyone wants waste to be picked up, but no one wants it to be put down. It goes almost without saying that the other adage, "not in my backyard" (NIMBY) is also accurate. The important point, though, is that whenever a material object is thrown away, regardless of its actual or potential value, it becomes a solid waste.

Garbage (with its tendency to decompose rapidly and create offensive odors) is often used as a synonym for solid waste, but garbage actually refers strictly to animal or vegetable wastes resulting from the handling, storage, preparation, or consumption of food.

The collective and continual production of all refuse (the sum of all solid wastes from all sources) is referred to as the *solid waste stream*. An estimated 6 billion metric tons of solid waste are produced in the United States each year. The two largest sources of solid wastes are agriculture (animal manure, crop residues, and other agricultural byproducts) and mining (dirt, waste rock, sand, and slag, the material separated from metals during the smelting process). About 10% of the total waste stream is generated by industrial activities (plastics, paper, fly ash, slag, scrap metal, and sludge or biosolids from treatment plants). From Figure 10.1, we see that paper and paperboard account for the largest percentage (about 33%) of refuse materials by volume of MSW. Yard wastes are the next most abundant material, accounting for almost 14%. Glass and metals make up almost 14% of MSW, food wastes just under 15%, and plastics about 12.3%.

Approximately 254 million tons of municipal solid waste were generated in the United States in 2007, equivalent to a bit more than 0.8 pounds per person per day (USEPA, 2007). It has been estimated that by the year 2010 waste generation in the United States would have risen to more than 250 million metric tons annually, almost 5.5 pounds per person per day.

SOURCES OF MUNICIPAL SOLID WASTE

Sources of municipal solid waste in a community are generally related to land use and zoning. MSW sources include residential, commercial, institutional, construction and demolition, municipal services, and treatment plants.

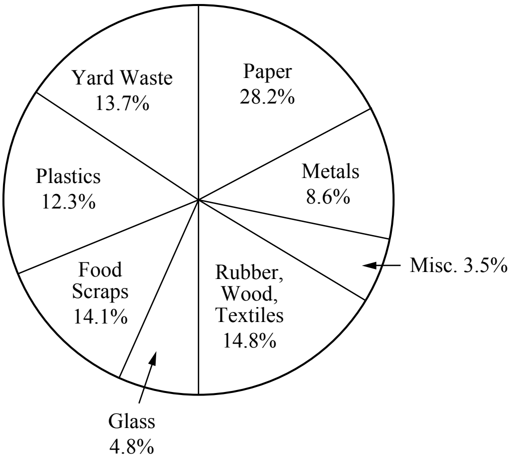

FIGURE 10.1 Composition of solid waste discarded in a typical day by each American. (Adapted from USEPA, *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2007*, U.S. Environmental Protection Agency, Washington, DC, 2007.)

RESIDENTIAL SOURCES OF MSW

Residential sources of MSW are generated by single and multifamily detached dwellings and apartment buildings. The types of solid wastes generated include food wastes, textiles, paper, cardboard, glass, wood, ashes, tin cans, aluminum, street leaves, and special bulky items, including yard wastes collected separately, white goods (refrigerators, washers, dryers, etc.), batteries, oil, tires, and household hazardous wastes (see Case Study 10.1).

COMMERCIAL SOURCES OF MSW

Commercial sources of MSW include restaurants, hotels, stores, motels, service stations, repair shops, markets, office buildings, and print shops. The types of solid wastes generated include paper, cardboard, wood, plastics, glass, special wastes such as white goods and other bulky items, and hazardous wastes.

INSTITUTIONAL SOURCES OF MSW

Institutional sources of MSW are generated in hospitals, schools, jails and prisons, and government centers. The types of solid wastes generated by institutional sources are the same as those generated by commercial sources.

CONSTRUCTION AND DEMOLITION SOURCES OF MSW

Construction and demolition sources of MSW include new construction sites, the razing of old buildings, road repair or renovation sites, and broken pavement. The solid wastes generated by construction and demolition sources are made up of standard construction materials such as wood, steel, plaster, concrete, and soil.

Case Study 10.1. Problem Wastes: Tire Disposal

Since the invention of the automobile, what to do with worn-out tires has presented a significant disposal problem. America's love affair with cars means that hundreds of millions of tires are discarded every year. Stockpiles across the country store billions of worn-out tires. Some of these stockpiles are legal, others are not, but all present us with problems, including the risk of catastrophic fire and the creation of prime breeding habitats for mosquitoes, some varieties of which carry encephalitis or West Nile virus (Maine DEP, 1994).

In recent years, tire fires have received national attention. Tire fires are particularly difficult to extinguish. Using water as an extinguishing agent can create an oily runoff, and burning tires emit toxic black smoke, resulting in pollution problems for air, surface, and groundwater supplies and the soil. Smothering the fire with dirt and sand appears to be the most cost-effective and efficient way to control burning tire stockpiles; however, sometimes more unusual problems occur with tire fires.

In January of 1996, a major road in Ilwaco, Washington, began to heat up, and 2 months later a major oil leak appeared that was the result of a massive underground fire. Although response teams immediately contained the oil, they were forced to allow the fire to smolder while they figured out how to even get to it (WHEN, 1998). Using scrap tires as subgrade road base is probably the most successful effort to recycle used tires, along with using shredded tires as supplemental fuel for modern, scrubber-equipped boilers; however, the potential for further episodes of burning roads, which could create contamination problems in all of our environmental media, means that the risks associated with the use of scrap tires are great. As more states enact legislation prohibiting the disposal of tires in landfills, reliance on recycling, stockpiling, and waste tire dumps will increase until we can properly manage, store, and process these wastes (PaDEP, 1998).

With the advent of the West Nile virus, another serious problem with tires has surfaced, one related to international shipping. In the past, shipping techniques and reliance on human labor meant that items shipped internationally by boat were en route and in port for long periods of time. Mechanized loading and unloading practices and modern shipping containers have drastically shortened shipping times—in general, a positive. Serious speculation on how the virus arrived in the United States, however, suggests that a likely culprit is the international market in used tires. Mosquito larvae (infected or not) living in water in the tires can survive container shipment, as the trip is too short for the disease-carrying insects to die. Whether or not West Nile virus came to the United States in this way, shipping used tires poses a recognized threat to public health.

Municipal Services Sources of MSW

Municipal services (excluding treatment plants) generate MSW during street cleaning; landscaping; and park, beach, recreational area, and catch basin maintenance and cleaning activities. The types of solid wastes generated by municipal services include rubbish; street sweepings; general wastes from parks, beaches, and recreational areas; and catch basin debris.

Treatment Plant Site Sources of MSW

Treatment plant sites generate MSW during water, wastewater, and other industrial treatment processes (e.g., incineration). The principal types of solid wastes generated by treatment plant sites are sludges or biosolids, fly ash, and general plant wastes.

WHAT IS A HAZARDOUS SUBSTANCE?

Hazardous wastes can be informally defined as a subset of all solid and liquid wastes that are disposed of on land rather than being shunted directly into the air or water and which have the potential to adversely affect human health and the environment. We have the tendency to think of hazardous wastes as resulting mainly from industrial activities, but households also play a role in the generation and improper disposal of substances that might be considered hazardous wastes. Hazardous wastes, via Bhopal and other disastrous episodes, have been given much attention, but surprisingly little is known of their nature and the actual scope of the problem. In this section, we examine definitions of hazardous materials, substances, wastes, and so forth and attempt to bring hazardous wastes into perspective as a major environmental concern.

Unfortunately, defining a hazardous substance is largely a matter of "pick and choose," with various regulatory agencies and pieces of environmental legislation defining that term and related terms somewhat differently. Many of the terms are used interchangeably. Even experienced professionals in environmental health and safety fields, such as certified hazardous materials managers, sometimes interchange and interrelate these terms, although the terms are generated by different federal agencies and different pieces of legislation and have somewhat different meanings, depending on the nature of the problem addressed. To understand the scope of the dilemma we face in defining hazardous substance, let's take a look at the terms commonly used today, used interchangeably, and often thought to mean the same thing.

HAZARDOUS MATERIALS

A hazardous material is a substance (gas, liquid, or solid) capable of causing harm to people, property, and the environment. The U.S. Department of Transportation (DOT) uses the term *hazardous materials* to cover nine categories identified by the United Nations Hazard Class Number System, including the following:

- Explosives
- Gases (compressed, liquefied, dissolved)
- Flammable liquids
- Flammable solids
- Oxidizers
- Poisonous materials
- Radioactive materials
- Corrosive materials
- Miscellaneous materials

HAZARDOUS SUBSTANCES

Hazardous substances is a term used by USEPA for chemicals that, if released into the environment above a certain amount, must be reported and, depending on the threat to the environment, for which federal involvement in handling the incident can be authorized. USEPA lists hazardous substances in 40 CFR Part 302, Table 302.4. The Occupational Safety and Health Administration (OSHA) uses the term *hazardous substance* in 29 CFR 1910.120 (which resulted from Title I of the Superfund Amendments and Reauthorization Act [SARA] and covers *emergency response*) differently than does USEPA. Hazardous substances as defined by OSHA include every chemical regulated by both the DOT and USEPA.

EXTREMELY HAZARDOUS SUBSTANCES

Extremely hazardous substances is a term used by USEPA for chemicals that must be reported to the appropriate authorities if released above the threshold reportable quantity (RQ). The list of extremely hazardous substances is identified in Title III of SARA of 1986 (40 CFR Part 355). Each substance has a threshold reporting quantity.

TOXIC CHEMICALS

Toxic chemicals is a term used by USEPA for chemicals whose total emissions or releases must be reported annually by owners and operators of certain facilities that manufacture, process, or otherwise use listed toxic chemicals. The list of toxic chemicals is identified in Title III of SARA.

HAZARDOUS WASTES

> The most alarming of all man's assaults upon the environment is the contamination of air, earth, rivers, and sea with dangerous and even lethal materials. This pollution is for the most part irrecoverable; the chain of evil it initiates not only in the world that must support life but in living tissues is for the most part irreversible. In this now universal contamination of the environment, chemicals are the sinister, and little-recognized, partners of radiation in changing the very nature of the world—the very nature of life.
>
> **Carson (1962)**

Rachel Carson was able to combine the insight and sensitivity of a poet with the realism and observations of science more adeptly than anyone before her. Famous for her classic and highly influential book *Silent Spring*, it seems strange to us today that such a visionary as Carson was (after the publication of her *magnum opus*) ostracized, vilified, laughed at, lambasted, accused of having a bell-jar view of reality, and disregarded. To those guilty of the sins that she revealed, Carson was an enemy to be discredited—and silenced. She was not, however, disregarded by those who understood. To these concerned folks with a conscience, her message was clear: Waste, if not properly treated and handled, threatens not only human life in the short term but also the environment as a whole in the long term. Her plea was also clear: Stop poisoning the Earth. Examined with the clear vision of retrospect, the environmental missionary Rachel Carson was well ahead of her time. The fears she expressed in 1962 were based on limited data but have since been confirmed. Rachel Carson was right. The U.S. Environmental Protection Agency uses the term *hazardous wastes* for chemicals regulated under the Resource Conservation and Recovery Act (40 CFR 261.33). Hazardous wastes in transportation are regulated by the DOT (49 CFR 170–179). For the purposes of this text, we define a hazardous waste as any hazardous substance that has been spilled or released to the environment. For example, chlorine gas is a hazardous material. When chlorine is released to the environment, it becomes a hazardous waste. Similarly, when asbestos is in place and undisturbed, it is a hazardous material. When it is broken, breached, or thrown away, it becomes a hazardous waste.

HAZARDOUS CHEMICALS

Hazardous chemicals is a term used by OSHA to denote any chemical that poses a risk to employees if they are exposed to it in the workplace. Hazardous chemicals include a broader group of chemicals than the other chemical lists.

AGAIN, WHAT IS A HAZARDOUS SUBSTANCE?

To form the strongest foundation for understanding hazardous waste and because the Resource Conservation and Recovery Act (RCRA) definition for a hazardous substance can also be used to describe a hazardous waste, we will use the RCRA definition in our discussion. The RCRA defines something as a hazardous substance if it possesses any of the following four characteristics:

- *Ignitability* refers to the characteristic of being able to sustain combustion and includes the category of flammability (ability to start fires when heated to temperatures less than 140°F or less than 60°C).
- *Corrosive* substances (or wastes) may destroy containers, contaminate soils and groundwater, or react with other materials to cause toxic gas emissions. Corrosive materials pose a specific hazard to human tissue and aquatic life where the pH levels are extreme.
- *Reactive* substances may be unstable or have a tendency to react, explode, or generate pressure during handling. Pressure-sensitive or water-reactive materials are included in this category.
- *Toxicity* is a function of the effect of hazardous materials (or wastes) that may come into contact with water or air and be leached into the groundwater or dispersed in the environment.

Toxic effects that may occur to humans, fish, or wildlife are the principal concerns here. Toxicity, until 1990, was tested using a standardized laboratory test called the *extraction procedure* (EP toxicity test). The EP toxicity test was replaced in 1990 by the *toxicity characteristics leaching procedure* (TCLP), because the EP test failed to adequately simulate the flow of toxic contaminants to drinking water. The TCLP test was designed to identify wastes likely to leach hazardous concentrations of particular toxic constituents into the surrounding soils or groundwater as a result of improper management. The TCLP extracts constituents from the tested waste in a manner designed to simulate leaching actions that occur in landfills. The extracts are then analyzed to determine if they possess any of the toxic constituents listed below in Table 10.2. If the concentrations of the toxic constituents exceed the levels listed in the table, the waste is classified as *hazardous*.

TABLE 10.2
Maximum Concentrations of Contaminants for TCLP Toxicity Test

Contaminant	Regulatory Level (mg/L)	Contaminant	Regulatory Level (mg/L)
Arsenic	5.0	Lead	5.0
Barium	100.0	Lindane	0.4
Benzene	0.5	Mercury	0.2
Cadmium	1.0	Methoxychlor	10.0
Carbon tetrachloride	0.5	Methyl ethyl ketone	200.0
Chlordane	0.03	Nitrobenzene	2.0
Chlorobenzene	100.0	Pentachlorophenol	100.0
Chloroform	6.0	Pyridine	5.0
Chromium	5.0	Selenium	1.0
Cresol	200.0	Silver	5.0
2,4-Dichlorobenzene	10.0	Tetrachloroethylene	0.7
1,4-Dichlorobenzene	7.5	Toxaphene	0.5
1,5-Dichloroethane	0.5	Trichloroethylene	0.5
2,4-Dinitrololuene	0.13	2,4,5-Trichlorophenol	400.0
Endrin	0.02	2,4,6-Trichlorophenol	2.0
Heptachlor	0.008	2,4,5-TP (Silvex)	1.0
Hexachlorobenzene	0.13	Vinyl chloride	0.2
Hexachloroethane	3.0		

Source: USEPA, 40 CFR 261.24, Toxicity characteristic, U.S. Environmental Protection Agency, Washington, DC, 1990.

WHAT IS A HAZARDOUS WASTE?

Recall our general rule of thumb that states that any hazardous substance spilled or released to the environment is no longer classified as a hazardous substance but as a hazardous waste. USEPA uses the same definition for hazardous waste as it does for hazardous substance. The four characteristics described in the previous section (reactivity, ignitability, corrosivity, or toxicity) can be used to identify hazardous wastes as well as hazardous substances.

The USEPA lists substances that it considers hazardous wastes. These lists take precedence over any other method used to identify and classify substances as hazardous (i.e., if a substance is listed in one of USEPA's lists described below, legally it is a hazardous substance, no matter what). USEPA-listed hazardous wastes are organized into three categories: *nonspecific source wastes*, *specific source wastes*, and *commercial chemical products*; all listed wastes are presumed hazardous regardless of their concentrations. USEPA developed these lists by examining different types of wastes and chemical products to determine whether they met any of the following criteria:

- Exhibit one or more of the four characterizations of a hazardous waste
- Meet the statutory definition of hazardous waste
- Are acutely toxic or acutely hazardous
- Are otherwise toxic

These categories of waste are summarized briefly below:

- *Nonspecific source wastes* are generic wastes commonly produced by manufacturing and industrial processes. Examples from this list include spent halogenated solvents used in degreasing and wastewater treatment sludge from electroplating processes, as well as dioxin wastes, most of which are considered "acutely hazardous" wastes because of the danger they present to human health and the environment.
- *Specific source wastes* are wastes from specially identified industries such as wood preserving, petroleum refining, and organic chemical manufacturing. These wastes typically include sludges, still bottoms, wastewaters, spent catalysts, and residues—for example, wastewater treatment sludge from pigment production.
- *Commercial chemical products* (also called "P" or "U" list wastes because their code numbers begin with these letters) are wastes from specific commercial chemical products, or manufacturing chemical intermediates. They include chemicals such as chloroform and creosote, acids such as sulfuric and hydrochloric, and pesticides such as DDT and kepone (40 CFR 261.31–33).

The USEPA ruled that any waste mixture containing a listed hazardous waste is also considered a hazardous waste—and must be managed accordingly. This applies regardless of what percentage of the waste mixture is composed of listed hazardous wastes. Wastes derived from hazardous wastes (residues from the treatment, storage, and disposal of a listed hazardous waste) are considered hazardous waste, as well (USEPA, 1990b).

WHERE DO HAZARDOUS WASTES COME FROM?

Hazardous wastes are derived from several waste generators. Most of these waste generators are in the manufacturing and industrial sectors and include chemical manufacturers, the printing industry, vehicle maintenance shops, leather products manufacturers, the construction industry, metal manufacturing, and others. These industrial waste generators produce a wide variety of wastes, including strong acids and bases, spent solvents, heavy metal solutions, ignitable wastes, cyanide wastes, and many more.

WHY ARE WE CONCERNED ABOUT HAZARDOUS WASTES?

From the pollution scientist's perspective, any hazardous waste release that could alter the environment in any way is of major concern. The specifics of their concern lie in acute and chronic toxicity to organisms, bioconcentration, biomagnification, genetic change potential, etiology, pathways, change in climate and/or habitat, extinction, persistence, and esthetics (visual impact). Remember that when a hazardous substance or hazardous material is spilled or released into the environment, it becomes a hazardous waste. Because specific regulatory legislation is in place regarding hazardous wastes, responding to hazardous waste leak and spill contingencies, and the proper handling, storage, transportation, and treatment of hazardous wastes, this distinction is important—the goal being, of course, protecting the environment and ultimately protecting ourselves. Why so much concern about hazardous substances and hazardous wastes? This question is relatively easy to answer because of hard lessons we have learned in the past. Our answers are based on experience—actual hazardous materials incidents that we know of, that we have witnessed, that have resulted in tragic consequences, not only to the environment but also to human life.

HAZARDOUS WASTE LEGISLATION

A few people (Rachel Carson for one) could have predicted that a disaster on the scale of Bhopal was ripe to occur—but humans are strange in many ways. We may know that a disaster is possible, is likely, could happen, is predictable. We predict it—but do we act? Do we act before someone dies? No. Not often. Not often enough. We don't think about the human element. We forget the innocents of the world—that is, until they're gone, after they suffer, after they die, after we can no longer help them.

Is it fair? Don't mouth that platitude about life not being fair. We all know it isn't, but ideally we strive to make it more so. Is it right? So what do we do about it? We legislate, of course. Because of Bhopal and other similar (but less catastrophic) chemical spill events, the U.S. Congress (pushed by public concern) developed and passed certain environmental laws and regulations to regulate hazardous substances/wastes in the United States. This section focuses on the two regulatory acts most crucial to the current management programs for hazardous wastes. The first, mentioned earlier, is the Resource Conservation and Recovery Act (RCRA). Specifically, RCRA provides guidelines for prudent management of new and future hazardous substances/wastes. The second act (more briefly mentioned) is the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), otherwise known as Superfund, which deals primarily with mistakes of the past: inactive and abandoned hazardous waste sites.

RESOURCE CONSERVATION AND RECOVERY ACT

The Resource Conservation and Recovery Act (RCRA) is the United State's single most important law dealing with the management of hazardous waste. RCRA and its amendment, Hazardous and Solid Waste Amendments (HSWA-1984), deal with the ongoing management of solid wastes throughout the country—with emphasis on hazardous waste. Keyed to the waste side of hazardous materials, rather than broader issues dealt with in other acts, RCRA is primarily concerned with land disposal of hazardous wastes. The goal is to protect groundwater supplies by creating a "cradle-to-grave" management system with three key elements: a tracking system, a permitting system, and control of disposal (Masters, 1991):

1. *Tracking system*, a manifest document accompanying any waste that is transported from one location to another
2. *Permitting system*, which helps ensure safe operation of facilities that treat, store, or dispose of hazardous wastes
3. *Disposal control system*, comprised of controls and restrictions governing the disposal of hazardous wastes onto, or into, the land

The RCRA regulates five specific areas for the management of hazardous waste, with the focus on treatment, storage, and disposal (Griffin, 1989):

1. Identifying what constitutes a hazardous waste and classifying each
2. Publishing requirements for generators to identify themselves, which includes notification of hazardous waste activities and standards of operation for generators
3. Adopting standards for transporters of hazardous wastes
4. Adopting standards for treatment, storage, and disposal facilities
5. Providing for enforcement of standards through a permitting program and legal penalties for noncompliance

Arguably, RCRA is our single most important law dealing with the management of hazardous waste—it certainly is the most comprehensive piece of legislation that the USEPA has promulgated to date.

CERCLA

The mission of the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (Superfund or SARA) is to clean up hazardous waste disposal mistakes of the past and to cope with emergencies of the present. It is often referred to as the Superfund law. As a result of its key provisions, a large trust fund (about $1.6 billion) was created; later, in 1986, when the law was revised, this fund was increased to almost $9 billion. The revised law is known as the Superfund Amendments and Reauthorization Act of 1986 (SARA). Key elements of CERCLA include the following:

1. CERCLA authorizes USEPA to deal with both short-term (emergency situations triggered by a spill or release of hazardous substances) as well as long-term problems involving abandoned or uncontrolled hazardous waste sites for which more permanent solutions are required.
2. CERCLA set up a remedial scheme for analyzing the impact of contamination on sites under a hazard ranking system. From this hazard ranking system, a list of prioritized disposal and contaminated sites is compiled; this list is the National Priorities List (NPL). The NPL identifies the worst sites in the nation, based on such factors as the quantities and toxicity of wastes involved, the exposure pathways, the number of people potentially exposed, and the importance and vulnerability of the underlying groundwater.
3. CERCLA forces those parties who are responsible for hazardous waste problems to pay the entire cost of cleanup.
4. Title III of SARA requires federal, state, and local governments and industry to work together in developing emergency response plans and reporting on hazardous chemicals. This requirement is commonly known as the Community Right-to-Know Act, and it allows the public to obtain information about the presence of hazardous chemicals in their communities and releases of these chemicals into the environment.

WASTE CONTROL TECHNOLOGY

> How to handle society's toxic chemical waste now ranks among the top environmental issues in most industrial countries. Without concerted efforts to reduce, recycle, and reuse more industrial waste, the quantities produced will overwhelm even the best treatment and disposal systems.
>
> **Postel (1987)**

One of the most challenging and pressing current environmental concerns (dilemmas) confronting pollution scientists (and many others) is what we should do with all of the solid and hazardous wastes our throwaway society produces. In simple (and simplistic) terms, we could say that we should shift from a throwaway society to a recycling one, which would help restore a gain in our living standards. We could also say that, because disposing hazardous waste is so expensive and risky, to make the situation better we should follow RCRA's waste management hierarchy (in descending order of desirability): (1) stop producing waste in the first place; (2) if we cannot avoid producing it, then produce only minimum quantities; (3) recycle it; (4) if it must be produced but cannot be recycled, then treat it; (5) if it cannot be rendered nonhazardous, then dispose of it in a safe manner; and (6) once it is disposed of, continuously monitor it for adverse effects to the environment.

This approach has merit. The question is, though, is it realistic? To a point, yes. We have developed several different strategies to curb the spread of hazardous substances or wastes. One approach is treatment of hazardous wastes to neutralize them or make them less toxic, but, again, a better strategy would be to reduce or eliminate the use of toxic substances and the generation of hazardous waste. To a degree, we can accomplish this, but to think that we can simply do away with all of our hazardous materials, processes that use hazardous materials, and processes that produce hazardous materials is, at the present time, wishful thinking.

What we need to do is refine our waste reduction programs as much as possible and develop technologies that will better treat waste products that we are not able to replace, do away with, or reduce. We have such technologies and practices available to us today. Environmental science and technology can be put to work to develop and use measures and practices by which hazardous chemical wastes can be minimized, recycled, treated, and disposed. We review these measures, practices, and technologies in this section.

WASTE MINIMIZATION

Waste minimization (or source reduction measures) is accomplished in a variety of ways and includes feedstock or input substitution, process modifications, and good operating practices. Note that before any source reduction measure can be put into place considerable amounts of information must be gathered. One of the first steps to be taken in the information-gathering process is determining the exact nature of the waste produced. The waste must initially be characterized and categorized by type, composition, and quantity, a task accomplished by performing a *chemical process audit* or *survey* of the chemical process. Keep in mind that during this information-gathering survey, it is important to look closely for any off-specification input materials that might produce defective outputs; any inadvertent contamination of inputs, process chemical, and outputs; and any obsolete chemicals (which should be properly disposed of). During the survey, particular attention should be given to problem areas—excessive waste amounts per unit of production, excessive process upsets or bad batches, or frequent off-specification inputs. The effect of process variables on the waste stream created and the relationship of waste-stream composition to the input chemicals and process methods used should be examined. For example, determine exactly how much process water is used. Can the amount of water used be reduced? Can process water be reused? Questions like these should be addressed during the chemical process survey (Lindgren, 1989).

To determine the feasibility of reuse, recycling, materials recovery, waste transfer, or proper methods of waste disposal, the exact nature of the waste must also be determined, which is usually accomplished by sampling the waste stream and then analyzing the sample in the laboratory. The nature of the waste can yield valuable information about the industrial process and the condition of process equipment.

Substitution of Inputs

After completing the chemical process survey, the information gathered may suggest or justify the substitution of certain chemicals, process materials, or feedstock to enable the process hazardous wastes to be reduced in volume or no longer be produced. Note that input substitutions are often inseparable from process modifications. A few specific examples of possible input substitutions include the following:

- Use of synthetic coolants in place of emulsified oil coolants
- Use of water-based paints instead of solvent-based paints
- Use of noncyanide-based electroplating solutions
- Use of cartridge filters in lieu of earth filters

Process Modifications

One of the key benefits derived by performing a chemical process audit or survey is that audits often point to or suggest modifications to production systems that work to minimize hazardous waste stream production. Whenever a chemical process can be made more efficient, a reduction in the volume and toxicity of the residuals usually results.

Good Operating Practices

Reducing wastage, preventing inadvertent releases of chemicals, and increasing the useful lifetime of process chemicals are all directly related to *good operating practices*. Ensuring good operating practices by workers can only be accomplished through effective worker training. This training should include not only proper process operations but also effective spill response training.

RECYCLING

> Use it up, wear it out, make it do, or do without.
>
> **—New England proverb**

If waste generation is unavoidable, then strategies that minimize the waste to the greatest extent possible should be pursued, such as recycling. Recycling is the process of collecting and processing materials that would otherwise be thrown away as trash and turning them into new products. Recycling can benefit communities and the environment, because recycling can

- Reduce the amount of waste sent to landfills and incinerators.
- Conserve natural resources such as timber, water, and minerals.
- Prevent pollution by reducing the need to collect new raw materials.
- Save energy.
- Reduce greenhouse gas emissions that contribute to global climate change.
- Help sustain the environment for future generations.
- Help create new well-paying jobs in the recycling and manufacturing industries in the United States.

Recycling includes three steps: collection and processing, manufacturing, and purchasing new products made from recycled materials, which create a continuous loop.

Collection and Processing

There are several methods for collecting recyclables, including curbside collection, drop-off centers, and deposit or refund programs. After collection, recyclables are sent to a recovery facility to be sorted, cleaned, and processed into materials that can be used in manufacturing. Recyclables are bought and sold just like raw materials are, and prices go up and down depending on supply and demand in the United States and the world.

Manufacturing

More and more of today's products are being manufactured with recycled content. Common household items that contain recycled materials include

- Newspapers and paper towels
- Aluminum, plastic, and glass soft-drink containers
- Steel cans
- Plastic laundry detergent bottles

Recycled materials are also used in such innovative ways as including recovered glass in asphalt to pave roads or recovered plastic in carpeting and park benches.

Purchasing New Products Made from Recycled Materials

Buying new products made from recycled materials helps close the recycling loop. Thousands of products contain recycled content. When shopping, consumers should look for (1) products that can be easily recycled, and (2) products that contain recycled content. Here are some of the terms used:

- *Recycled-content product*—This means that the product was manufactured with recycled materials, either collected from a recycling program or from waste recovered during the normal manufacturing process. Sometimes the label will indicate how much of the content came from recycled materials.
- *Postconsumer content*—This is very similar to recycled content, but the material comes only from recyclables collected from consumers or businesses through a recycling program.
- *Recyclable product*—These are products that can be collected, processed, and manufactured into new products after they have been used. These products do not necessarily contain recycled materials.

Some of the common products that are made with recycled content include

- Aluminum cans
- Car bumpers
- Carpeting
- Cereal boxes
- Comic books
- Egg cartons
- Glass containers
- Laundry detergent bottles
- Motor oil
- Nails
- Newspapers
- Paper towels
- Steel products
- Trash bags

Recycling Hazardous Wastes

With regard specifically to hazardous wastes, various strategies have been developed to recycle (and thus minimize) the volume of hazardous wastes to dispose of. These strategies recover or recycle resources, either materials or energy, from the waste stream. The key point to note in chemical process recycling is that the product must receive some processing before reuse. Wastes generally recognized as having components of potential value include

- Flammable and combustible liquids
- Oils
- Slags and sludge
- Precious metal wastes

- Catalysts
- Acids
- Solvents

From the list above, we can see that one such recycling or recovery effort involves the reclamation of organic solvents. Usually accomplished by using highly effective distillation techniques, solvents contaminated with metals and organics are heated to produce a liquid phase and a vapor phase. Lighter components with high volatiles rise to the top of the liquid phase and begin to vaporize. By carefully controlling the waste mixture's temperature, the desired substance can be vaporized and recovered by condensation, leaving the heavier contaminants behind. What remains is a concentrated, highly toxic mixture (far reduced in volume) referred to as *still bottoms*. Bottoms may contain usable metals and other solvents. As distillation technology improves, more of these bottom materials will be recovered and possibly reused.

TREATMENT TECHNOLOGIES

Because of the 1984 and 1991 amendments to RCRA, hazardous wastes must be treated prior to ultimate disposal in a landfill. Even with process modifications, material substitution, and recycling, some portions of some waste streams may still be hazardous and must be properly contained. These hazardous waste components require additional treatment that takes place in vessels (tanks), reactors, incinerators, kilns, boilers, or impoundments. At the present time, several technologies are available for the treatment of hazardous waste streams. In this section, we discuss a few examples, including biological treatment, thermal treatment, activated carbon sorption, electrolytic recovery techniques, air stripping, stabilization and solidification, and filtration and separation treatment systems.

> ***Note:*** Some of these treatment techniques were covered in greater detail earlier, such as *in situ* and non-*in situ* soil contamination treatment; some of the technologies discussed here combine two or more of these basic technologies.

BIOLOGICAL TREATMENT

Several biological treatment processes are available for treating liquid hazardous waste streams (contaminated soils and solids are more difficult to treat), including activated sludge, aerobic lagoons, anaerobic lagoons, spray irrigation, trickling filters, and waste stabilization ponds. These processes are normally associated with biological treatment of municipal and industrial wastewater and are generally used for removal of organic pollutants from wastewater. Generally effective on wastewaters with low-to-moderate concentrations of simple organic compounds and lower concentrations of complex organics, these are generally ineffective in attacking mineral components and useless against heavy metals. Biological treatment of toxic organic components requires considerably more sophisticated operational control (including pretreatment) than is necessary with nontoxic wastewaters. Microorganisms used in biological treatment processes can easily be destroyed by rapid increases in the rate of feed. Acclimation and development of a functional population of biota may require considerable time, and the system is continuously subject to upset (Blackman, 1993).

The two biological processes used for treatment of toxic waste are *aerobic processes* (treatment in the presence of oxygen, or conventional aeration) and *anaerobic processes* (treatment in the absence of oxygen, such as in a simple septic tank). In aerobic treatment, organisms require both an energy source and a carbon source for growth, and both affect what type of organisms will grow in a particular environment. Many hazardous waste streams satisfy both basic requirements, and if appropriate nutrients are present a thriving organic population for waste treatment can exist. Under these conditions, if pH and temperature are controlled, substances that are toxic to the active organisms can be eliminated.

The most important aspect limiting the applicability of aerobic biological treatment of hazardous waste is the biodegradability of the waste—its conversion by biological processes to simple inorganic molecules and to biological materials. Biodegradability of a particular waste is very system specific, and the correct conditions for successful treatment (*detoxification*, or biological conversion of a toxic substance to one less toxic) must be maintained to encourage the correct microbe mixture.

Anaerobic treatment of toxic waste streams has been effectively practiced on many different types of toxic waste streams. This form of treatment is basically a *fermentation* process in which organic waste is both oxidized and reduced.

THERMAL PROCESSES

Thermal treatment processes (incineration) are commonly used to treat both liquids and solids to either destroy the hazardous components or allow disposal of the process residue or treated waste in a USEPA-approved hazardous waste landfill. During *incineration*, carbon-based (organic) materials are burned at high temperatures (typically ranging from 1500 to 3000°F) to break them down, chiefly into hydrogen, carbon, sulfur, nitrogen, and chlorine. These constituent elements then combine with oxygen to form inorganic gases such as water vapor, carbon dioxide, and nitrogen oxides. After combustion, the gases pass through a pollution control system to remove acidic gases and particulate matter prior to being released to the atmosphere. Hazardous waste incineration serves two purposes: (1) to permanently reduce or eliminate the hazardous character of the waste, and (2) to substantially reduce the volume of the waste being disposed. Waste characteristics and treatment requirements determine the incinerator design to accommodate liquid or solid wastes. Temperature, turbulence, and retention time (commonly known as the three T's of incineration) are the prime factors determining incineration treatment design for both solid and liquid wastes. Hazardous waste incinerators are regulated by USEPA and require a permit for operation. To receive an operating permit, an incineration facility must demonstrate a 99.99% destruction and removal efficiency (DRE) for each principal organic hazardous constituent in the feed material. Non-*in situ* thermal processes (primarily incinerators) include designs such as liquid injection and boilers, rotary kilns, fluidized beds, and catalytics. More sophisticated and less common types of thermal treatment systems include wet oxidation, pyrolytic, and plasma processes. Some of these processes can be conducted *in situ*—with steam injection, radiofrequency heating, and vitrification (molten glass treatment) processes.

ACTIVATED CARBON SORPTION

Organic substances may be removed from aqueous hazardous waste streams with activated carbon by sorption, which is the transfer of a substance from a solution to a solid phase. In *adsorption*—a final chemical reaction that forms a cementitious precipitated sludge, not to be confused with *absorption*, which is defined as a physical process that does not chemically stabilize a waste material—chemical substances are removed from the waste stream onto a carbon matrix. The carbon may be used in either granular or powdered form, depending on the application. The effectiveness of activated carbon in removing hazardous constituents from aqueous streams is directly proportional to the amount of surface area of the activated carbon; in some cases, it is adequate for complete treatment. It can also be applied to pretreatment of industrial hazardous waste streams prior to follow-up treatment. Activated carbon sorption is most effective for removing from water those hazardous waste materials that are not water soluble.

ELECTROLYTIC RECOVERY TECHNIQUES

The electrolytic recovery technique (used primarily for recovery of metals from process streams, to clean process waters, or to treat wastewaters prior to discharge) is based on the *oxidation–reduction* reaction, where electrode surfaces are used to collect the metals from the waste stream. Typically, an electrolytic recovery system consists of a treatment vessel (e.g., tank) with electrodes, an electrical power supply, and a gas handling and treatment system. Recovered metal must be removed from the electrodes periodically when the design thickness is achieved for the recovered metal.

Air Stripping

The air stripping technique for removing hazardous constituents from waste streams, although not particularly effective, has been used for many years. Stripping is a means of separating volatile components from less volatile ones in a liquid mixture by partitioning the more volatile materials to a gas phase of air or steam. In air stripping, the moving gas is usually ambient air, which is used to remove volatile dissolved organic compounds from liquids including groundwaters and wastewaters. Additional treatment must be applied to the exhaust vapors to destroy or capture the separated volatiles. The process is driven by the concentration gradient between air and liquid phase equilibrium for particular molecules according to *Henry's law*, which states that at constant temperature the weight of gas absorbed by a given volume of a liquid is proportional to the pressure at which the gas is supplied.

Stabilization and Solidification

Stabilization and solidification are techniques used to convert hazardous waste from the original form to a physically and chemically more stable material. Accomplished by reducing the mobility of hazardous compounds in the waste prior to its land disposal, stabilization and solidification are particularly useful when recovery, removal, or converting hazardous components (as required by RCRA) from a waste prior to disposal in a landfill is not possible. A wide variety of stabilization and solidification treatment processes use Portland cement as a binding agent. Waste–concrete composites can be formed that have exceptional strength and excellent durability and that retain wastes very effectively (Blackman, 1993). Stabilization and solidification treatment processes improve handling and physical characteristics and result in a reduction of solubility or limit the leachability of hazardous components with a waste.

Filtration and Separation

Filtration and separation hazardous waste treatment processes are physical processes. Filtration, the separation of solid particles from a liquid stream through the use of semiporous media, is driven by a pressure difference across the media. This pressure difference is caused by gravity, centrifugal force, vacuum, or elevated pressure. Filtration applied to hazardous waste treatment falls into two categories: clarification and dewatering. *Clarification* takes place when liquids of less than 200 ppm are placed within a clarifier, and the solids are allowed to settle out, producing a cleaner effluent. *Dewatering* is performed on slurries and sludges. The goal of dewatering is to concentrate the solids into a semisolid form for further treatment or land disposal.

ULTIMATE DISPOSAL

Most of us are familiar with open dumps; however, you might not be familiar with some of the dumping practices that occurred because of environmental legislation of the 1970s, which placed increasingly stringent controls on releases to the atmosphere and to the nation's waterways. To protect our atmosphere and our waterways, the legislative mindset of the 1970s drove us to dump hazardous materials into open dumps. Land disposal is safer and more appropriate, but we are now well aware that the land is not a bottomless sink that can be used to absorb all of our discards. We have learned that we must pretreat our wastes to detoxify them, to degrade them, to make them less harmful, to make them more Earth friendly—before we deposit them on or in the ground, the soil, the land—our Earth. Regardless of the treatment, destruction, and immobilization techniques used, some residues that must be contained somewhere will always remain from hazardous wastes. This "somewhere" can include burial in land, deep wells, surface impoundments, waste piles, and landfills. In this section, we discuss each of these ultimate disposal methods.

DEEP-WELL INJECTION

The practice of deep-well injection is not new, as it was used in the 1880s by the petroleum industry to dispose of saltwater produced when drilling for oil; however, disposing of hazardous materials by deep-well injection is a relatively recent development. USEPA estimates that about 9 billion gallons of all of the hazardous waste produced in the United States (about 22% of the total produced) is injected deep into the ground. Most of the deep-well injection sites are located in the Great Lakes region and along the Gulf Coast.

Deep-well injection involves the injection of liquid waste under pressure to underground strata isolated by impermeable rock where geologists believe they will be contained permanently, isolated from aquifers and typically at a depth of more than 700 meters below the surface. A high-pressure pump forces the hazardous liquids into pores in the underground rock, where they displace the water, oil, and gases already there. Sandstone and other sedimentary rock formations are used because they are porous and allow the movement of liquids.

In theory, when properly constructed, operated, and monitored, deep-well injection systems may be the most environmentally sound disposal method for toxic and hazardous wastes currently available. As with anything else, though, that in theory is "perfect" or affords us the "best available technology," deep-well injection has its problems. Although the wastes are stored at a depth below the groundwater table, fractures in the underground geology could allow waste to go where it is not wanted—namely, into the groundwater. The biggest problem with deep-well injection is all of the unknowns. We are not certain of the exact fate of hazardous substances after injection—another example of the "we don't know what we don't know" syndrome.

Because of our uncertainty about the results of our hazardous waste disposal practices, the 1984 amendments to RCRA ban unsafe, untreated wastes from land disposal. For those land disposal facilities allowed to accept hazardous substances, USEPA (1986) implemented restrictions requiring

- Banning liquids from landfills
- Banning underground injection of hazardous waste within 1/4 mile of a drinking water well
- Requiring more stringent structural and design conditions for landfills and surface impoundments, including two or more liners, leachate collection systems above and between the liners, and groundwater monitoring
- Requiring cleanup or corrective action if hazardous waste leaks from a facility
- Requiring information from disposal facilities on pathways of potential human exposure to hazardous substances
- Requiring location standards that are protective of human health and the environment

SURFACE IMPOUNDMENTS

Surface impoundments are diked or excavated areas used to store liquid hazardous wastes. Because most surface impoundments are temporary and relatively inexpensive to construct and allow easy access for treatment, they have been popular for many years. Unfortunately, in the past, surface impoundments were poorly constructed (literally quickly dug out or diked and put into operation), poorly sited (built on a thin layer of permeable soil that allowed leachate to infiltrate to groundwater), located too close to sources of high-quality drinking water (wells or running water sources), and either not monitored at all or poorly monitored. In 1984, the USEPA estimated that, of the more than 180,000 surface impoundments surveyed, prior to 1980 only about 25% were lined and fewer than 10% had monitoring systems.

Because of the problems associated with poor siting, construction, and management of the early surface impoundments, USEPA regulations have toughened the requirements for construction of new surface impoundments. Under the 1984 Hazardous and Solid Waste Amendments (HSWA), for example, USEPA now requires new surface impoundments to include

- The installation of two or more liners
- A leachate collection system between liners
- Groundwater monitoring

Provisions must be made to prevent liquid escaping from overfilling or run-on and to prevent erosion of dams and dikes. During construction and installation, liners must be inspected for uniformity, damage, and imperfections. These liners must also meet permit specifications for materials and thickness.

WASTE PILES

Waste piles are normally associated with industrial sites, where common practice for years was to literally pile up industrial waste and later, when the pile became too large to ignore, dispose of it into a landfill. Industrial practice has been to list such piles as "treatment" piles, and even 40 CFR 264/265, subpart L, refers to such piles as treatment or storage units. The environmental problem with such piles is similar to the problems we discussed related to mining waste. Like mining waste, industrial waste piles are subject to weather exposure, including evaporation of volatile components to the atmosphere and wind and water erosion. The most significant problem related to industrial waste piles is related to precipitation—leaching of contaminants (producing leachate), which may percolate into the subsurface.

The RCRA specifications for waste piles are similar to those for landfills (to be discussed in the next section) and are listed in 40 CFR 264/265, subpart L. Under the RCRA guidelines, the owner or operator of a waste pile used for storage or treatment of noncontainerized solid hazardous wastes is given a choice between compliance with either the waste pile or landfill requirements. If the waste pile is used for disposal, it must comply with landfill requirements. The waste pile must be placed on an impermeable surface, and if leachate is produced a control and monitor system must be in place. Waste piles must also be protected from wind dispersion.

LANDFILLING

Landfilling wastes has a history of causing environmental problems, including fires, explosions, production of toxic fumes, and storage problems when incompatible wastes are commingled. Landfills also have a history of contaminating surface and groundwaters (USEPA, 1990). *Sanitary landfills* are designed and constructed to dispose of municipal solid waste only and are not designed, constructed, or allowed to be operated for disposal of bulk liquids or hazardous wastes. Landfills that can legally receive hazardous wastes are known as *secure landfills*.

Under RCRA, the design and operation of hazardous waste landfills have become much more technically sophisticated. Instead of the past practice of gouging out a huge maw from the subsurface and then dumping countless truckloads of assorted waste materials (including hazardous materials) into it until full, a hazardous waste landfill is now designed as a modular series of three-dimensional control cells. Design and operating procedures have evolved to include elaborate safeguards against leakage and migration of leachate. Secure landfills for hazardous waste disposal are equipped with double liners. Leakage detection, leachate collection and monitoring, and groundwater monitoring systems are required. Liners used in secure landfills must meet regulatory specifications (see Figure 10.2); for example, the upper liner must consist of a 10- to 100-mil-thick *flexible-membrane liner* (FML), usually made of sheets of rubber or plastic. The

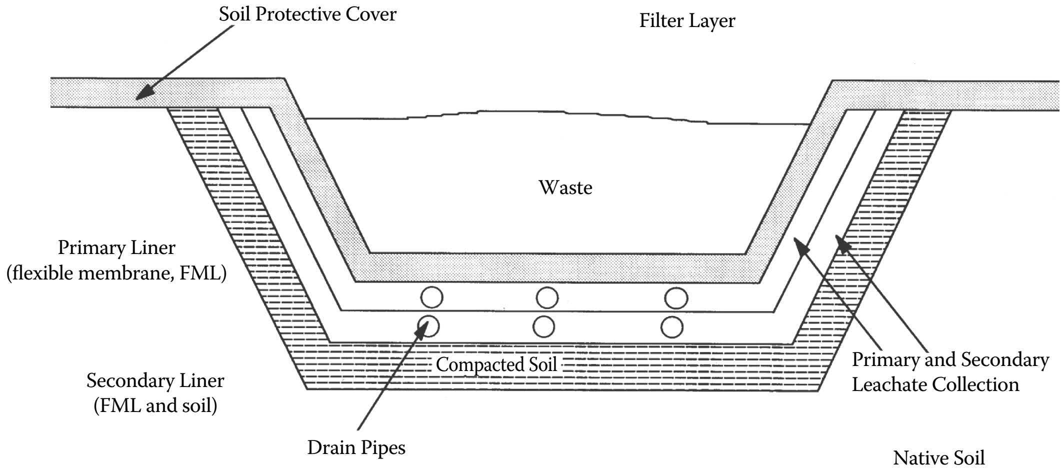

FIGURE 10.2 Cross-section of a secure landfill double liner system.

lower liner is usually FML, but recompacted clay 3 feet thick is also acceptable. Secure landfills must be constructed to allow the collection of leachate (usually via perforated drainage pipes with an attached pumping system) that accumulates above each liner. Leachate control is critical. To aid in this control process (especially from leachate produced by precipitation), a low-permeability cap must be placed over completed cells. When the landfill is finally closed, a cap that will prevent leachate formation via precipitation must be put in place. This cap should be sloped to allow drainage away from the wastes. When a landfill is filled and capped, it cannot be completely abandoned, ignored, or forgotten. The site must be monitored to ensure that leachate is not contaminating the groundwater. This is accomplished by installing test wells downgradient to detect any leakage from the site.

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11 Industrial Hygiene

Industrial hygiene is an area of specialization within the broader field of industrial health and safety.

Goetsch (1996)

WHAT IS INDUSTRIAL HYGIENE?

According to the Occupational Safety and Health Administration (OSHA), industrial hygiene is the science of anticipating, recognizing, evaluating, and controlling workplace conditions that may cause workers injury or illness. Industrial hygienists use environmental monitoring and analytical methods to detect the extent of worker exposure, and they use employee engineering, administrative controls, and other methods, such as personal protective equipment (PPE), to control potential health hazards (OSHA, 1998).

INDUSTRIAL HYGIENE TERMINOLOGY

Every branch of science, every profession, and every engineering process has its own language for communication. Industrial hygiene is no different. In this section, we define and identify many of the key terms and concepts used by industrial hygienists when applying their skills to make our dynamic technological world safer. Practicing industrial hygienists or students of industrial hygiene should know these concepts—without such knowledge it is difficult, if not impossible, to practice industrial hygiene. In addition, environmental engineers who become involved in designing or maintaining workplace safety and who are responsible for ensuring the environmental health of workers in the workplace must be knowledgeable of all aspects of industrial hygiene practice. To work effectively even at the margin of industrial hygiene the practitioner must be familiar with industrial hygiene terminology. As Voltaire said: *"If you wish to converse with me, define your terms."*

INDUSTRIAL HYGIENE TERMS AND CONCEPTS

Abatement period—The amount of time given an employer to correct a hazardous condition that has been cited.

Abrasive blasting—A process for cleaning surfaces by means of materials such as sand, alumina, or steel grit in a stream of high-pressure air.

Absorption—The taking up of one substance by another, such as a liquid by a solid or a gas by a liquid.

Accident—An unplanned and sometimes injurious or damaging event that interrupts the normal progress of an activity and is invariably preceded by an unsafe act or unsafe condition thereof. An accident may be seen as resulting from a failure to identify a hazard or from some inadequacy in an existing system of hazard controls. Based on applications in casualty insurance, an accident is an event that is definite in point of time and place but unexpected as to either its occurrence or its results.

Accident analysis—A comprehensive, detailed review of the data and information compiled from an accident investigation. An accident analysis should be used to determine causal factors only and not to point the finger of blame at any one. When the causal factors have been determined, corrective measures should be prescribed to prevent recurrence.

Accident prevention—The act of averting a circumstance that could cause loss or injury to a person.

Accommodation—The ability of the eye to quickly and easily readjust to other focal points after viewing a video display terminal (VDT) so as to be able to focus on other objects, particularly objects at a distance.

Accuracy—The exactness of an observation obtained from an instrument or analytical technique with regard to the true value.

ACGIH—American Conference of Governmental Industrial Hygienists.

Acid—Any chemical with a low ph that in a water solution can burn the skin or eyes. Acids turn litmus paper red and have pH values of 0 to 6.

Acoustics—In general, the experimental and theoretical science of sound and its transmission; in particular, that branch of the science that has to do with the phenomena of sound in a particular space such as a room or theater. Safety engineering is concerned with the technical control of sound and involves architecture and construction, studying control of vibration, soundproofing, and the elimination of noise to engineer out the noise hazard.

Action level—Term used by OSHA and the National Institute for Occupational Safety and Health (NIOSH), a federal agency that conducts research on safety and health concerns, and defined in the Code of Federal Regulations (CFR), Title 40, Protection of Environment. Under OSHA, an action level is the level of toxicant that requires medical surveillance, usually 50% of the permissible exposure level (PEL). Note that OSHA also uses action levels in ways other than setting the level of a toxicant. For example, in its hearing conservation standard, 29 CFR 1910.95, OSHA defines the action level as an 8-hour time-weighted average (TWA) of 85 decibels measured on the A-scale, slow response, or equivalently a dose of 50%. Under 40 CFR 763.121, action level means an airborne concentration of asbestos of 0.1 fiber per cubic centimeter (f/cc) of air calculated as an 8-hour time-weighted average.

Activated charcoal—Charcoal is an amorphous form of carbon formed by burning wood, nutshells, animal bones, and other carbonaceous material. Charcoal becomes activated by heating it with steam to 800 to 900°C. During this treatment, a porous, submicroscopic internal structure is formed that gives the charcoal an extensive internal surface area. Activated charcoal is commonly used as a gas or vapor adsorbent in air-purifying respirators and as a solid sorbent in air sampling.

Acute—Health effects that show up a short length of time after exposure. An acute exposure runs a comparatively short course and its effects are easier to reverse than those of a chronic exposure.

Acute toxicity—The discernible adverse effects induced in an organism within a short period of time (days) of exposure to an agent.

Administrative controls—Methods of controlling employee exposures through job rotation, work assignment, time periods away from the hazard, or training in specific work practices designed to reduce exposure.

Adsorption—The taking up of a gas or liquid at the surface of another substance, usually a solid (e.g., activated charcoal adsorbs gases).

Aerosols—Liquid or solid particles so small they can remain suspended in air long enough to be transported over a distance.

Air—The mixture of gases that surrounds the Earth; its major components are 78.08% nitrogen, 20.95% oxygen, 0.03% carbon dioxide, and 0.93% argon. Water vapor (humidity) varies.

Air cleaner—A device designed to remove atmospheric airborne impurities, such as dusts, gases, vapors, fumes, and smoke.

Air contamination—The result of introducing foreign substances into the air so as to make the air contaminated.

Air-line respirator—A respirator that is connected to a compressed breathing air source by a hose with a small inside diameter. The air is delivered continuously or intermittently in a sufficient volume to accommodate the wearer's breathing.

Air monitoring—The sampling for and measurement of pollutants in the atmosphere.

Air pollution—Contamination of the atmosphere (indoor or outdoor) caused by the discharge (accidental or deliberate) of a wide range of toxic airborne substances.

Air-purifying respirator—A respirator that uses chemicals to remove specific gases and vapors from the air or that uses a mechanical filter to remove particulate matter. An air-purifying respirator must only be used when there is sufficient oxygen to sustain life and the air contaminant level is below the concentration limits of the device.

Air sampling—Safety engineers are interested in knowing what contaminants workers are exposed to and the contaminant concentrations. Determining the quantities and types of atmospheric contaminants is accomplished by measuring and evaluating a representative sample of air. The types of air contaminants that occur in the workplace depend on the raw materials used and the processes employed. Air contaminants can be divided into two broad groups, depending on physical characteristics: (1) gases and vapors, and (2) particulates.

Air-supplying respirator—Respirator that provides a supply of breathable air from a clean source outside of the contaminated work area.

Allergens—Because of the presence of allergens on spores, all molds studied to date have the potential to cause allergic reaction in susceptible people. Allergic reactions are believed to be the most common exposure reaction to molds (Rose, 1999).

Alpha particle—A small, positively charged particle made up of two neutrons and two protons of very high velocity, generated by many radioactive materials, including uranium and radium.

Alveoli—Tiny air sacs in the lungs that are located at the ends of bronchioles. Through the thin walls of the alveoli, blood takes in oxygen and gives up carbon dioxide during respiration.

Ambient—Descriptive of any condition of the environment surrounding a given point. For example, ambient air means that portion of the atmosphere, external to buildings, to which the general public has access. Ambient sound is the sound generated by the environment.

Amorphous—Noncrystalline.

ANSI—American National Standards Institute, a voluntary membership organization (run with private funding) that develops consensus standards nationally for a wide variety of devices and procedures.

Aromatic—Term applied to a group of hydrocarbons and their derivatives characterized by the presence of the benzene nucleus.

Asbestosis—Disease of the lungs caused by inhalation of fine airborne asbestos fibers.

Asphyxiant—A vapor gas that can cause unconsciousness or death by suffocation.

Asphyxiation—Suffocation due to a lack of oxygen. A substance (e.g., carbon monoxide) that combines with hemoglobin to reduce the blood's capacity to transport oxygen results in chemical asphyxiation. Simple asphyxiation is the result of exposure to a substance (such as methane) that displaces oxygen. Asphyxiation is one of the principal potential hazards of working in confined spaces.

ASTM—American Society for Testing and Materials.

Atmosphere—In physics, a unit of pressure whereby 1 atmosphere (atm) equals 14.7 pounds per square inch (psi).

Atmosphere-supplying respirator—A respirator that provides breathing air from a source independent of the surrounding atmosphere. The two types are air-line and self-contained breathing apparatus.

Atmospheric pressure—The pressure exerted in all directions by the atmosphere. At sea level, mean atmospheric pressure is 29.92 in. Hg, 14.7 psi, or 407 in. wg.

Atomic weight—Approximately the sum of the number of protons and neutrons found in the nucleus of an atom. This sum is also called the mass number. The atomic weight of oxygen is approximately 16, as most oxygen atoms contain 8 neutrons and 8 protons.

Attenuate—To reduce in amount; used to refer to noise or ionizing radiation.

Attenuation—The reduction of intensity at a designated first location as compared with intensity at a second location farther from the source (reducing the level of noise by increasing distance from the source is a good example).

Audible range—The frequency range over which normal hearing occurs—approximately 20 Hz through 20,000 Hz. Above the range of 20,000 Hz, the term *ultrasonic* is used. Below 20 Hz, the term *subsonic* is used.

Audiogram—A record of hearing loss or hearing level measured at several different frequencies, usually 500 to 6000 Hz. The audiogram may be presented graphically or numerically. Hearing level is shown as a function of frequency.

Audiometric testing—Objective measuring of a person's hearing sensitivity. By recording the response to a measured signal, a person's level of hearing sensitivity can be expressed in decibels, as related to an audiometric zero, or no-sound base.

Authorized person—A person designated or assigned by an employer or supervisor to perform a specific type of duty or duties, to use specified equipment, or to be present in a given location at specified times (e.g., an authorized or qualified person is used in confined space entry).

Auto-ignition temperature—The lowest temperature at which a vapor-producing substance or a flammable gas will ignite even without the presence of a spark or flame.

Avogadro's number—The number of molecules in a mole of any substance (6.02217×10^3). Named after Italian physicist Amedeo Avogadro (1776–1856). At 0°C and 29.92 in. Hg, 1 mole occupies 22.4 liters of volume.

Background noise—Radiation coming from sources other than the particular noise sources being monitored.

Baghouse—Term commonly used for the housing containing bag filters for recovery of fumes from arsenic, lead, sulfa, etc.

Base—A compound that reacts with an acid to form a salt. It is another term for alkali.

Baseline data—Data collected prior to a project for later use in describing conditions before the project began. Also commonly used to describe the first audiogram given (within 6 months) to a worker after he or she has been exposed to the action level (85 dBA) to establish his or her baseline for comparison to subsequent audiograms.

Behavior-based safety (BBS) management models—A management theory based on the work of B.F. Skinner, it explains behavior in terms of stimulus, response, and consequences.

Bel—A unit equal to 10 decibels (see decibel).

Benchmarking—A process for rigorously measuring company performance vs. "best-in-class" companies and using analysis to meet and exceed the best in class.

Benign—Not malignant. A benign tumor is one that does not metastasize or invade tissue. Benign tumors may still be lethal, due to pressure on vital organs.

Beta particle—Beta radiation; a small electrically charged particle thrown off by many radioactive materials, identical to the electron. Beta particles emerge from radioactive material at high speeds.

Bioaerosols—Mold spores, pollen, viruses, bacteria, insect parts, animal dander, etc.

Biohazard—Organisms or products of organisms that present a risk to humans.

Boiler code—ANSI/ASME Pressure Vessel Code, a set of standards prescribing requirements for the design, construction, testing, and installation of boilers and unfired pressure vessels.

Boiling point—Temperature at which the vapor pressure of a liquid equals atmospheric pressure.

Boyle's law—The product of a given pressure and volume is constant with a constant temperature.

Breathing zone—A hemisphere-shaped area from the shoulders to the top of the head.

Cancer—Cellular tumor formed by mutated cells.

Capture velocity—Air velocity at any point in front of an exhaust hood necessary to overcome opposing air currents and to capture the contaminated air by causing it to flow into the hood.

Carbon monoxide—A colorless, odorless toxic gas produced by any process that involves the incomplete combustion of carbon-containing substances. It is emitted through the exhaust of gasoline-powered vehicles.

Carcinogen—A substance or agent capable of causing or producing cancer in mammals, including humans. A chemical is considered to be a carcinogen if (1) it has been evaluated by the International Agency for Research on Cancer (IARC) and found to be a carcinogen or potential carcinogen, (2) it is listed as a carcinogen or potential carcinogen in the latest edition of the *Annual Report on Carcinogens* published by the National Toxicology Program (NTP), or (3) it is regulated by OSHA as a carcinogen.

Carpal tunnel syndrome—An injury to the median nerve inside the wrist, frequently caused by ergonomically incorrect repetitive motion.

CAS—Chemical Abstracts Service, an organization under the American Chemical Society, which abstracts and indexes chemical literature from all over the world. CAS numbers are used to identify specific chemicals or mixtures.

Catalyst—A substance that alters the speed of, or makes possible, a chemical or biochemical reaction but remains unchanged at the end of the reaction.

Catastrophe—A loss of extraordinarily large dimensions in terms of injury, death, damage, and destruction.

Causal factor—A person, thing, or condition that contributes significantly to an accident or to a project outcome.

Ceiling limit—An airborne concentration of a toxic substance in the work environment that should never be exceeded.

CERCLA—Comprehensive Environmental Response, Compensation, and Liability Act of 1980; commonly known as "Superfund."

CFR—Code of Federal Regulations, a collection of the regulations that have been promulgated under U.S. law.

Charles's law—The volume of a given mass of gas at constant pressure is directly proportional to its absolute temperature (in Kelvin).

Chemical cartridge respirator—A respirator that uses various chemical substances to purify inhaled air of certain gases and vapors. This type of respirator is effective for concentrations no more than ten times the threshold limit value (TLV) of the contaminant, if the contaminant has warning properties (odor or irritation) below the TLV.

Chemical change—Change that occurs when two or more substances (reactants) interact with each other, resulting in the production of different substances (products) with different chemical compositions. A simple example of chemical change is the burning of carbon in oxygen to produce carbon dioxide.

Chemical hazards—Includes hazardous chemicals conveyed in various forms—mists, vapors, gases, dusts, and fumes.

Chemical spill—An accidental dumping, leakage, or splashing of a harmful or potentially harmful substance.

CHEMTREC—Chemical Transportation Emergency Center, a public service of the Chemical Manufacturers Association that provides immediate advice for those at the scene of hazardous materials emergencies. CHEMTREC has a 24-hour toll-free telephone number (800-424-9300) for help responding to chemical transportation emergencies.

Chromatograph—An instrument that separates and analyzes mixtures of chemical substances.

Chronic—Persistent, prolonged, repeated exposure. Chronic exposure occurs when repeated exposure to or contact with a toxic substance occurs over a period of time, the effects of which become evident only after multiple exposures.

Coefficient of friction—A numerical correlation of the resistance of one surface against another surface.

Colorimetry—A term used for all chemical analysis involving reactions in which a color is developed when a particular contaminant is present in the sample and reacts with the collection medium. The resultant stain length or color intensity is measured to determine the actual concentration.

Combustible gas indicator—An instrument that samples air and indicates whether an explosive mixture is present, and the percentage of the lower explosive limit (LEL) of the air–gas mixture that has been reached.

Combustible liquid—Liquids having a flash point at or above 37.8°C (100°F).

Combustion—Burning, defined in chemical terms as the rapid combination of a substance with oxygen, accompanied by the evolution of heat and usually light.

Competent person—As defined by OSHA, one who is capable of recognizing and evaluating employee exposure to hazardous substances or to unsafe conditions and who is capable of specifying protective and precautionary measures to be taken to ensure the safety of employees as required by particular OSHA regulations under the conditions to which such regulations apply.

Concentration—Amount of a given substance in a stated unit of measure. Common methods of stating concentration are percent by weight or by volume, weight per unit volume, normality, etc.

Conductive hearing loss—Type of hearing loss usually caused by a disorder affecting the middle or external ear.

Confined space—A vessel, compartment, or any area having limited access and (usually) no alternative escape route, having severely limited natural ventilation or an atmosphere containing less that 19.5% oxygen, and having the capability of accumulating a toxic, flammable, or explosive atmosphere, or of being flooded (engulfing a victim).

Contact dermatitis—Dermatitis caused by contact with a substance.

Containment—In fire terminology, restricting the spread of fire. For chemicals, restricting chemicals to an area that is diked or walled off to protect personnel and the environment.

Contingency plan (*emergency response plan*)—Under 40 CFR 260.10, a document that sets forth an organized, planned, and coordinated course of action to be followed in the event of an emergency that could threaten human health or the environment.

Convection—The transfer of heat from one location to another by way of a moving medium, including air and water.

Corrosive material—Any material that dissolves metals or other materials or that burns the skin.

Coulometer—A chemical analysis instrument that determines the amount of a substance released in electrolysis by measurement of the quantity of electricity used. The number of electrons transferred in terms of coulombs is an indication of the contaminant concentration.

Cumulative injury—Any physical or psychological disability that results from the combined effects of related injuries or illnesses in the workplace.

Cumulative trauma disorder—A disorder caused by the highly repetitive motion required of one or more parts of a worker's body, which in some cases, can result in moderate to total disability.

Cutaneous—Pertaining to or affecting the skin.

Cyclone device—A dust-collecting instrument that has the ability to separate particles by size.

Dalton's law of partial pressures—In a mixture of theoretically ideal gases, the pressure exerted by the mixture is the sum of the pressures exerted by each component gas of the mixture.

Decibel (dB)—A unit of measure used originally to compare sound intensities and subsequently electrical or electronic power outputs; now also used to compare voltages. In hearing conservation, it is a logarithmic unit used to express the magnitude of a change in level of sound intensity.

Decontamination—The process of reducing or eliminating the presence of harmful substances such as infectious agents to reduce the likelihood of disease transmission from those substances.

Degrees Celsius (Centigrade)—Temperature scale where the freezing point of water is 0°C and the boiling point is 100°C. To convert to degrees Fahrenheit, use the following formula: $°F = (°C \times 1.8) + 32$.

Degrees Fahrenheit—Temperature scale where the boiling point of water is 212°F and the freezing point is 32°F.

Density—A measure of the compactness of a substance; it is equal to its mass per unit volume and is measured in kilogram per cubic meter or pounds per cubic foot (Density = Mass/Volume).

Dermatitis—Inflammation or irritation of the skin from any cause. Industrial dermatitis is an occupational skin disease.

Dermatosis—A broader term than dermatitis; includes any cutaneous abnormality, thus encompassing folliculitis, acne, pigmentary changes, and nodules and tumors.

Design load—The weight that can be safely supported by a floor, equipment, or structure, as defined by its design characteristics.

Dike—An embankment or ridge of either natural or manmade materials used to prevent the movement of liquids, sludges, solids, or other materials.

Dilute—Adding material to a chemical by the user or manufacturer to reduce the concentration of active ingredient in the mixture.

Direct reading instruments—Devices that provide an immediate indication of the concentration of aerosols, gases, and vapors by means of a color change in colorimetric devices or a register on a meter or instrument.

Dose—An exposure level. Exposure is expressed as weight or volume of test substance per volume of air (mg/L), or as parts per million (ppm).

Dose–response relationship—Correlation between the amount of exposure to an agent or toxic chemical and the resulting effect on the body.

Dosimeter—Measuring tool that provides a time-weighted average over a period of time such as one complete work shift.

Dry bulb temperature—Temperature reading by an ordinary thermometer; the temperature of a gas or mixture of gases as indicated on a thermometer after correction for radiation.

Duct—A conduit used for moving air at low pressures.

Duct velocity—Air velocity through the duct cross-section.

Dusts—Various types of solid particles produced when a given type of organic or inorganic material is scraped, sawed, ground, drilled, heated, crushed, or otherwise deformed.

Dyspnea—Shortness of breath, difficult or labored breathing.

Electrical grounding—Precautionary measures designed into an electrical installation to eliminate dangerous voltages in and around the installation and to operate protective devices in case of current leakage from energized conductors to their enclosures.

Emergency response plan—See contingency plan.

Energized—Refers to the conductors of an electrical circuit; having voltage applied to such conductors and to surfaces that a person might touch; having voltage between such surfaces and other surfaces that might complete a circuit and allow current to flow.

Energy—The capacity for doing work. Potential energy (PE) is energy deriving from position; thus, a stretched spring has elastic PE, and an object raised to a height above the surface of the Earth or the water in an elevated reservoir has gravitational PE. A lump of coal and a tank of oil, together with the oxygen required for their combustion, have chemical energy. Other sorts of energy include electrical and nuclear energy, light, and sound. Moving bodies possess kinetic energy (KE). Energy can be converted from one form to another, but the total quantity stays the same (in accordance with the conservation of energy principle). For example, as an orange falls, it loses gravitational PE but gains KE.

Engineering—The application of scientific principles to the design and construction of structures, machines, apparatus, manufacturing processes, and power generation and utilization, for the purpose of satisfying human needs. Safety engineering is concerned with control of environment and humankind's interface with it, especially safety interaction with machines, hazardous materials, and radiation.

Engineering controls—Methods of controlling employee exposures by modifying the source or reducing the quantity of contaminants released into the workplace environment.

Epidemiological theory—This theory holds that the models used for studying and determining epidemiological relationships can also be used to study causal relationships between environmental factors and accidents or diseases.

Ergonomics—A multidisciplinary activity dealing with interactions between humans and their total working environment, plus stresses related to such environmental elements as atmosphere, heat, light, and sound, as well as all tools and equipment of the workplace.

Etiology—The study or knowledge of the causes of disease.

Evaporation—The process by which a liquid is changed into the vapor state.

Evaporation rate—The ratio of the time required to evaporate a measured volume of a liquid to the time required to evaporate the same volume of a reference liquid (butyl acetate, ethyl ether) under ideal test conditions. The higher the ratio, the slower the evaporation rate. The evaporation rate can be useful in evaluating the health and fire hazards of a material.

Exhaust ventilation—A mechanical device used to remove air from any space.

Exposure—Contact with a chemical, biological, or physical hazard.

Exposure ceiling—The concentration level of a given substance that should not be exceeded at any point during an exposure period.

Face velocity—Average air velocity into an exhaust system measured at the opening into the hood or booth.

Fall arresting system—A system consisting of a body harness, a lanyard or lifeline, and an arresting mechanism with built-in shock absorber, designed for use by workers performing tasks in locations from which falls would be injurious or fatal, or where other kinds of protection are not practical.

Federal Register—Publication of U.S. government documents officially promulgated under the law, documents whose validity depends upon such publication. It is published on each day following a government working day. It is, in effect, the daily supplement to the Code of Federal Regulations (CFR).

Fiber—Particle with an aspect ratio greater than 3:1 (NIOSH, 5:1).

Fire—A chemical reaction between oxygen and a combustible fuel.

Fire point—Lowest temperature at which a material can evolve vapors fast enough to support continuous combustion.

Flame ionization detector—A direct reading instrument that ionize gases and vapors with an oxyhydrogen flame and measures the differing electrical currents thus generated.

Flammable liquid—Any liquid having a flash point below 37.8°C (100°F), except any mixture having components with flashpoints of 100°F or higher, the total of which make up 99% or more of the total volume of the mixture.

Flammable range—The difference between the lower and upper flammable limits, expressed in terms of percentage of vapor or gas in air by volume; also often referred to as the "explosive range."

Flammable solid—A non-explosive solid liable to cause fire through friction, absorption of moisture, spontaneous chemical change, or heat retained from a manufacturing process, or that can be ignited readily and when ignited burns so vigorously and persistently as to create a serious hazard.

Flash point—The lowest temperature at which a liquid gives off enough vapor to form ignitable moisture with air and produce a flame when a source of ignition is present. Two tests are used: open cup and closed cup.

Foot-candle—The illumination at a point on a surface 1 foot from and perpendicular to a uniform point source of 1 candle.

Fume—Airborne particulate matter formed by the evaporation of solid materials (e.g., metal fume emitted during welding); usually less that 1 micron in diameter.

Gamma rays—High-energy x-rays.

Gas—A state of matter in which the material has very low density and viscosity, can expand and contract greatly in response to changes in temperature and pressure, easily diffuses into other gases, and readily and uniformly distributes itself throughout any container.

Gas chromatography—A detection technique that separates a gaseous mixture by passing it through a column, enabling the components to be released at various times depending on their molecular structure; used as an analytical tool for air sampling gases and vapors.

Gauge pressure—Pressure measured with respect to atmospheric pressure.

Geiger–Müller counter—A gas-filled electrical instrument that indicates the presence of an atomic particle or ray by detecting the ions produced.

General ventilation—A ventilation system using natural or mechanically generated make-up air to mix and dilute contaminants in the workplace.

Globe thermometer—A thermometer set in the center of a black metal sphere to measure radiant heat.

Grab sample—A sample taken within a short duration to quantify or identify air contaminants.

Gram (g)—A metric unit of weight. One ounce equals 28.4 grams.

Ground-fault circuit interrupter (GFCI)—A sensitive device intended for shock protection which functions to de-energize an electrical circuit or portion thereof within a fraction of a second, in case of leakage to ground of current sufficient to be dangerous to persons but less than that required to operate the overcurrent protective device of the circuit.

Grounded system—A system of conductors in which at least one conductor or point is intentionally grounded, either solidly or through a current-limiting (current transformer) device.

Half-life—For a single radioactive decay process, the time required for the activity to decrease to half its value by that process.

Hazard—The potential for an activity, condition, circumstance, or changing conditions or circumstances to produce harmful effects. Also, an unsafe condition.

Hazard analysis—A systematic process for identifying hazards and recommending corrective action.

Hazard and operability (HAZOP) analysis—A systematic method in which process hazards and potential operating problems are identified using a series of guide words to investigate process deviations.

Hazard assessment—A qualitative evaluation of potential hazards in the interrelationships between and among the elements of a system, upon the basis of which the occurrence probability of each identified hazard is rated.

Hazard Communication Standard (HazCom)—An OSHA workplace standard found in 29 CFR 1910.1200 that requires all employers to become aware of the chemical hazards in their workplace and relay that information to their employees. In addition, a contractor conducting work at a client's site must provide chemical information to the client regarding the chemicals that are brought onto the work site.

Hazard control—A means of reducing the risk from exposure to a hazard.

Hazard identification—The pinpointing of material, system, process, and plant characteristics that can produce undesirable consequences through the occurrence of an accident.

Hazardous material—Any material possessing a relatively high potential for harmful effects upon persons.

Hazardous substance—Any substance that has the potential for causing injury by reason of its being explosive, flammable, toxic, corrosive, oxidizing, irritating, or otherwise harmful to personnel.

Hazardous waste—A solid, liquid, or gaseous waste that may cause or significantly contribute to serious illness or death, or that poses a substantial threat to human health or the environment when the waste is improperly managed.

Hearing conservation—The prevention of or minimizing of noise-induced deafness through the use of hearing protection devices, the control of noise through engineering controls, annual audiometric tests, and employee training.

Heat cramps—A type of heat stress (a possible side-effect of dehydration) that occurs as a result of salt and potassium depletion.

Heat exhaustion—A condition usually caused by loss of body water from exposure to excess heat. Symptoms include headache, tiredness, nausea, and sometimes fainting.

Heat rash—Rash caused by sweating and inadequate hygiene practices.

Heat stroke—A serious disorder resulting from exposure to excess heat. It results from sweat suppression and increased storage of body heat, characterized by high fever, collapse, and sometimes convulsions or coma.

HEPA filter—High-efficiency particulate air filter; a disposable, extended medium, dry-type filter with a particle removal efficiency of no less than 99.97% for 0.3-m particles.

Homeland Security—Federal cabinet-level department created to protect the United States and her citizens as a result of 9/11. The new Department of Homeland Security (DHS) has three primary missions: prevent terrorist attacks within the United States, reduce America's vulnerability to terrorism, and minimize the damage from potential attacks and natural disasters.

Hood entry loss—Pressure loss from turbulence and friction as air enters a ventilation system.

Hot work—Work involving electric or gas welding, cutting, brazing, or similar flame or spark-producing operations.

Human factor engineering/ergonomics—For practical purposes, the terms are synonymous, and focus on human beings and their interaction with products, equipment, facilities, procedures, and environments used in work and everyday living. The emphasis is on human beings (as opposed to engineering, where the emphasis is more strictly on technical engineering considerations) and how the design of things influences people. Human factors, then, seek to change the things people use and the environments in which they use these things to better match the capabilities, limitations, and needs of people (Sanders and McCormick, 1993).

Immediately dangerous to life or health (IDLH)—An atmospheric concentration of any toxic, corrosive, or asphyxiant substance that poses an immediate threat to life or would cause irreversible or delayed adverse health effects or would interfere with an individual's ability to escape from a dangerous atmosphere.

Ignition source—Anything that provides heat, spark, or flame sufficient to cause combustion or an explosion.

Ignition temperature—The temperature at which a given fuel bursts into flame.

Illumination—The amount of light flux a surface receives per unit area; may be expressed in lumens per square foot or in foot-candles.

Impaction—Forcibly lodging particles into matter.

Impervious—A material that does not allow another substance to pass through or penetrate it; frequently used to describe gloves or chemical clothing.

Impingement—The process of collecting particles by pulling contaminated air through a device filled with water or reagent such that the particles remain in the liquid.

Impulse noise—A noise characterized by rapid rise time, high peak value, and rapid decay.

Inches of mercury column—A unit used in measuring pressures. One inch of mercury column equals a pressure of 1.66 kpa (0.491 psi).

Inches of water column—A unit used in measuring pressures. One inch of water column equals a pressure of 0.25 kpa (0.036 psi).

Incident—An undesired event that, under slightly different circumstances, could have resulted in personal harm or property damage; any undesired loss of resources.

Incompatible—Materials that could cause dangerous reactions from direct contact with one another.

Indoor air quality (IAQ)—The effect, good or bad, of the contents of the air inside a structure on its occupants. Usually temperature (too hot and cold), humidity (too dry or too damp), and air velocity (draftiness or motionless) are considered comfort rather than indoor air quality issues. Unless they are extreme, they may make someone unhappy but they will not make a person ill; nevertheless, most IAQ professionals will take these factors into account when investigating air quality situations.

Industrial hygiene—The American Industrial Hygiene Association (AIHA) defines industrial hygiene as "that science and art devoted to the anticipation, recognition, evaluation, and control of those environmental factors or stresses—arising in the workplace—which may cause sickness, impaired health and well-being, or significant discomfort and inefficiency among workers or among citizens of the community."

Ingestion—Entry of a foreign substance into the body through the mouth.

Inhalation—Breathing of a substance in the form of a gas, vapor, fume, mist, or dust.

Injury—A wound or other specific damage.

Insoluble—Incapable of being dissolved in a liquid.

Interlock—A device that interacts with another device or mechanism to govern succeeding operations, such as the interlock on an elevator door that prevents the car from moving unless the door is properly closed.

Ionizing radiation—Radiation that becomes electrically charged (i.e., changed into ions).

Irritant—A substance that produces an irritating effect when it contacts skin, eyes, nose, or respiratory system.

Job hazard (safety) analysis—Breaking down into its components any method or procedure to determine the hazards connected therewith and the requirements for performing it safely.

Kelvin—Temperature scale, also called absolute temperature, where the temperature is measured based on the average kinetic energy per molecule of a perfect gas.

Kinetic energy—The energy resulting from a moving object.

Laboratory Safety Standard—A specific hazard communication program for laboratories, found in 29 CFR 1910.1450. These regulations are essentially a blend of hazard communication and emergency response for laboratories. The cornerstone of the Laboratory Safety Standard is the requirement for a written chemical hygiene plan.

Laser—Light amplification by stimulated emission of radiation.

Latent period—Time that elapses between exposure and the first manifestation of damage.

LC_{50}—Lethal concentration that will kill 50% of the test animals within a specified time.

LD_{50}—Dose required to produce death in 50% of exposed species within a specified time.

Liter (L)—A measure of capacity; 1 quart equals 0.9 L.

Local exhaust ventilation—A ventilation system that captures and removes contaminants at the point of generation before escaping into the workplace.

Lockout/tagout procedure—An OSHA procedure found in 29 CFR 1910.147. A tag or lock is used to "tag out" or "log out" a device so that no one can inadvertently actuate the circuit, system, or equipment that is temporarily out of service.

Log and Summary of Occupational Injuries and Illnesses (OSHA Form 300)—A cumulative record that employers (generally of more than 10 employees) are required to maintain, showing essential facts of all reportable occupational injuries and illnesses.

Loss—The degradation of a system or component. Loss is best understood when related to dollars lost. Examples include death or injury to a worker, destruction or impairment of facilities or machines, destruction or spoiling of raw materials, and creation of delay. In the insurance business, loss connotes dollar loss, and some underwriters have been known to write it as LO$$ to make that point.

Lower explosive limit (LEL)—The minimum concentration of a flammable gas in air required for ignition in the presence of an ignition source; listed as a percent by volume in air.

Makeup air—Clean, tempered outdoor air supplied to a workplace to replace air removed by exhaust ventilation.

Malignant—As applied to a tumor, condition of being cancerous and capable of undergoing metastasis or invasion of surrounding tissue.

Material Safety Data Sheet (MSDS)—Chemical information sheets provided by the chemical manufacturer that include such information as chemical and physical characteristics; long- and short-term health hazards; spill control procedures; personal protective equipment (PPE) to be used when handling the chemical; reactivity with other chemicals; incompatibility with other chemicals; and manufacturer's name, address, and phone number. Employee access to and understanding of MSDSs are important parts of the HazCom program.

Medical monitoring—The initial medical exam of a worker, followed by periodic exams. The purpose of medical monitoring is to assess workers' health, determine their fitness to wear personal protective equipment, and maintain records of their health.

Mesothelioma—Cancer of the membranes that line the chest and abdomen; almost exclusively associated with asbestos exposure.

Metabolic heat—Produced within a body as a result of activity that burns energy.

Metastasis—Transfer of the causal agent (cell or microorganisms) of a disease from a primary focus to a distant one through the blood or lymphatic vessels. Also, spread of malignancy from site of primary cancer to secondary sites.

Meter—A metric unit of length equal to about 39 inches.

Micron (micrometer, m)—A unit of length equal to 1 millionth of a meter; approximately 1/25,000 of an inch.

Milligram (mg)—A unit of weight in the metric system; 1000 milligrams equals 1 gram.

Milligrams per cubic meter (mg/m^3)—Unit used to measure air concentrations of dusts, gases, mists, and fumes.

Milliliter (mL)—A metric unit used to measure volume; 1 milliliter equals 1 cubic centimeter.

Millimeter or mercury (mmHg)—Unit of pressure equal to the pressure exerted by a column of liquid mercury 1 millimeter high at a standard temperature.

Mists—Minute liquid droplets suspended in air.

Molds—The most typical forms of fungus found on earth, comprising approximately 25% of the Earth's biomass (McNeel and Kreutzer, 1996).

Monitoring—Periodic or continuous surveillance or testing to determine the level of compliance with statutory requirements and/or pollutant levels in various media or in humans, animals, or other living things.

Mucous membranes—Lining of the hollow organs of the body, notably the nose, mouth, stomach, intestines, bronchial tubes, and urinary tract.

Mutagen—A substance or material that causes change in the genetic material of a cell.

Mycotoxins—Some molds are able to produce mycotoxins, natural organic compounds that are capable of initiating a toxic response in vertebrates (McNeel and Kreutzer, 1996).

NFPA—National Fire Protection Association, a voluntary membership organization whose aim is to promote and improve fire protection and prevention. The NFPA publishes 16 volumes of codes known as the National Fire Codes.

NIOSH—National Institute for Occupational Safety and Health, a federal agency that conducts research on health and safety concerns, tests and certifies respirators, and trains occupational health and safety professionals.

Non-ionizing radiation—Radiation on the electromagnet spectrum that has a frequency of 10^{15} or less and a wavelength in meters of 3×10^{-7}.

NTP—National Toxicology Program, which publishes an annual report on carcinogens.

Nuisance dusts—Dusts that have a long history of little adverse effect on the lungs and do not produce significant organic disease or toxic effect when exposures are kept under reasonable control.

Occupational Safety and Health Act (OSH Act)—A federal law passed in 1970 to ensure, as far as possible, that every working man and woman in the nation has safe and healthful working conditions. To achieve this goal, the Act authorizes several functions, such as encouraging safety and health programs in the workplace and encouraging labor-management cooperation in health and safety issues.

OSHA Form 300—Log and Summary of Occupational Injuries and Illnesses; formerly OSHA Form 200.

Oxidation—When a substance either gains oxygen or loses hydrogen or electrons in a chemical reaction; a chemical treatment method.

Oxidizer—Also known as an oxidizing agent, a substance that oxidizes another substance. Oxidizers are a category of hazardous materials that may assist in the production of fire by readily yielding oxygen.

Oxygen-deficient atmospheres—The legal definition of an atmosphere where the oxygen concentration is less than 19.5% by volume of air.

Oxygen-enriched atmosphere—An atmosphere containing more than 23.5% oxygen by volume.

Particulate matter—Substances (such as diesel soot and combustion products resulting from the burning of wood) released directly into the air; any minute, separate particle of liquid or solid material.

Performance standards—OSHA regulation standards that list the ultimate goal of compliance but do not explain exactly how compliance is to be accomplished. Compliance is usually based on accomplishing the act or process in the safest manner possible, based on experience (past performance).

Permissible exposure limit (PEL)—The time-weighted average concentration of an airborne contaminant that a healthy worker may be exposed to 8-hours per day or 40-hours per week without suffering any adverse health effects. Established by legal means and enforceable by OSHA.

Personal protective equipment (PPE)—Any material or device worn to protect a worker from exposure to or contact with any harmful substance or force.

pH—Expresses the degree of acidity or alkalinity of a solution, with neutrality indicated as 7.

Pitot tube—Device used for measuring static pressure within ventilation ducts.

Polymerization—A chemical reaction in which two or more small molecules (monomers) combine to form larger molecules (polymers) that contain repeating structural units of the original molecules. A hazardous polymerization is the above reaction with an uncontrolled release of energy.

ppm—Parts of vapor, gas, or other contaminants per million parts of air by volume; used to measure air concentrations of vapors and gases.

Precision—The degree of exactness of repeated measurements.

Preliminary assessment—A quick analysis to determine how serious the situation is and to identify all potentially responsible parties. The preliminary assessment relies upon readily available information, including forms, records, aerial photographs, and personnel interviews.

Pressure—The force exerted against an opposing fluid or thrust, distributed over a surface.

psi—Pounds per square inch, a measure of the pressure a material exerts on the walls of a confining vessel or enclosure. For technical accuracy, pressure must be expressed as psig (pounds per square inch gauge) or psia (pounds per square absolute, equal to gauge pressure plus sea level atmospheric pressure or psig plus approximately 14.7 pounds per square inch).

Radiant heat—The result of electromagnetic non-ionizing energy that is transmitted through space without the movement of matter within that space.

Radiation—Energetic nuclear particles, including alpha rays, beta rays, gamma rays, neutrons, high-speed electrons, and high-speed protons.

Raynaud's syndrome—An abnormal constriction of blood vessels in the fingers when exposed to cold temperatures; caused by vibrating hand tools.

RCRA—Resource Conservation and Recovery Act of 1976.

Reactivity (chemical)—A substance that reacts violently by catching on fire, exploding, or giving off fumes when exposed to water, air, or low heat.

Reactivity hazard—The ability of a material to release energy when in contact with water. Also, the tendency of a material, when in its pure state or as a commercially produced product, to vigorously polymerize, decompose, condense, or otherwise self-react and undergo violent chemical change.

Reportable quantity (RQ)—The minimum amount of a hazardous material that, if spilled while in transport, must be reported immediately to the National Response Center. Minimum reportable quantities range from 1 pound to 5000 pounds per 24-hour day.

Respirable size particulates—Particulates in a size range that permits them to penetrate deep into the lungs upon inhalation.

Respirator (approved)—A device that has met the requirements of 30 CFR Part 11 and is designed to protect the wearer from inhalation of harmful atmospheres and has been approved by the National Institute for Occupational Safety and Health (NIOSH) and the Mine Safety and Health Administration (MSHA).

Respiratory system—Consists of (in descending order) the nose, mouth, nasal passages, nasal pharynx, pharynx, larynx, trachea, bronchi, bronchioles, air sacs (alveoli) of the lungs, and muscles of respiration.

Risk—The combination of the expected frequency (event/year) and consequence (effects/event) of a single accident or a group of accidents; the result of a loss-probability occurrence and the acceptability of that loss.

Risk assessment—A process that uses scientific principles to determine the level of risk that actually exists in a contaminated area.

Risk characterization—The final step in the risk assessment process, it involves determining a numerical risk factor. This step ensures that exposed populations are not at significant risk.

Risk management—The professional assessment of all loss potentials in an organization's structure and operations, leading to the establishment and administration of a comprehensive loss control program.

Rotameters—A small tapered tube with a solid ball (float) inside used to measure the flow rate of air sampling equipment.

Safety—A general term denoting an acceptable level of risk or relative freedom from and low probability of harm.

Safety factor—Based on experimental data, the amount added (e.g., 1000-fold) to ensure worker health and safety.

Safety standard—A set of criteria specifically designed to define a safe product, practice, mechanism, arrangement, process, or environment; a standard produced by a body representative of all concerned interests and based on currently available scientific and empirical knowledge concerning the subject or scope of the standard.

SARA—Superfund Amendments and Reauthorization Act of 1986.

SCBA—Self-contained breathing apparatus.

Secondary containment—A method using two containment systems so that if the first is breached, the second will contain all of the fluid in the first. For USTs, secondary containment consists of either a double-walled tank or a liner system.

Sensitizers—Chemicals that in very low doses trigger an allergic response.

Short-term exposure limit (STEL)—The time-weighted average concentration to which workers can be exposed continuously for a short period of time (typically 15 minutes) without suffering irritation, chronic or irreversible tissue damage, or impairment for self-rescue.

Silica (SIO_2)—A major component of the Earth's crust and the cause of silicosis.

"Skin"—A notation (sometimes used with PEL or TLV exposure data) indicating that the stated substance may be absorbed by the skin, mucous membranes, and eyes—either airborne or by direct contact—and that this additional exposure must be considered part of the total exposure to avoid exceeding the PEL or TLV for that substance.

Solubility in water—A term expressing the percentage of a material (by weight) that will dissolve in water at ambient temperature. Solubility information can be useful in determining spill cleanup methods and re-extinguishing agents and methods for a material.

Solvent—A substance, usually a liquid, in which other substances are dissolved. The most common solvent is water.

Sorbent—(1) A material that removes toxic gases and vapors from air inhaled through a canister or cartridge. (2) Material used to collect gases and vapors during air sampling.

Specific gravity—The ratio of the density of a substance to water.

Stability—An expression of the ability of a material to remain unchanged. For MSDS purposes, a material is stable if it remains in the same form under expected and reasonable conditions of storage or use. Conditions that may cause instability are stated. Examples are temperatures above 150°F and shock from dropping.

Synergism—Cooperative action of substances whose total effect is greater than the sum of their separate effects.

Systemic—Refers to spreading throughout the body, affecting all body systems and organs; not localized in one spot or area.

Temporary threshold shift (TTS)—Temporary hearing loss due to noise exposure; may be partially or completely recovered when exposure ends.

Tendonitis—Inflammation of a tendon.

Tenosynovitis—Inflammation of the connective tissue sheath of a tendon.

Threshold—The lowest dose or exposure to a chemical at which a specific effect is observed.

Threshold limit value (TLV)—The same concept as PEL, except that TLVs do not have the force of governmental regulations behind them but are based on recommended limits established and promoted by the American Conference of Governmental Industrial Hygienists.

Time-weighted average (TWA)—A mathematical average of exposure concentration over a specific time: Exposure (ppm) × Time (hours) × 1/4 Time (hours).

Total quality management (TQM)—A way of managing a company that entails a total and willing commitment of all personnel at all levels to quality.

Toxicity—The relative property of a chemical agent with reference to a harmful effect on some biologic mechanism and the condition under which this effect occurs. The quality of being poisonous.

Toxicology—The study of poisons, which are substances that can cause harmful effects to living things.

Toxin—A poison.

Unsafe condition—Any physical state that deviates from that which is acceptable, normal, or correct in terms of past production or potential future production of personal injury and/or damage to property; any physical state that results in a reduction in the degree of safety normally present.

Upper explosive limit (UEL)—The maximum concentration of a flammable gas in air required for ignition in the presence of an ignition source.

Vapor—Gaseous form of substances that are normally solid or liquid at room temperature and pressure. A vapor can be changed back to the solid or liquid state by either increasing the pressure or decreasing the temperature alone. Vapors also diffuse. Evaporation is the process by which a liquid is changed into the vapor state and mixed with the surrounding air. Solvents with low boiling points will volatize readily. Examples include benzene, methyl alcohol, mercury, and toluene.

Vapor pressure—Pressure (measured in pounds per square inch absolute, psia) exerted by a vapor. If a vapor is kept in confinement over its liquid so that the vapor can accumulate above the liquid (the temperature being held constant), the vapor pressure approaches a fixed limit called the maximum (or saturated) vapor pressure, dependent only on the temperature and the liquid.

Velometer—Device used in ventilation to measure air velocity.

Viscosity—The property of a fluid that resists internal flow by releasing counteracting forces.

Volatility—The tendency or ability of a liquid to vaporize. Such liquids (e.g., alcohol, gasoline), because of their well-known tendency to evaporate rapidly, are called volatile liquids.

Vulnerability assessment—A very regulated, controlled, cooperative, and documented evaluation of an organization's security posture from outside in and inside out for the purpose of defining or greatly enhancing security policy.

Water column—A unit used in measuring pressure.

Wet-bulb globe thermometer—Temperature as determined by the wet-bulb thermometer or a standard sling psychrometer or its equivalent. It is influenced by the evaporation rate of water which, in turn, depends on relative air humidity. A wet-bulb thermometer consists of a bulb covered with a cloth saturated with water.

Workers' compensation—A system of insurance required by state law and financed by employers that provides payments to employees and their families for occupational illnesses, injuries, or fatalities incurred while at work and resulting in loss of wage income, usually regardless of the employer's or employee's negligence.

Zero energy state—The state of equipment in which every power source that can produce movement of a part of the equipment, or the release of energy, has been rendered inactive.

Zoonoses—Diseases communicable from animals to humans under natural conditions.

HISTORY OF INDUSTRIAL HYGIENE

There has been an awareness of industrial hygiene since antiquity (OSHA, 1998). The relationship between the environment and worker health was recognized as early as the fourth century BC when Hippocrates noted lead toxicity in the mining industry. In the first century AD, Pliny the Elder, a Roman scholar, perceived health risks among those working with zinc and sulfur. He devised a face mask made from an animal bladder to protect workers from exposure to dust and lead fumes. In the second century AD, the Greek physician Galen accurately described the pathology of lead poisoning and also recognized the hazardous exposures of copper miners to acid mists.

In the Middle Ages, guilds assisted sick workers and their families. In 1556, the German scholar Agricola advanced the science of industrial hygiene even further when, in his book *De Re Metallica* (*On the Nature of Metals*), he described diseases of miners and prescribed preventive measures. The book included suggestions for mine ventilation and worker protection, discussed mining accidents, and described diseases associated with mining occupations such as silicosis. Industrial hygiene gained further respectability in 1700 in Italy when Bernardo Ramazzini, known as the "father of industrial medicine," published the first comprehensive book on industrial medicine, *De Morbis Artificum Diatriba* (*The Diseases of Workmen*). The book contained accurate descriptions of the occupational diseases of most of the workers of his time. Ramazzini greatly affected the future of industrial hygiene because he asserted that occupational diseases should be studied in the work environment rather than in hospital wards. Industrial hygiene received another major boost in 1743 when Ulrich Ellenborg published a pamphlet on occupational diseases and injuries among gold miners. Ellenborg also wrote about the toxicity of carbon monoxide, mercury, lead, and nitric acid.

In England in the 18th century, Percival Pott, as a result of his findings on the insidious effects of soot on chimney sweepers, was a major force in getting the British Parliament to pass the Chimney-Sweepers Act of 1788. The passage of the English Factory Acts beginning in 1833 marked the first effective legislative acts in the field of industrial safety. These acts, however, were intended to provide compensation for accidents rather than to control their causes. Later, various other European nations developed workers' compensation acts, which stimulated the adoption of increased factory safety precautions and the establishment of medical services within industrial plants.

In the early 20th century in the United States, Dr. Alice Hamilton led efforts to improve industrial hygiene. She observed industrial conditions first hand and startled mine owners, factory managers, and state officials with evidence that there was a correlation between worker illness and their exposure to toxins. She also presented definitive proposals for eliminating unhealthful working conditions. At about the same time, U.S. federal and state agencies began investigating health conditions in industry. In 1908, the public's awareness of occupationally related diseases stimulated the passage of compensation acts for certain civil employees. States passed the first workers' compensation laws in 1911, and in 1913 the New York Department of Labor and the Ohio Department of Health established the first state industrial hygiene programs. All states enacted such legislation by 1948. In most states, there is some compensation coverage for workers contracting occupational disease.

The U.S. Congress has passed three landmark pieces of legislation relevant to safeguarding workers' health: (1) Metal and Nonmetallic Mines Safety Act of 1966, (2) Federal Coal Mine Safety and Health Act of 1969, and (3) Occupational Safety and Health Act of 1970. Today, nearly every employer is required to implement the elements of an industrial hygiene and safety, occupational health, or hazard communication program and to be responsive to the Occupational Safety and Health Administration (OSHA) and the act and its regulations.

OSHA, NIOSH, AND INDUSTRIAL HYGIENE

The principal piece of federal legislation relating to industrial hygiene is the Occupational Safety and Health Act of 1970 (OSH Act) as amended. Under the OSH Act, the Occupational Safety and Health Administration develops and sets mandatory occupational safety and health requirements applicable to the more than 6 million workplaces in the United States. OSHA relies on, among other personnel, industrial hygienists to evaluate jobs for potential health hazards. Developing and setting mandatory occupational safety and health standards involves determining the extent of employee exposure to hazards and deciding what is needed to control these hazards, thereby protecting the workers. Industrial hygienists are trained to anticipate, recognize, evaluate, and recommend controls for environmental and physical hazards that can affect the health and well-being of workers. More than 40% of the OSHA compliance officers who inspect America's workplaces are industrial hygienists. Industrial hygienists also play a major role in developing and issuing OSHA standards to protect workers from health hazards associated with toxic chemicals, biological hazards, and harmful physical agents. They also provide technical assistance and support to the agency's national and regional offices. OSHA also employs industrial hygienists who assist in setting up field enforcement procedures and who issue technical interpretations of OSHA regulations and standards. Industrial hygienists analyze, identify, and measure workplace hazards or stressors that can cause sickness, impaired health, or significant discomfort in workers through chemical, physical, ergonomic, or biological exposures. Two roles of the OSHA industrial hygienist are to spot those conditions and help eliminate or control them through appropriate measures (OSHA, 1998).

The OSH Act sets forth the following requirements relating to industrial hygiene (Goetsch, 1996):

- Use of warning labels and other means to make employees aware of potential hazards, symptoms of exposure, precautions, and emergency treatment
- Prescription of appropriate personal protective equipment and other technological preventive measures (29 CFR Subpart I, 1910.133 and 1910.134)
- Provision of medical tests to determine the effect on employees of exposure to environmental stressors
- Maintenance of accurate records of employee exposures to environmental stressors that are required to be measured or monitored
- Making monitoring tests and measurement activities open to the observation of employees
- Making records of monitoring tests and measurement activities available to employees on request
- Notification of employees who have been exposed to environmental stressors at a level beyond the recommended threshold and corrective action begin taken

Effective management of worker safety and health protection is a decisive factor in reducing the extent and severity of work-related injuries and illnesses and their related costs. To assist employers and employees in developing effective safety and health program, OSHA published recommended safety and health program management guidelines (OSHA, 1989). These voluntary guidelines apply to all places of employment covered by OSHA. The guidelines identify four general elements that are critical to the development of a successful safety and health management program:

- Management commitment and employee involvement
- Worksite analysis
- Hazard prevention and control
- Safety and health training

The National Institute for Occupational Safety and Health (NIOSH) is part of the Department of Health and Human Services (HHS). This agency is important to industrial hygiene professionals. The main focus of the agency's research is on toxicity levels and human tolerance levels of hazardous substances. NIOSH prepares recommendations for OSHA standards dealing with hazardous substances, and NIOSH studies are made available to employers.

INDUSTRIAL HYGIENE AND WORKPLACE STRESSORS

The industrial hygienist focuses on evaluating the healthfulness of the workplace environment, either for short periods or for a work-life of exposure. When required, industrial hygienists recommend corrective procedures to protect health based on solid quantitative data, experience, and knowledge. The control measures they often recommend include isolation of a work process, substitution of a less harmful chemical or material, or other measures designed solely to increase the healthfulness of the work environment.

To ensure a healthy workplace environment and associated environs, industrial hygienists focus on the recognition, evaluation, and control of chemical, physical, or biological and ergonomic stressors that can cause sickness, impaired health, or significant discomfort to workers. The key word here is *stressors*, or simply, *stress*—that is, stress caused by the workplace external environment demands placed on a worker. Increases in external stressors beyond workers' tolerance levels affect their on-the-job performance and overall health. Industrial hygienists must understand that not only do workplace stressors exist but they are also sometimes cumulative. For example, studies have shown that some assembly line processes are little affected by neither low illumination nor vibration; however, when these two stressors are combined, assembly-line performance deteriorates. Other cases have shown just the opposite effect. For example, the worker who has had little sleep and then is exposed to a work area where noise levels are high actually benefits (to a degree, depending on the intensity of the noise level and the worker's exhaustion level) from increased arousal level; a lack of sleep combined with a high noise level is compensatory.

In order to recognize environmental stressors and other factors that influence worker health, industrial hygienists must be familiar with work operations and processes. An essential part of a new industrial hygienist's employee orientation process should be an overview of all pertinent company work operations and processes. Obviously, a newly hired industrial hygienist who has not been fully indoctrinated on company work operations and processes is not qualified to study the environmental effects of such processes and suffers from another disability—a lack of credibility with supervisors and workers. This point cannot be emphasized strongly enough. Know your organization and what it is all about.

What are the workplace and general environmental stressors that industrial hygienists, safety professionals, and environmental professionals should be concerned with? The stressors of concern should be those that are likely to accelerate the aging process; they can cause significant discomfort and inefficiency, as well as chronic illness, or they may be immediately dangerous to life or health (Spellman, 1998). Stressors can fall into these categories:

- *Chemical stressors*—Gases, dusts, fumes, mists, liquids, or vapors
- *Physical stressors*—Noise, vibration, extremes of pressure and temperature, and electromagnetic and ionizing radiation
- *Biological stressors*—Bacteria, fungi, molds, yeasts, insects, mites, and viruses
- *Ergonomic stressors*—Repetitive motion, work pressure, fatigue, body position in relation to work activity, monotony/boredom, and worry

These health stressors are listed by OSHA as major job risks. Each is explained further in the following discussion (OSHA, 1998).

CHEMICAL STRESSORS

Chemical stressors are harmful chemical compounds in the form of solids, liquids, gases, mists, dusts, fumes, and vapors that exert toxic effects by inhalation (breathing), absorption (direct contact with the skin), or ingestion (eating or drinking). Airborne chemical hazards exist as concentrations of mists, vapors, gases, fumes, or solids. Some are toxic through inhalation and some of them irritate the skin on contact; some can be toxic by absorption through the skin or through ingestion, and some are corrosive to living tissue. The degree of individual risk from exposure to any given substance depends on the nature and potency of the toxic effects and the magnitude and duration of exposure.

Information on the risk to workers from chemical hazards can be obtained from the Material Safety Data Sheet (MSDS) that OSHA's Hazard Communication Standard requires be supplied by the manufacturer or importer to the purchaser of all hazardous materials. The MSDS is a summary of the important health, safety, and toxicological information for the chemical or the mixture's ingredients. Other provisions of the Hazard Communication Standard require that all containers of hazardous substances in the workplace have appropriate warning and identification labels.

PHYSICAL STRESSORS

Physical stressors include excessive levels of ionizing and non-ionizing electromagnetic radiation, noise, vibration, illumination, and temperature. In occupations where there is exposure to *ionizing* radiation, factors such as time, distance, and shielding are important tools for ensuring worker safety. Danger from radiation increases with the amount of time one is exposed to it; hence, the shorter the time of exposure the smaller the radiation danger. Distance also is a valuable tool in controlling exposure to both ionizing and non-ionizing radiation. Radiation levels from some sources can be estimated by comparing the squares of the distances between the work and the source. For example, at a reference point of 10 feet from a source, the radiation is 1/100 of the intensity at 1 foot from the source. Shielding also is a way to protect against radiation. The greater the protective mass between a radioactive source and the worker, the lower the radiation exposure. Non-ionizing radiation is also dealt with by shielding workers from the source. Sometimes limiting exposure times to non-ionizing radiation or increasing the distance is not effective. Laser radiation, for example, cannot be controlled effectively by imposing time limits. An exposure faster than the blink of an eye can be hazardous. Increasing the distance from a laser source may require miles before the energy level reaches a point where the exposure would not be harmful.

Noise, another significant physical hazard, can be controlled by various measures. Noise can be reduced by installing equipment and systems that have been engineered, designed, and built to operate quietly; by enclosing or shielding noisy equipment; by making certain that equipment is in good repair and properly maintained with all worn or unbalanced parts replaced; by mounting noisy equipment on special mounts to reduce vibration; and by installing silencers, mufflers, or baffles. Substituting quiet work methods for noisy ones is another significant way to reduce noise—for example, by welding parts rather than riveting them. Also, treating floors, ceilings, and walls with acoustical material can reduce reflected or reverberant noise. In addition, erecting sound barriers at adjacent work stations around noisy operations will reduce worker exposure to noise generated at adjacent work stations.

It is also possible to reduce noise exposure by increasing the distance between the source and the receiver by isolating workers in acoustical booths, limiting workers' exposure time to noise, and by providing hearing protection. OSHA requires that workers in noisy surroundings be periodically tested as a precaution against hearing loss. Another physical hazard is radiant heat exposure in factories such as steel mills. Radiant heat can be controlled by installing reflective shields and by providing protective clothing.

BIOLOGICAL STRESSORS

Biological stressors include bacteria, viruses, fungi, and other living organisms that can cause acute and chronic infections by entering the body either directly or through breaks in the skin. Occupations that deal with plants or animals or their products or with food and food processing may expose workers to biological hazards. Laboratory and medical personnel also can be exposed to biological hazards. Any occupations that result in contact with bodily fluids pose a risk to workers from biological hazards. In occupations where animals are involved, biological hazards are dealt with by preventing and controlling diseases in the animal population as well as proper care and handling of infected animals. Also, effective personal hygiene, particularly proper attention to minor cuts and scratches, especially those on the hands and forearms, helps keep worker risks to a minimum. In occupations where there is potential exposure to biological hazards, workers should practice proper personal hygiene, particularly hand washing. Hospitals should provide proper ventilation, proper personal protective equipment such as gloves and respirators, adequate infectious waste disposal systems, and appropriate controls including isolation in instances of particularly contagious diseases such as tuberculosis.

ERGONOMIC STRESSORS

The science of ergonomics studies and evaluates a full range of tasks including, but not limited to, lifting, holding, pushing, walking, and reaching. Many ergonomic problems result from technological changes such as increased assembly line speeds, adding specialized tasks, and increased repetition; some problems arise from poorly designed job tasks. Any of those conditions can cause ergonomic hazards such as excessive vibration and noise, eye strain, repetitive motion, and heavy lifting problems. Improperly designed tools or work areas also can be ergonomic hazards. Repetitive motions or repeated shocks over prolonged periods of time as in jobs involving sorting, assembling, and data entry can often cause irritation and inflammation of the tendon sheath of the hands and arms, a condition known as carpal tunnel syndrome.

Ergonomic hazards are avoided primarily by the effective design of a job or jobsite and better designed tools or equipment that meet workers' needs in terms of physical environment and job tasks. Through thorough worksite analyses, employers can set up procedures to correct or control ergonomic hazards by using the appropriate engineering controls (e.g., designing or redesigning work stations, lighting, tools, and equipment); teaching correct work practices (e.g., proper lifting methods); employing proper administrative controls (e.g., shifting workers among several different tasks, reducing production demand, increasing rest breaks); and, if necessary, providing and mandating personal protective equipment. Evaluating working conditions from an ergonomics standpoint involves looking at the total physiological and psychological demands of the job on the worker.

Overall, environmental health professionals point out that the benefits of a well-designed, ergonomic work environment can include increased efficiency, fewer accidents, lower operating costs, and more effective use of personnel. In the workplace, the industrial hygienist should review the following to anticipate potential health stressors:

- Raw materials
- Support materials
- Chemical reactions
- Chemical interactions
- Products
- Byproducts
- Waste products
- Equipment
- Operating procedures

INDUSTRIAL HYGIENE: AREAS OF CONCERN

From the list of health stressors above, it can be seen that industrial hygienists have many areas of concern related to protecting the health of workers on the job. This section focuses on the major concerns of industrial hygienists in the workplace and discusses the important areas of industrial toxicology and industrial health hazards. The text then covers industrial noise, vibration, and environmental control. All of these areas are important to industrial hygienists (and to workers, of course), but they are not all inclusive, as industrial hygienists are also concerned with such other issues as ionizing and non-ionizing radiation, among many others.

INDUSTRIAL TOXICOLOGY

The practice of industrial toxicology (especially in the area of industrial poisons) owes its genesis in the United States to the work of Alice Hamilton (1869–1970). In 1919, Hamilton became the first woman to be appointed to the staff at the Harvard Medical School. She did studies on industrial pollution for the federal government and the United Nations and also wrote several books, including *Industrial Poisons in the United States* (1925), *Industrial Toxicology* (1934), and *Exploring the Dangerous Trades* (1943). Currently, we have witnessed unprecedented industrialization, explosive population growth, and a massive introduction of new chemical agents into the workplace. Unfortunately, we lag far behind in our understanding of the impact that many of these new chemicals, particularly mixtures, have on the health or workers and other members of our ecosystem.

Industrial hygienists must be well versed and knowledgeable in toxicology; they must be students and practitioners who continually study the nature and effects of poison and their treatment in the workplace. Thus, the importance of the industrial hygienist possessing a full understanding of industrial toxicology cannot be overstated. Normally, we give little thought to the materials that we are exposed to on a daily, almost constant basis unless they interfere with our lifestyles, irritate us, or noticeably physically affect us. Keep in mind, however, that all chemical substances have the potential for being injurious at some sufficiently high concentration and level of exposure. Industrial hygienists understand this and must apply their knowledge of general toxicology to preventing lethal effects of over-exposure for workers.

What Is Toxicology?

Toxicology is a very broad, interdisciplinary science that studies the adverse effects of chemicals on living organisms, using knowledge and research methods drawn from virtually all areas of the biomedical sciences. It deals with chemicals used in industry, drugs, food, and cosmetics, as well as those occurring naturally in the environment. Toxicology is the science that deals with the poisonous or toxic properties of substances. The primary objective of industrial toxicology is the prevention of adverse health effects in workers exposed to chemicals in the workplace. The industrial hygienist's responsibility is to consider all types of exposure and the subsequent effects on workers. Following the prescribed precautionary measures and limitations placed on exposure to certain chemical substances by industrial toxicologists is the worker's responsibility. Industrial hygienists uses toxicity information to prescribe safety measures for protecting workers.

To gain a better appreciation for what industrial toxicology is all about, it is necessary to understand some basic terms, many of which are concerned with determining the degree of hazard particular chemicals present. It is important to differentiate between *toxicity* and *hazard*. Toxicity is the intrinsic ability of a substance to produce an unwanted effect on humans and other living organisms when the chemical has reached a sufficient concentration at a certain site in the body. Hazard is the probability that a substance will produce harm under specific conditions. Industrial hygienists and other safety professionals employ the opposite of hazard—*safety*, the probability that harm will not occur under specific conditions. A toxic chemical used under safe conditions may not be hazardous.

Basically, all toxicological considerations are based on the *dose–response relationship*, another toxicological concept important to industrial hygienists. In its simplest terms, the dose of a chemical to the body resulting from exposure is directly related to the degree of harm. This relationship means that the toxicologist is able to determine a *threshold level* of exposure for a given chemical—the highest amount of a chemical substance to which one can be exposed with no resulting adverse health effect. Stated differently, chemicals present a threshold of effect, or a no-effect level.

Threshold levels are critically important parameters. For example, under the OSH Act, threshold limits have been established for the air contaminants most frequently found in the workplace. The contaminants are listed in three tables in 29 CFR 1910 subpart Z—Toxic and Hazardous Substances. The threshold limit values listed in these tables are drawn from values published by the American Conference of Governmental Industrial Hygienists (ACGIH) and from the Standards of Acceptable Concentrations of Toxic Dusts and Gases issued by the American National Standards Institute (ANSI).

An important and necessary consideration when determining levels of safety for exposure to contaminants is their effect over a period of time. For example, during an 8-hour work shift, a worker may be exposed to a concentration of substance A (with a 10-ppm time-weighted average [TWA], 25-ppm ceiling, and 50-ppm peak) above 25 ppm (but never above 50 ppm) only for a maximum period of 10 minutes. Such exposure must be compensated by exposures to concentrations less than 10 ppm, so that the cumulative exposure for the entire 8-hour work shift does not exceed a weighted average of 10 ppm. Formulas are provided in the regulations for computing the cumulative effects of exposures in such instances. Note that the computed cumulative exposure to a contaminant may not exceed the limit value specified for it.

AIRBORNE CONTAMINANTS

One of the primary categories of industrial health hazards that the industrial hygienist must deal with is airborne contaminants. Air contaminants are commonly classified as either particulate or gas and vapor contaminants. The most common particulate contaminants include dusts, fumes, mists, aerosols, and fibers. *Dusts* are solid particles that are formed or generated from solid organic or inorganic materials by reducing their size through mechanical processes such as crushing, grinding, drilling, abrading, or blasting. Industrial atmospheric contaminants exist in virtually every workplace. Sometimes they are readily apparent to workers, because of their odor, or because they can actually be seen. Industrial hygienists, however, cannot rely on odor or vision to detect or measure airborne contaminants. They must rely on measurements taken by monitoring, sampling, or detection devices.

Fumes are formed when material from a volatilized solid condenses in cool air. In most cases, the solid particles resulting from the condensation react with air to form an oxide. The term *mist* is applied to a finely divided liquid suspended in the atmosphere. Mists are generated by liquids condensing from a vapor back to a liquid or by breaking up a liquid into a dispersed state such as by splashing, foaming, or atomizing. *Aerosols* are also a form of a mist characterized by highly respirable, minute liquid particles. *Fibers* are solid particles whose length is several times greater than their diameter.

Gases are formless fluids that expand to occupy the space or enclosure in which they are confined. Examples are welding gases such as acetylene, nitrogen, helium, and argon, as well as carbon monoxide generated from the operation of internal combustion engines or by its use as a reducing gas in a heat treating operation. Another example is hydrogen sulfide, which is formed wherever there is decomposition of materials containing sulfur under reducing conditions.

Liquids change into vapors and mix with the surrounding atmosphere through evaporation. *Vapors* are the volatile form of substances that are normally in a solid or liquid state at room temperature and pressure. Vapors are the gaseous form of substances that are normally in the solid or liquid state at room temperature and pressure. They are formed by evaporation from a liquid or solid and can be found where parts cleaning and painting take place and where solvents are used.

Although air contaminant values are useful as a guide for determining conditions that may be hazardous and may demand improved control measures, industrial hygienists must recognize that the susceptibility of workers varies. Even though it is essential not to permit exposures to exceed the stated values for substances, note that even careful adherence to the suggested values for any substance will not ensure an absolutely harmless exposure. Thus, the air contaminant concentration values should only serve as a tool for indicating harmful exposures, rather than the absolute reference on which to base control measures.

ROUTES OF ENTRY

For a chemical substance to cause or produce a harmful effect, it must reach the appropriate site in the body (usually via the bloodstream) at a concentration (and for a length of time) sufficient to produce an adverse effect. Toxic injury can occur at the first point of contact between the toxicant and the body or in later, systemic injuries to various organs deep in the body. Common routes of entry are ingestion, injection, skin absorption, and inhalation; however, entry into the body can occur by

TABLE 11.1
Selected Toxic Contaminants and Target Organs They Endanger

Target Organ	Toxic Contaminants
Blood	Benzene, carbon monoxide, arsenic, aniline, toluene
Kidneys	Mercury, chloroform
Heart	Aniline
Brain	Lead, mercury, benzene, manganese, acetaldehyde
Eyes	Cresol, acrolein, benzyl chloride, butyl alcohol
Skin	Nickel, phenol, trichloroethylene
Lungs	Asbestos, chromium, hydrogen sulfide, mica, nitrogen dioxide
Liver	Chloroform, carbon tetrachloride, toluene

Source: Spellman, F.R., *Surviving an OSHA Audit*, CRC Press, Boca Raton, FL, 1998.

more than one route (e.g., inhalation of a substance that can be absorbed through the skin). *Ingestion* of toxic substances is not a common problem in industry, as most workers do not deliberately swallow substances they handle in the workplace. Ingestion does sometimes occur either directly or indirectly. Industrial exposure to harmful substances through ingestion may occur when workers eat lunch, drink coffee, chew tobacco, apply cosmetics, or smoke in a contaminated work area. The substances may exert their toxic effect on the intestinal tract or at specific organ sites.

Injection of toxic substances may occur just about anywhere in the body where a needle can be inserted but is a rare event in the industrial workplace. *Skin absorption* or contact is an important route of entry in terms of occupational exposure. Although the skin (the largest organ in the human body) may act as a barrier to some harmful agents, other materials may irritate or sensitize the skin and eyes or travel through the skin into the bloodstream, thereby impacting specific organs. *Inhalation* is the most common route of entry for harmful substances in industrial exposures. Nearly all substances that are airborne can be inhaled. Dusts, fumes, mists, gases, vapors, and other airborne substances may enter the body via the lungs and may produce local effects on the lungs, or they may be transported by the blood to specific organs in the body. Upon finding a route of entry into the body, chemicals and other substances may exert their harmful effects on specific organs of the body, such as the lungs, liver, kidneys, central nervous system, and skin. These specific organs are termed *target organs* and will vary with the chemical of concern (see Table 11.1).

The toxic action of a substance can be divided into short-term (acute) and long-term (chronic) effects. Short-term adverse effects are usually related to an accident where exposure symptoms may occur within a short time period following either a single exposure or multiple exposures to a chemical. Long-term adverse effects usually occur slowly after a long period of time, following exposures to small quantities of a substance (just as lung disease may follow cigarette smoking). Chronic effects may sometimes occur following short-term exposures to certain substances.

INDUSTRIAL HEALTH HAZARDS

The current edition of the NIOSH *Occupational Health Guidelines for Chemical Hazards* (http://www.cdc.gov/niosh/docs/81-123/) summarizes information on permissible exposure limits, chemical and physical properties, and health hazards. It provides recommendations for medical surveillance, respiratory protection, and personal protection and sanitation practices for specific chemicals subject to federal occupational safety and health regulations. These recommendations reflect good industrial hygiene practices, and their implementation can assist in the development and maintenance of an effective occupational health program. Practicing industrial hygienists should maintain a current copy of this important and useful document within easy reach.

Generally, determining whether or not a substance is hazardous is simple if the following is known: (1) what the agent is and what form it is in, (2) the concentration, and (3) the duration and form of exposure. It should be noted, however, that because of the dynamic character of the chemical and product industries practicing industrial hygienists may have to try to determine the uncertain toxicity of new chemical products that are frequently introduced into the workplace each year. Another related problem occurs when manufacturers develop chemical products with unfamiliar trade names and do not properly label them to indicate the chemical constituents of the compounds (which, under OSHA's Hazard Communication Program, 29 CFR 1910.1200, is illegal). Many commercially available instruments can detect and evaluate the concentration of many different contaminants. Some of these instruments are so simple that nearly any worker can learn to properly operate them; however, an untrained worker may receive an instrument reading that seems to indicate a higher degree of safety than may actually exist. Thus, the qualitative and quantitative measurement of atmospheric contaminants generally is the job of the industrial hygienist. Any samples taken should also be representative; that is, samples should be taken of the actual air the workers breathe, at the point where they inhale them, and in their breathing zone—between the top of the head and their shoulders.

Environmental Controls

Industrial hygienists recognize that engineering controls, work practice controls, administrative controls, and personal protective equipment (PPE) are the primary means of reducing employee exposure to occupational hazards. Workplace exposure to toxic materials and physical hazards can be reduced or controlled by a variety of these control methods, or by a combination of methods.

Engineering Controls

Engineering controls are methods of environmental control whereby the hazard is "engineered out," either by initial design specifications or by applying methods of substitution (e.g., replacing toxic chlorine used in disinfection processes with relatively nontoxic sodium hypochlorite). Engineering controls may entail utilization of isolation methods. For example, an operating diesel generator producing noise levels in excess of 120 decibels (120 dBA) could be controlled by enclosing it inside a soundproofed enclosure, effectively isolating the noise hazard. Another example of hazard isolation can be seen in the use of tightly closed enclosures that isolate an abrasive blasting operation. This method of isolation is typically used in conjunction with local exhaust ventilation. Ventilation is one of the most widely used and effective engineering controls (because it is so crucial in controlling workplace atmospheric hazards).

Work Practice Controls

Work practice controls alter the manner in which a task is performed. Some fundamental and easily implemented work practice controls include (1) following proper procedures that minimize exposures while operating production and control equipment, (2) inspecting and maintaining process and control equipment on a regular basis, (3) implementing good housekeeping procedures, (4) providing good supervision, and (5) mandating that eating, drinking, smoking, chewing tobacco or gum, and applying cosmetics in regulated areas be prohibited.

ADMINISTRATIVE CONTROLS

After the design, construction, and installation phase, installing engineering controls to control a workplace hazard or hazards often becomes difficult and expensive. A question industrial hygienists face on almost an ongoing basis is "If I can't engineer out the hazard, what can I do?" This question would not arise, of course, if the industrial hygienist had been invited to sit in and participate in the design, construction, and installation phases; however, based on experience, such participation is the exception to the rule. Being excluded is not good engineering practice but happens more often than not.

As a remedial action, as a third line of defense, after determining that engineering controls and work practice controls cannot be applied for technological, budgetary, or any other reasons, administrative controls might be the alternative. Administrative controls include controlling workers' exposure by scheduling production and workers' tasks, or both, in ways that minimize exposure levels. The employer might schedule operations with the highest exposure potential during periods when the fewest workers are present. For example, a worker who is required to work in an extremely high noise area where engineering controls and work practice controls are not possible would be rotated from the high noise area to a quiet area when the daily permissible noise exposure limit has been reached.

It should be noted that reducing exposures by limiting the duration of exposure, usually implemented by modifying the work schedule, must be carefully managed. Most managers soon find that juggling worker exposures and schedules requires a considerable amount of time, effort, and imagination. When practiced, reducing worker exposure is based on limiting the amount of time a worker is exposed, ensuring that OSHA permissible exposure limits (PELs) are not exceeded.

Because administrative controls are not easy to implement and manage, many practicing industrial hygienists do not particularity like the practice; furthermore, they feel that such a strategy merely spreads the exposure out and does nothing to control the source. Experience has shown that in many instances this view is correct; nevertheless, work schedule modifications are commonly used for exposures to such stressors as noise and lead.

Although mentioned under work practice controls, *good housekeeping practices* are also an administrative control. Think about it. If dust and spilled chemicals are allowed to accumulate in the work area, workers will be exposed to these substances. This is of particular importance for flammable and toxic materials (e.g., for the prevention of fires, explosions, poisoning). Housekeeping practices that prevent toxic or hazardous materials from being dispersed into the air are also essential.

Administrative controls implemented at work can also reach beyond the workplace. For example, if workers abate asbestos all day, they should wear only approved protective suits and other required personal protective equipment (PPE). After the work assignment is completed each day, the workers must be decontaminated following the standard protocol. Moreover, these workers should be prohibited from wearing personal clothing while removing asbestos. They should be required to decontaminate and remove their contaminated protective clothing and change into uncontaminated personal clothing before leaving the job site. The proper procedure is to leave any contaminated clothing at work and not to take it into the household where family members could be exposed. The bottom line is to leave asbestos (and any other contaminant) at the worksite.

Implementation of standardized *materials handling* or *transferring procedures* is another administrative control often used to protect workers. In the handling of chemicals, any transfer operations should be closed system (i.e., chemicals are directly transferred from the storage container to the application point) or should have adequate exhaust systems to prevent worker exposure to contamination of the workplace air. This practice should also include the use of spill trays to collect overfill spills or leaking materials between transfer points.

Administrative controls that involve visual inspection and automatic sensor services (leak detection programs) allow not only for quick detection but also for quick repair and minimal exposure. When automatic system sensors and alarms are deployed as administrative controls, tying the alarm system into an automatic shutdown system (e.g., close a valve, open an electrical circuit) allows the sensor to detect a leak, sound the alarm, and initiate corrective action (e.g., immediate shutdown of the system).

Two other administrative control practices are *training* and *personal hygiene*. For workers to best protect themselves from workplace hazards (to reduce the risk of injury or illness), they must be made aware of the hazards; they must be trained. OSHA puts great emphasis on the worker training requirement. This emphasis is well placed. No worker can be expected to know about every workplace process or equipment hazard unless he or she has been properly trained on the hazards or potential hazards. Thus, an important part of the training process is worker awareness. Legally (and morally) workers have the right to know what they are working with and what they are exposed to while on the job; they must be made aware of the hazards. They must also be trained on what actions to take when they are exposed to specific hazards.

Personal hygiene practices are an important part of worker protection. The industrial hygienist must ensure that appropriate cleaning agents and facilities such as soap, sinks, showers, and toilets are available to workers. In addition, such equipment as emergency eyewashes, deluge showers, and changing rooms must be made available and conveniently located for worker use.

PERSONAL PROTECTIVE EQUIPMENT

Personal protective equipment (PPE) is a worker's last line of defense against injury on the job. Industrial hygienists prefer to incorporate engineering, work practice, and administrative controls whenever possible; however, when the work environment cannot be made safe by any other method, PPE is used as the last resort. PPE imposes a barrier between the worker and the hazard but does nothing to reduce or eliminate the hazard. Typical PPE includes safety goggles, helmets, face shields, gloves, safety shoes, hearing protection devices, full-body protective clothing, barrier creams, and respirators (Olishifski, 1988). To be effective, PPE must be individually selected, properly fitted, and periodically refitted; it must be conscientiously and properly worn, regularly maintained, and replaced as necessary.

HAZARD COMMUNICATION

The Bhopal incident in India, the ensuing chemical spill, and the resulting tragic deaths and injuries are well known, but not all of the repercussions of this incident are as well known. After Bhopal a worldwide outcry arose. "How could such an incident occur? Why wasn't something done to protect the inhabitants? Weren't there safety measures taken or in place to prevent such a disaster from occurring?" In the United States, these questions and others were bandied around and about by the media and government, and Congress took the first major step toward preventing such incidents from occurring here by directing OSHA to take a close look at chemical manufacturing in the United States to see if such an incident could occur in this country. OSHA did a study and then reported to Congress that a Bhopal-type incident in the United States was very unlikely. Within a few months of OSHA's report to Congress, however, a chemical spill occurred in Institute, West Virginia, that was similar to Bhopal but fortunately not as deadly (no deaths but over 100 people became ill).

Needless to say, Congress was upset. Because of what happened in Bhopal and Institute, West Virginia, in 1984 OSHA implemented its Hazard Communication Standard (HCS), which mandated the Hazard Communication Program (HazCom), 29 CFR 1910.1200. Later, OSHA mandated other programs such as the Superfund Amendments and Reauthorization Act (SARA) Title III reporting requirements for all chemical users, producers, suppliers, and storage entities.

There is no all-inclusive list of chemicals covered by the HazCom standard; however, the regulation refers to "any chemical which is a physical or health hazard." Those specifically deemed hazardous include the following:

- Chemicals regulated by OSHA in 29 CFR Part 1910, Subpart Z, Toxic and Hazardous Substances
- Chemicals included in the American Conference of Governmental Industrial Hygienists' (ACGIH) latest edition of *Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices*
- Chemicals found to be suspected or confirmed carcinogens by the National Toxicology Program in the *Registry of Toxic Effects of Chemicals Substances* published by NIOSH, or appearing in the latest edition of the *Annual Report on Carcinogens*, or by the International Agency for Research on Cancer in the latest editions of its *IARC Monographs*

Congress decided that personnel involved in working with or around hazardous materials have a right to know about the hazards they present. Thus, OSHA's Hazard Communication Standard was created. The Hazard Communication Standard is, without a doubt, the regulation most important to the communication of hazards to employees. Under the standard (more commonly known as HazCom or the Right-to-Know Law), OSHA requires employers who use or produce chemicals on the worksite to inform all employees of the hazards that might be involved with those chemicals. HazCom states that employees have the right to know what chemicals they are handling or could be exposed to with the intent to make the workplace safer. The employer is required to fully evaluate all chemicals on the worksite for possible physical and health hazards, and all information relating to these hazards must be made available to employees 24 hours a day. The standard is written in a performance manner, meaning that the specifics are left to the employer to develop.

HAZCOM AND THE ENVIRONMENTAL PROFESSIONAL

The environmental professional responsible for implementation of or oversight of the Hazard Communication Standard in the workplace must take a personal interest in ensuring that the facility is in full compliance with the standard for three major reasons:

1. It is the law.
2. It is consistently the number one cause of citations issued by OSHA for noncompliance.
3. Compliance with the standard goes a long way toward protecting workers.

Major elements of the Hazard Communication Standard that environmental professionals must ensure are part of their organization's HazCom program include hazard determination, written hazard communication program, labels and other forms of warning, safety data sheets, and employee training.

MODIFICATION OF THE HAZARD COMMUNICATION STANDARD

To conform to the United Nations' Globally Harmonized System (GHS) of Classification and Labeling of Chemicals, OSHA has adopted an international approach to hazard communication. The original HazCom standard required the *employer* to ensure proper labeling of each chemical, including chemicals that might be produced by a *process* (process hazards). For example, in the wastewater industry, deadly methane gas is generated in the waste stream. Another common wastewater hazard is the generation of hydrogen sulfide, which produces the characteristic rotten-egg odor during degradation of organic substances in the waste stream and can kill quickly. HazCom requires the employer to label methane and hydrogen sulfide hazards so that workers are warned and safety precautions are followed.

Labels are required to be designed to be clearly understood by all workers. Employers are required to provide both training and written materials to make workers aware of what they are working with and what hazards they might be exposed to. Employers are also required to make Safety Data Sheets

(SDSs) available to all employees. An SDS is a fact sheet for a chemical posing a physical or health hazard at work. Each SDS must be in English and contain the following information:

- Identity of the chemical (label name)
- Physical hazards
- Control measures
- Health hazards
- Whether or not the chemical is a carcinogen
- Emergency and first aid procedures
- Date of preparation of latest revision
- Name, address, and telephone number of manufacturer, importer, or other responsible party

Blank spaces are not permitted on an SDS. If relevant information in any one of the categories is unavailable at the time of preparation, the SDS must indicate that no information was available. Every facility must have an SDS for each hazardous chemical it uses. Copies must be made available to other companies working on the worksite (outside contractors, for example), and they must do the same for the host site. The facility Hazard Communication Program must be in writing and, along with SDSs, made available to all workers 24 hours each day/each shift.

In the Globally Harmonized System, all of these original requirements still stand and are still required. The difference is that under GHS the employer must now abide by agreed-upon criteria for classification of chemical hazards and incorporate into their labeling procedure a standardized approach to label elements and Safety Data Sheets. The GHS was negotiated over several years by hazard communication experts from many different countries, international organizations, and stakeholder groups. It is based on major existing systems around the world, including OHSA's Hazard Communication Standard and the chemical classification and labeling systems of other U.S. agencies.

The result of this negotiation process is the United Nations' document entitled *Globally Harmonized System of Classification and Labeling of Chemicals*, commonly referred to as the *Purple Book*. This document provides harmonized classification criteria for health, physical, and environmental hazards of chemicals. It also includes standardized label elements that are assigned to these hazard classes and categories and provide the appropriate signal words, pictograms, and hazard and precautionary statements to convey the hazards to users. A standardized order of information for Safety Data Sheets is also provided. These recommendations can be used by regulatory authorities such as OSHA to establish mandatory requirements for hazard communication, but they do not constitute a model regulation.

The Hazard Communication Standard has been modified to adopt the GHS to improve the safety and health of workers through more effective communications on chemical hazards. Since it was first promulgated in 1983, HazCom has provided employers and employees extensive information about the chemicals in their workplaces. The original standard was performance oriented, allowing chemical manufacturers and importers to convey information on labels and Material Safety Data Sheets in whatever format they choose. Although the information made available in this way has been helpful in improving employee safety and health, a more standardized approach to classifying the hazards and conveying the information should prove more effective and further improve American workplaces. The GHS provides such a standardized approach, including detailed criteria for determining what hazardous effects a chemical poses, as well as standardized label elements assigned by hazard class and category. Such an approach can enhance both employer and worker comprehension of the hazards, which will help to ensure appropriate handling and safe use of workplace chemicals. In addition, the Safety Data Sheet requirements establish an order of information that is standardized. The harmonized format of the Safety Data Sheets will enable employers, workers, health professionals, and emergency responders to access the information more efficiently and effectively, thus increasing their utility.

The specific changes to the Hazard Communication Standard are in the hazard classification, labels, and Safety Data Sheets:

- *Hazard classification*—The definitions of hazards have been changed to provide specific criteria for the classification of health and physical hazards, as well as classification of mixtures. These specific criteria will help to ensure that evaluations of hazardous effects are consistent across manufacturers and that labels and Safety Data Sheets are more accurate as a result.
- *Labels*—Chemical manufacturers and importers are required to provide a label that includes a harmonized signal word, pictogram, and hazard statement for each hazard class and category. Precautionary statements must also be provided.
- *Safety Data Sheets*—A specified 16-section format is required.

Although the revised Hazard Communication Standard is a modification of the existing standard, the parts of the standard that did not relate to the GHS (such as the basic framework, scope, and exemptions) remain largely unchanged. There have been some modifications to terminology in order to align the revised HazCom with language used in the GHS; for example, the term "hazard determination" was changed to "hazard classification," and "Material Safety Data Sheet" was changed in "Safety Data Sheet."

Under both the original standard and the revised version, an evaluation of chemical hazards must be performed considering the available scientific evidence concerning such hazards. Under the original standard, the hazard determination provisions have definitions of hazards and the evaluator determines whether or not the data on a chemical meet those definitions. It is a performance-oriented approach that provides parameters for the evaluation but not specific, detailed criteria. The hazard classification approach in the revised standard is quite different, as it provides specific criteria for each health and physical hazard, along with detailed instructions for hazard evaluation and determinations as to whether mixtures or substances are covered. It also establishes both hazard classes and hazard categories for most of the effects; the classes are divided into categories that reflect the relative severity of the effect. The original standard does not include categories for most of the health hazards covered, so the new approach provides additional information that can be related to the appropriate response to address the hazard. OSHA has included the general provisions for hazard classification in paragraph (d) of the revised rule and added extensive appendixes that address the criteria for each health or physical effect.

Adoption of the GHS in the United States and around the world should help to improve information received from other countries, as the United States is both a major importer and exporter of chemicals and American workers often see labels and Safety Data Sheets from other countries. The diverse and sometimes conflicting national and international requirements have created confusion among those who seek to use hazard information effectively. For example, in the past, labels and Safety Data Sheets may have included symbols and hazard statements that are unfamiliar to users or not well understood. Containers may be labeled with such a large volume of information that important statements are not easily recognized. Given the differences in hazard classification criteria, labels may also be incorrect when used in other countries. When countries around the world have adopted the GHS, these problems will be minimized, and chemicals crossing borders will have consistent information, thus improving communication globally. Table 11.2 summarizes the phase-in dates required under the revised Hazard Communication Standard.

Note: During the phase-in period, employers would be required to be in compliance with either the existing HazCom standard or the revised standard, or both. OSHA recognizes that hazard communication programs will go through a period of time where labels and SDSs under both standards will be present in the workplace. This will be considered acceptable, and employers are not required to maintain two sets of labels and SDSs for compliance purposes.

TABLE 11.2
Phase-In Dates Required by Revised Hazard Communication Standard

Effective Completion Date	Requirements	Who
December 1, 2013	Train employees on the new label elements and Safety Data Sheet (SDS) format.	Employers
June 1, 2015[a]	Comply with all modified provisions of the final rule, except as noted in next entry.	Chemical manufacturers, importers, distributors, and employers
December 1, 2015	Distributor shall not ship containers labeled by the chemical manufacturer or importer unless it is a GHS label.	Chemical manufacturers, importers, distributors, and employers
June 1, 2016	Update alternative workplace labeling and hazard communication program as necessary and provide additional employee training for newly identified physical or health hazards.	Employers
Transition period to the effective completion dates noted above	Comply with either 29 CFR 1910.1200 (final standard) or current standard, or both.	Chemical manufacturers, importers, distributors, and employers

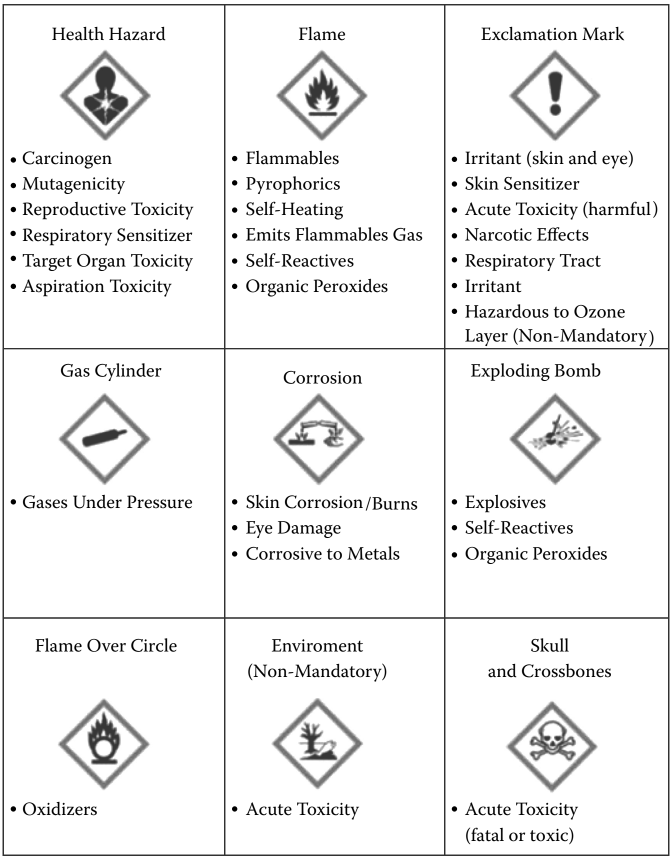
[a] This date coincides with the EU implementation date for classification of mixtures.

It is important to point out that even though full compliance with HazCom modifications is to be phased in and the GHS does not include harmonized training provisions, OSHA required that employees be trained on the new label elements (i.e., pictograms, hazard statement, precautionary statements, and signal words) and the SDS format by December 1, 2013, while full compliance with the final rule begins in 2015. OSHA believes that American workplaces will soon begin to receive labels and SDSs that are consistent with the GHS, as many American and foreign chemical manufactures have already begun to produce HazCom 2012/GHS-compliant labels and SDSs. It is important to ensure that when employees begin to see the new labels and SDSs in the workplaces that they will be familiar with them, understand how to use them, and access the information effectively.

Under the current Hazard Communication Standard, the label preparer must provide the identity of the chemical and the appropriate hazard warnings. This may be done in a variety of ways, and the method to convey the information is left to the preparer. Under the revised standard, when the hazard classification has been completed, the standard specifies what information is to be provided for each hazard class and category. Labels must have the following elements:

- *Pictogram*—A symbol plus other graphic elements, such as a border, background pattern, or color that is intended to convey specific information about the hazards of a chemical. Each pictogram consists of a different symbol on a white background within a red square frame set on a point (i.e., a red diamond). There are nine pictograms under the GHS; however, only eight pictograms are required under the HazCom standard.
- *Signal words*—A single word used to indicate the relative level of severity of a hazard and alert the reader to a potential hazard on the label. The signal words used are “danger” (more severe hazards) and “warning” (less severe hazards).
- *Hazard statement*—A statement assigned to a hazard class and category that describes the nature of the hazard(s) of a chemical, including, where appropriate, the degree of hazard.
- *Precautionary statement*—A phrase that describes recommended measures to be taken to minimize or prevent adverse effects resulting from exposure to a hazardous chemical or improper storage or handling of a hazardous chemical.

The required pictograms required under GHS are shown in Figure 11.1.



Health Hazard • Carcinogen • Mutagenicity • Reproductive Toxicity • Respiratory Sensitizer • Target Organ Toxicity • Aspiration Toxicity	Flame • Flammables • Pyrophorics • Self-Heating • Emits Flammables Gas • Self-Reactives • Organic Peroxides	Exclamation Mark • Irritant (skin and eye) • Skin Sensitizer • Acute Toxicity (harmful) • Narcotic Effects • Respiratory Tract • Irritant • Hazardous to Ozone Layer (Non-Mandatory)
Gas Cylinder • Gases Under Pressure	Corrosion • Skin Corrosion/Burns • Eye Damage • Corrosive to Metals	Exploding Bomb • Explosives • Self-Reactives • Organic Peroxides
Flame Over Circle • Oxidizers	Enviroment (Non-Mandatory) • Acute Toxicity	Skull and Crossbones • Acute Toxicity (fatal or toxic)

FIGURE 11.1 GHS pictograms and hazards required under the revised HazCom standard.

Under the revised standard, the former Material Safety Data Sheet has been replaced by the Safety Data Sheet, which has been slightly modified. Essentially, the information required on the Safety Data Sheet will remain the same as that in the original standard, which indicates what information has to be included on an SDS but does not specify a format for presentation or order of information. The revised standard requires that the information on the SDS be presented using specific headings in a specified sequence. Paragraph (g) of the final rule provides the headings of information to be included on the SDS and the order in which they are to be provided. In addition, Appendix D provides the information to be included under each heading:

Section 1. Identification
Section 2. Hazard(s) identification
Section 3. Composition/information on ingredients
Section 4. First-aid measures
Section 5. Fire-fighting measures
Section 6. Accidental release measures
Section 7. Handling and storage
Section 8. Exposure controls/personal protection
Section 9. Physical and chemical properties
Section 10. Stability and reactivity
Section 11. Toxicological information
Section 12. Ecological information

Section 13. Disposal considerations
Section 14. Transport information
Section 15. Regulatory information
Section 16. Other information, including date of preparation or last revision

OCCUPATIONAL ENVIRONMENTAL LIMITS

Many processes and procedures generate hazardous air contaminants that can get into the air people breathe. Normally, the body can take in limited amounts of hazardous air contaminants, metabolize them, and eliminate them from the body without producing harmful effects. Safe levels of exposure to many hazardous materials have been established by governmental agencies after much research on their short-term (acute) and cumulative (chronic) health effects using available human exposure data (usually from industrial sources) and animal testing. When the average air concentrations repeatedly exceed certain thresholds, called *exposure limits*, adverse health effects are more likely to occur. Exposure limits do change with time as more research is conducted and more occupational data are collected.

EXPOSURE LIMITS

A fairly standard terminology has come to be used with regard to occupational environmental limits (OELs). Let's pause right here to talk about *permissible exposure limits* (PELs) and *threshold limit values* (TLVs). A workplace exposure level, such as a PEL or TLV, is expressed as the concentration of the air contaminant in a volume of air. It is important to know what they are and what significance they play in an industrial hygienist's daily activities. Let's begin with TLVs.

Threshold limit values (TLVs) are published by the American Conference of Governmental Industrial Hygienists (ACGIH) (an organization made up of physicians, toxicologists, chemists, epidemiologists, and industrial hygienists) in its *Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices*. These values are used to assess the risk of a worker exposed to a hazardous chemical vapor; concentrations in the workplace can often be maintained below these levels with proper controls. The substances listed by the ACGIH are evaluated annually, limits are revised as needed, and new substances are added to the list as information becomes available. The values are established from the experience of many groups in industry, academia, and medicine, as well as from laboratory research.

The chemical substance exposure limits listed under both the ACGIH and OSHA are based strictly on airborne concentrations of chemical substances in terms of milligrams per cubic meter (mg/m^3), parts per million (ppm; the number of parts of air contaminant per million parts of air), and fibers per cubic centimeters (fibers/cm^3). The smaller the concentration number, the more toxic the substance is by inhalation. The ACGIH has established some rules of thumb with regard to exposure limits. Substances with exposure limits below 100 ppm are considered highly toxic by inhalation. Those substances with exposure limits of 100 to 500 ppm are considered moderately toxic by inhalation. Substances with exposure limits greater than 500 ppm are considered slightly toxic by inhalation. Allowable limits are based on three different time periods of average exposure: (1) 8-hour work shifts known as time-weighted averages (TWAs), (2) short terms of 15 minutes referred to as short-term exposure limits (STELs), and (3) instantaneous exposure (C, or ceiling). Unlike the OSHA PELs, TLVs are recommended levels only and do not have the force of regulation to back them up.

The limits promulgated by OSHA for personnel exposure in workplace air for approximately 400 chemicals are listed in Tables Z1, Z2, and Z3 in Part 1910.1000 of the Federal Occupational Safety and Health Standard. These limits are defined as permissible exposure limits and like TLVs are based on 8-hour time-weighted averages or ceiling limits when preceded by a "C." (Exposure limits expressed in terms other than ppm must be converted to ppm before comparing them to the guidelines.) Keeping within the limits in the Subpart Z tables is the only requirement specified by OSHA for these chemicals. The significance of the OSHA PELs is that they have the force of regulatory law behind them to back them up—compliance with the OSHA PELs is the law.

Evaluation of personnel exposure to physical and chemical stresses in the industrial workplace requires the use of the guidelines provided by TLVs and the regulatory guidelines of PELs. For industrial hygienists to carry out the goals of recognizing, measuring, and implementing controls of any type for workplace stresses, such limits are a necessity and have become the ultimate guidelines in the science of industrial hygiene. A word of caution is advised, however. These values are set only as guides for best practice and are not to be considered absolute values. These values provide reasonable assurance that occupational disease will not occur if exposures are kept below these levels. On the other hand, occupational disease is likely to develop in some people if the recommended levels are exceeded on a consistent basis.

The time-weighted average (TWA) is the fundamental concept of most PELs. It is usually presented as the average concentration over an 8-hour workday for a 40-hour workweek. An 8-hour threshold limit value–time-weighted average (TLV-TWA) has been established for over 400 chemical agents commonly found in the workplace. NIOSH lists the sampling and analytical methods for most of these agents. Short-term exposure limits (STELs) are recommended when exposures of even short duration to high concentrations of a chemical are known to produce acute toxicity. The STEL is the concentration to which workers can be exposed continuously for a short period of time without suffering from (1) irritation, (2) chronic or irreversible tissue damage, or (3) narcosis of a sufficient degree to increase the likelihood of accidental injury, impaired self-rescue, or reduced work efficiency. The STEL is defined as a 15-minute TWA exposure that should not be exceeded at any time during a workday, even if the overall 8-hour TWA is within limits, and it should not occur more than four times per day. There should be at least 60 minutes between successive exposures in this range. If warranted, an averaging period other than 15 minutes can also be used. STELS are not available for all substances.

The ceiling (C) is the concentration that should not be exceeded during any part of the working exposure, assessed over a 15-minute period. The action level is the concentration or level of an agent at which it is deemed that some specific action should be taken. Action levels are found only in certain substance-specific OSHA standards. In practice, the action level is usually set at one half of the TLV. The "skin" notation denotes the possibility that dermal absorption may be a significant contribution to the overall body burden of the chemical. When this notation follows the exposure limit it indicates that a significant exposure can be received if the skin is in contact with the chemical in the gas, vapor, or solid form.

Airborne particulate matter is divided into three classes based on likely deposition within the respiratory tract. Although past practice was to provide TLVs in terms of total particulate mass, the current approach is to take into account the aerodynamic diameter of the particle and its site of action. The three classes of airborne particulate matter are described below:

1. *Inhalable particulate mass (IPM)* TLVs are designated for compounds that are toxic if deposited at any site within the respiratory tract. The typical size for these particles can range from submicron size to approximately 100 microns.
2. *Thoracic particulate mass (TPM)* TLVs are designated for compounds that are toxic if deposited within either the airways of the lung or the gas-exchange region. The typical size for these particles can range from approximately 5 to 15 microns.
3. *Respirable particulate mass (RPM)* TLVs are designated for those compounds that are toxic if deposited within the gas-exchange region of the lung. The typical size for these particles is approximately 5 microns or less.

The term *nuisance dust* is no longer used because all dusts have biological effects at some dose. The term *particulates not otherwise classified* is now being used in place of nuisance dusts. *Biological exposure indices* (BEIs) are reference values that cover nearly 40 chemicals. A BEI has been defined as the level of a chemical marker ("determinant") that is most likely to be observed in specimens (such as blood, urine, or air) collected from a worker with an internal dose equivalent to that arising solely from inhalation exposure at the TLV concentration.

AIR MONITORING AND SAMPLING

Air monitoring is widely used to measure human exposure and to characterize emission sources. It is often employed within the context of the general survey, investigating a specific complaint, or simply for regulatory compliance. It is also used for more fundamental purposes, such as in confined space entry operations. Although just about any confined space entry team member can be trained to properly calibrate and operate air monitors for safe confined space entry, a higher level of knowledge and training is often required in the actual evaluation of confined spaces for possible oxygen deficiency or air contaminant problems. After an overview of the basics of air monitoring and sampling, we discuss air monitoring requirements for permit-required confined space entry.

AIR SAMPLE VOLUME

The publications *Sampling and Analytical Methods* (OSHA) and *Manual of Analytical Methods* (NIOSH) list a range of air sample volumes, from minimum volume (VOL-MIN) to maximum volume (VOL-MAX), that should be collected for an exposure assessment. The volume is based on the sampler's sorptive capacity and assumes that the measured exposure is the OSHA PEL. The range of volumes listed may not collect a sufficient mass for accurate laboratory analysis if the actual contaminant concentration is less than the PEL or the TLV-TWA. If a collection method recommends sampling 10 liters of air, the industrial hygienist cannot be sure that an 8.5-liter air sample will collect sufficient mass for the lab to quantify. This makes an important point—that is, finding that an insufficient air volume was sampled after the lab results are returned can turn out to be an enormous waste of resources. To avoid this situation, it is essential to understand the restrictions faced by analytical labs: *limit of detection* (LOD) and *limit of quantification* (LOQ). To compute a minimum air sample volume required to provide useful information for the evaluation of airborne contaminant concentrations in the workplace, industrial hygienist musts understand how to correctly manipulate the LOD and the LOQ. Knowledge of these limits will provide increased flexibility in sampling.

LIMIT OF DETECTION

The limit of detection (LOD) has many definitions in the literature. For example, the American Chemical Society (ACS) Committee on Environmental Analytical Chemistry has defined the LOD as the lowest concentration level that can be determined to be statistically different from a blank sample, which is a sample of a carrying agent—a gas, liquid, or solid—that is normally used to selectively capture a material of interest and that is subjected to the usual analytical or measurement process to establish a zero baseline or background value, which is then used to adjust or correct routine analytical results. For our purposes, the ACS definition of LOD is used in this handbook. The analytical instrument output signal produced by the sample must be three to five times the instrument's background noise level to be at the limit of detection; that is, the signal-to-noise (S/N) ratio is three to one (3:1). The S/N ratio is the analytical method's lower limit of detection.

LIMIT OF QUANTIFICATION

The limit of quantification (LOQ) is the concentration level above which quantitative results may be obtained with a certain degree of confidence; that is, the LOQ is the minimum mass of the analyte above which the precision of the reported result is better than a specified level. The recommended value of the LOQ is the amount of analyte that will give rise to a signal that is 10 times the standard deviation of the signal from a series of media blanks.

Precision, Accuracy, and Bias

Sample results are only as good as the sampling technique and equipment used. Thus, in any type of air monitoring operation (air, water, or soil), it is important for industrial hygienists to factor in the precision, accuracy, and any possible bias involved in the monitoring process. *Precision* is the reproducibility of replicate analyses of the same sample (mass or concentration); for example, how close to each other is a target shooter able to place a set of shots anywhere on the target? *Accuracy* is the degree of agreement between measured values and the accepted reference value. Investigators must carefully design their sampling program and use certain statistical tools to evaluate the data before making any inferences from the data. In our target shooting analogy, accuracy can be equated to how close does a target shooter come to the bull's eye? *Bias* is the error introduced into sampling that causes estimates of parameters to be inaccurate. More specifically, bias is the difference between the average measured mass or concentration and a reference mass or concentration, expressed as a fraction of the reference mass or concentration. For example, how far from the bull's eye is the target shooter able to place a cluster of shots?

CALIBRATION REQUIREMENTS

The American National Standards Institute has defined calibration as the set of operations that establishes, under specified conditions (i.e., instrument manufacturer's guidelines or regulator's protocols), the relationship between values indicated by a measuring instrument or measuring system, and the corresponding standard or known values derived from the standard. Note that before any air monitoring device can be relied on as accurate it must be calibrated. Calibration procedures can be found in OSHA's *Personal Sampling for Air Contaminants* (https://www.osha.gov/dts/osta/otm/otm_ii/otm_ii_1.html).

TYPES OF AIR SAMPLING

Although the information provided in the following discussion is area specific (*area sampling*), it is important to point out that one of the most important air sampling operations is *personal sampling*, which puts the sample detection device on the worker. This is done to obtain samples that represent the worker's exposure while working. As the preferred method of evaluating worker exposure to airborne contaminants, personal sampling requires the worker to wear the detection device on their person in the breathing zone area. A small air pump and associated tubing connected to the detector are also worn by the worker. Personal sampling allows the industrial hygienist to define a potential hazard, check compliance with specific regulations, and determine the worker's daily time-weighted average (TWA) exposure.

ANALYTICAL METHODS FOR GASES AND VAPORS

In routine practice, industrial hygienists will collect air samples to determine the concentration of a known contaminant or group of contaminants and will request or conduct analyses for these compounds. The first step in this procedure is to develop a sampling plan. When developing a sampling plan or strategy, the sampler should review the specific sampling and analytical methods available for the contaminants of interest. Several organizations have compiled and published collections of sampling and analytical methods for gases and vapors:

- *NIOSH Manual of Analytical Methods*, 4th ed.
  National Institute for Occupational Safety and Health
  Centers for Disease Control and Prevention
  4676 Columbia Parkway
  Cincinnati, OH 45226

- *Annual Book of ASTM Standards*
  American Society for Testing and Materials
  100 Barr Harbor Drive
  West Conshohocken, PA 19428
- *OSHA Analytical Methods Manual*
  Occupational Safety and Health Administration
  OSHA Salt Lake Technical Center
  P.O. Box 65200
  Salt Lake City, UT 84165
- *Methods of Air Sampling and Analysis*
  James P. Lodge, Jr., Editor
  Lewis Publishers
  2000 Corporate Blvd. NW
  Boca Raton, FL 33431

For discussion purposes, analytical methods for gases and vapors (a vapor is the gaseous phase of a substance that is liquid or solid at normal temperature and pressure; vapors diffuse) are grouped into chromatographic, volumetric, and optical methods. In the following we briefly discuss chromatography.

The primary type of analytical equipment used in chromatography for the analysis of gases and vapors in air samples is the *gas chromatograph* (GC), which is a powerful tool for the analysis of low-concentration air contaminants. It is generally a reliable analytical instrument. GC analysis is applicable to compounds with sufficient vapor pressure and thermal stability to dissolve in the carrier gas and pass through the chromatographic column in sufficient quantity to be detectable. Air samples to be analyzed by GC are typically collected on sorbent tubes and desorbed into a liquid for analysis. It should be noted that the GC instrument cannot be used for reliable identification of specific substances. Because of this limitation, the GS is often married to the mass spectrometer (MS) instrument to provide specific results. When industrial hygienists or engineering analysts use the GC instrument to separate compounds before analysis with an MS instrument, a complementary relationship exists. The technician has access to both the retention times and mass spectral data. Many environmental professionals consider GC/MS analysis to be a tool for conclusive proof of identity—the "gold standard" in scientific analysis. Some common applications of GC/MS include the following:

1. Evaluation of complex mixtures
2. Identification of pyrolysis and combustion products from fries
3. Analysis of insecticides and herbicides (conventional analytical methods frequently cannot resolve or identify the wide variety of industrial pesticides currently in use, but GC/MS can both identify and quantify these compounds)

AIR MONITORING VS. AIR SAMPLING

In the practice of industrial hygiene, the terms *air monitoring* and *air sampling* are often used interchangeably to mean the same thing. But are they the same? It depends. In reality, they are different; that is, air monitoring and air sampling are separate functions. The difference is related to time: real time vs. time integration. Air monitoring is real-time monitoring and generally includes monitoring with hand-held, direct-reading units such as portable gas chromatographs (GCs), photoionization detectors (PIDs), flame ionization detectors (FIDs), dust monitors, and colorimetric tubes. Real-time air monitoring instrumentation is generally easily portable and allows the user to collect multiple samples in a relatively short sample period—ranging from a few seconds to a few minutes. Most portable real-time instruments measure low parts per million (ppm) of total volatile organics.

Real-time monitoring methods have higher detection limits than time-integrated sampling methods, react with entire classes of compounds, and, unless real-time monitoring is conducted continuously, provide only a snapshot of the monitored ambient air concentration. Air monitoring instruments and methods provide results that are generally used to evaluate short-term exposure limits and can provide timely information to those engaged in various activities such as confined space entry operations. In confined space operations, proper air monitoring can detect the presence or absence of life-threatening contaminants or insufficient oxygen levels within the confined space, alerting the entrants not to enter before making the space safe (e.g., by using forced air ventilation) for entry.

On the other hand, time-integrated air sampling is intended to document actual exposure for comparison to long-term exposure limits. Air sampling data are collected at fixed locations along the perimeter of the sample area (work area) and at locations adjacent to other sensitive receptors. Because most contaminants are or will be present in ambient air at relatively low levels, some type of sample concentrating is necessary to meet detection limits normally required to evaluate long-term health risks. Air sampling is accomplished using air-monitoring instrumentation designed to continuously sample large volumes of air over extended periods of time (typically from 8 to 24 hours). Air sampling methods involve collecting air samples on sampling media designed specifically for collection of the compounds of interest or as whole air samples. Upon completion of the sampling period the sampling media are collected, packaged, and transported for subsequent analysis. Analysis of air samples usually requires a minimum of 48 hours to complete. Both air sampling and air monitoring are important and significant tools in the industrial hygienist's toolbox.

To effectively evaluate a potentially hazardous worksite, industrial hygienists must obtain objective and quantitative data. To do this, they must perform some form of air sampling, depending on the airborne contaminant in question. Moreover, sampling operations involve the use of instruments to measure the concentration of the particulate, gas, or vapor of interest. Many instruments perform both sampling and analysis. The instrument of choice in conducting sampling and analysis typically is a direct-reading type of instrument. Industrial hygienists must be familiar with the uses, advantages, and limitations of such instruments. In addition, they must be able to use math calculations to calculate sample volumes, sample times, TLVs, and air concentrations from vapor pressures and to determine the additive effects of chemicals when multiple agents are used in the workplace. These calculations must take into account changing conditions, such as temperature and pressure changes, in the workplace. Finally, industrial hygienists must understand how particulates, gases, and vapors are generated, how they enter the human body, how they impact workers' health, and how to evaluate particulate-, gas-, and vapor-laden workplaces.

Because air sampling is integral to just about everything industrial hygienists do and are about, the following text includes important sections focusing on air sampling principles, airborne particulates, airborne gases and vapors, direct-reading instruments, and basic air sampling calculations.

AIR SAMPLING FOR AIRBORNE PARTICULATES

Airborne particulates (or particulate matter, PM) includes solid and liquid matter such as

- Dusts
- Fumes
- Mists
- Smokes
- Bioaerosols

Inhalation of particulates is a major cause of occupational illness and disease. Pneumoconiosis ("dusty lung") is a lung disease caused by inhaling dust (e.g., coal dust). There are four critical factors that influence the health impact of airborne particulates. Each of these four factors is interrelated in such a way that no one factor can be considered independently of the others:

- Size of the particles
- Duration of exposure time
- Nature of the dust in question
- Airborne concentration of the dust in the breathing zone of the exposure person

Note: The *breathing zone* of the worker is described by a hemisphere between the shoulders and the top of the head.

DUSTS

Dusts are generated by mechanical processes such as grinding or crushing. Dusts range in size from 0.5 to 50 µm in size. Note that *dust* is a relatively new term used to describe dust that is hazardous when deposited anywhere in the respiratory tree, including the nose and mouth. It has a 50% cut-point of 10 µm and includes the big and the small particles. The cut-point describes the performance of cyclones and other particle size selective devices. For personal sampling, the 50% cut-point is the size of the dust that the device collects with 50% efficiency. Common workplace dusts are either inorganic or organic.

Inorganic dusts are derived from metallic and nonmetallic sources (Alpaugh and Hogan, 1988). Nonmetallic dusts can be silica bearing—that is, in combined or free silica as crystalline or amorphous form. Organic dusts are either synthetic or natural. Natural organic dust can be animal or vegetable derived. Examples of organic and inorganic dust include sand (inorganic, nonmetallic, silica bearing, free silica, crystalline), beryllium (inorganic, metallic), and cotton (organic, naturally occurring, vegetable). Dusts can also be classified on the basis of their health effects (Grantham, 1992):

- *Innocuous*—Iron oxide, limestone (may also be considered as nuisance dusts)
- *Acute respiratory hazards*—Cadmium fume
- *Chronic respiratory hazards*—Airborne asbestos fibers
- *Sensitizers*—Many hardwood dusts

DURATION OF EXPOSURE

The duration of exposure may be *acute* (short term) or *chronic* (long term). Some airborne particulates, such as beryllium, may exert a toxic effect after a single acute exposure, or metal fume fever may occur following acute exposure to metal fumes. Other particulates, such as lead or manganese, may exert a toxic effect following a longer period of exposure, maybe several days to several weeks. Such exposures could be termed *subchronic*. Chronic lung conditions, such as pneumoconiosis or mesothelioma, may follow prolonged exposure to silica dusts or asbestos (crocidolite or blue asbestos), respectively.

PARTICLE SIZE

Particle size is critical in determining where particulates will settle in the lung. Smaller particles outnumber larger ones but vary widely in size. Larger particles will settle in the upper respiratory tract in the bronchi and the bronchioles, and will not tend to penetrate the smaller airways found in the alveolar (air sac) region. These are termed *inspirable* particles. The smaller sized particles that can penetrate the alveolar (gas-exchange) region of the lungs are termed *respirable* particles. Particle size is expressed as aerodynamic or equivalent diameter. This is equal to the diameter of spherical particles of unit density that have the same falling velocity (terminal velocity or settling velocity) in air as the particle in question. The terminal velocity is proportional to the specific gravity of the particle and the square of its diameter.

Particles with an aerodynamic diameter greater than approximately 20 μm will be trapped in the nose and upper airways. Particles in the region of 7 to 20 μm will penetrate to the bronchioles and are inspirable, whereas particles in the size range of 0.5 to 7 μm are respirable. Particles smaller than this will not settle out because their terminal velocity is so small that there is insufficient time for them to be deposited in the alveolus and they are exhaled out again.

An understanding of aerodynamic diameter is important when calculating terminal settling rates of particulates. Constants for these calculations include the following:

1 gm/cm^3 = Unit density
Gravity = 32.2 ft/sec^2 or 98 cm/sec^2

Stokes's Law

Stokes's law is the relationship that relates the "settling rate" to a particle's density and diameter. Stokes's law applies to the fate of particulates in the atmosphere and can be given as

$$u = \frac{gd^2\rho_1 - \rho_2}{18\eta}$$

where

u = Settling velocity (cm/s).
g = Acceleration due to gravity (cm/s^2).
d^2 = Diameter of particle squared (cm^2).
ρ_1 = Particle density (g/cm^3).
ρ_2 = Air density (g/cm^3).
η = Air viscosity (poise; g/cm · s).

What Stokes's law tells us is that, all other things being constant, dense particles settle faster, larger particles settle faster, and denser, more viscous air causes particles to settle more slowly. Stokes's law is used in several ways. We can predict the settling rate for a given particle if its diameter and density are known, or we can use it to estimate particle diameters (Stokes's diameters) from the observed settling rates.

Airborne Dust Concentration

The concentration of dust to which a person is exposed is a critical factor with regard to the impact on the health of the worker exposed. The concentration is measured in the breathing zone of the worker. Airborne concentrations of dust are usually assessed by collecting dust on a pre-weighed filter. A known volume of air is drawn through the filter, which is then re-weighed. The difference in weight is the mass of dust, usually in milligrams (mg) or micrograms (μg), and the volume is expressed as cubic meters of air (m^3). Hence, the overall concentration of dust in air is measured in mg/m^3 or μg/m^3.

PARTICULATE COLLECTION

In order to evaluate workplace atmosphere for particulates a sample must be taken and analyzed. To obtain a sample the following collection mechanisms are used:

- Impaction
- Sedimentation
- Diffusion
- Direct interception
- Electrostatic attraction

The filter is the most common particulate collection device. The mixed cellulose ester membrane filter is the most commonly used type of filter. This type filter is used for collecting asbestos and metals. Other filter types include polyvinyl chloride, silver, glass-fiber, and Teflon.

ANALYSIS OF PARTICULATES

There are several methods for analysis of particulates:

- *Gravimetric*—Coal dust, free silica, total dust
- *Instrumental*—Atomic absorption (AA) for metals
- *Optical microscopy*—Fibers, asbestos, dust
- *Direct-reading instruments*—Aerosol photometers, piezoelectric instruments
- *Wet chemical*—Lead, isocyanates, free silica

HEALTH AND ENVIRONMENTAL IMPACTS OF PARTICULATES

Particulates have a wide variety of health and environmental impacts. Many scientific studies have linked breathing particulates to a series of significant health problems, such as

- Aggravated asthma
- Increases in respiratory symptoms such as coughing and difficult or painful breathing
- Chronic bronchitis
- Decreased lung function
- Premature death

Particulate matter is the major cause of reduced visibility (haze) in parts of the United States, including many of our national parks. Particles can be carried over long distances by wind and then settle on ground or water. The effects of this settling include the following:

- Making lakes and streams acidic
- Changing the nutrient balance in coastal waters and large river basins
- Depleting the nutrients in soil
- Damaging sensitive forests and farm crops
- Affecting the diversity of ecosystems

Soot particulate stains and damages stone and other materials, including culturally important objects such as monuments and statues.

CONTROL OF PARTICULATES

As with all other methods of industrial hygiene hazard control, control of particulates is most often accomplished through the use of engineering controls, administrative controls, and PPE. The best method for controlling particulates is the use of ventilation—an engineering control. To be most effective, the particulate generating process should be totally enclosed with a negative pressure exhaust ventilation system in place. Administrative controls include using wet methods of housekeeping and wet cleanup methods to minimize dust regeneration and prohibiting the use of compressed air to clean work surfaces. PPE, used as a last resort, includes equipping workers with proper respiratory protection for prevention of inhalation of particulates and protective clothing to protect worker contact with particulates.

AIR SAMPLING FOR GASES AND VAPORS

Gases and vapors are elastic fluids, so-called because they take the shape and volume of their containers. A fluid is generally termed a gas if its temperature is very far removed from that required for liquefaction; it is called a vapor if its temperature is close to that of liquefaction. In the industrial hygiene field, a substance is considered a gas if this is its normal physical state at room temperature and atmospheric pressure. It is considered a vapor if, under the existing environmental conditions, conversion of its liquid or solid form to the gaseous state results from its vapor pressure affecting its volatilization or sublimation into the atmosphere of the container, which may be the process equipment or the worksite. Our chief interest in distinguishing between gases and vapors lies in our need to assess the potential occupational hazards associated with the use of specific chemical agents, an assessment that requires knowledge of the physical and chemical properties of these substances (NIOSH, 2004). The type of air sampling for gases and vapors employed depends on the purpose of sampling, environmental conditions, equipment available, and nature of the contaminant.

TYPES OF AIR SAMPLES

No matter the type of air sampling used, workplace samples must be obtained that represent the worker's exposure (i.e., a representative sample). In taking a representative sample, a sampling plan should be used that specifies the following:

- Where to sample
- Whom to sample
- How long to sample
- How many samples to take
- When to sample

Generally, two methods of sampling for airborne contaminants are used: personal air sampling and area sampling. Personal air sampling (where the worker wears a sampling device that collects an air sample) is the preferred method of evaluating worker exposure to airborne contaminants. Area monitoring (e.g., in confined spaces) is used to identify high exposure areas.

METHODS OF SAMPLING

Standardized sampling methods provide the information needed to sample air for specific contaminants. Standard air sampling methods specify procedures, collection media, sample volume, flow rate, and chemical analysis to be used. For example, NIOSH's *Manual of Analytical Methods* and OSHA's *Chemical Information Manual* provide the information necessary to sample for air of specific contaminants. Generally, two methods of sampling are used to sample for airborne contaminants: *grab sampling* and *continuous* (or integrated) *sampling*. Grab sampling (i.e., instantaneous sampling) is conducted using a heavy-walled evacuated (air removed) flask. The flask is placed in the work area and a valve is opened to allow air to fill the flask. The sample represents a snapshot of an environmental concentration at a particular point in time. The sample is analyzed either in the laboratory or with suitable field instruments. Continuous sampling is the preferred method for determining time-weighted average (TWA) exposures. The sample is taken from a sample air stream.

AIR SAMPLING COLLECTION PROCESSES

Airborne contaminants are collected on media or in liquid media through absorption or adsorption processes. *Absorption* is the process of collecting gas or vapor in a liquid (dissolving gas/vapor in a liquid). Absorption theory states that gases and vapors will go into solution up to an equilibrium concentration. Samplers include gas washing bottles (impingers), fritted bubblers, spiral and helical absorbers, and glass-bead columns. *Gas adsorbents* (gas onto a solid) typically use activated charcoal, silica gel, or other materials to collect gases. *Diffusive samplers* (passive samplers) depend on the flow of contaminant across a quiescent layer of air (where no pump is used to draw air across an adsorbent) or a membrane. Diffusion depends on well-established rules from physical chemistry, known as Fick's law.

CALIBRATION OF AIR SAMPLING EQUIPMENT

In order to gather accurate sampling data, the equipment used must be properly calibrated. The calibration of any instrument is an absolute necessity if the data are to have any meaning. Various devices are used to calibrate air sampling equipment. Calibration is based on primary or secondary calibrations standards. Primary calibration standards include

- Soap bubble meter (or frictionless piston meter)
- Spirometer (measures displaced air)
- Mariotti bottle (measures displaced water)
- Electronic calibrators (provide instantaneous airflow readings)

Secondary calibration standards include

- Wet test meter
- Dry gas meter
- Rotameters

DIRECT-READING INSTRUMENTS FOR AIR SAMPLING

Direct-reading instruments are used for onsite evaluations for a number of reasons:

- To find the sources of emission of hazardous contaminants on the spot
- To ascertain if select OSHA air standards are being exceeded
- To check the performance of control equipment
- To continuously monitor fixed locations
- To trigger an alarm system in the event of breakdown in a process control that could result in the accidental release of copious amounts of harmful substances to the workroom atmosphere
- To obtain permanent recorded documentation of the concentrations of a contaminant in the atmospheric environment for future use in epidemiological and other types of occupational studies, in legal actions, to inform employees as to their exposure, and for information required for improved design of control measures

Such onsite evaluations of the atmospheric concentrations of hazardous substances make possible the immediate assessment of undesirable exposures and allow industrial hygienists to make an immediate correction of an operation, in accordance with their evaluation of the seriousness of a situation, without permitting further risk of injury to the workers (NIOSH, 2004).

The two types of direct reading instruments used in air sampling are direct-reading physical instruments and direct-reading colorimetric devices.

Direct-Reading Physical Instruments

The physical properties of gases, aerosols, and vapors are used in the design of direct-reading physical instruments for quantitative estimations of these types of contaminants in the atmosphere. The various types of these instruments, the principle of operation, and a brief description of application are presented in the following discussion.

Aerosol photometry—Measures, records, and controls particulates continuously in areas requiring sensitive detection of aerosol levels; detects particles 0.05 to 40 μm in diameter. Computer interface equipment is available.

Chemiluminescence—Measurement of NO in ambient air selectivity and NO_x after conversion to NO by hot catalyst; specific measurement of O_2. No atmospheric interferences.

Colorimetry—Measures and separately records NO_{2-}, NO_x, SO_2, total oxidants, H_2S, HF, NH_3, Cl_2, and aldehydes in ambient air.

Combustion—Detects and analyzes combustible gases in terms of percent lower explosive limit (LEL) on a graduated scale; available with alarm set at 1/3 LEL.

Conductivity, electrical—Records SO_2 concentrations in ambient air. Some operate off a 12-volt car battery and some can operate unattended for periods up to 30 days.

Coulometry—Continuous monitoring of NO, NO_2, O_x, and SO_2 in ambient air. Provided with strip chart recorders; some require attention only once a month.

Flame ionization (hydrocarbon analyzer)—Continuous monitoring of total hydrocarbons in ambient air; potentiometric or optional current outputs compatible with any recorder. Electronic stability from 32° to 110°F.

Flame ionization (with gas chromatograph)—Continuous determination and recording of methane, total hydrocarbons, and carbon monoxide. Catalytic conversion of SO to CH_4. Operates up to 3 days unattended. Separate model for continuous monitoring of SO_2, H_2S, and total sulfur in air. Unattended operation up to 3 days.

Gas chromatograph, portable—Onsite determination of fixed gases, solvent vapors, nitro and halogenated compounds, and light hydrocarbons. Instruments available with choice of flame ionization, electron capture, or thermal conductivity detectors and appropriate columns for desired analyses. Rechargeable batteries.

Infrared analyzer (photometry)—Continuous determination of a given component in a gaseous or liquid stream by measuring the amount of infrared energy absorbed by the component of interest using a pressure sensor technique. Wide variety of applications for CO, CO_2, freons, hydrocarbons, nitrous oxide, NH_3, SO_2, and water vapor.

Particle counting (near-forward scattering)—Reads and prints directly particle concentrations at one of three preset time intervals of 100, 1000, or 10,000 seconds, corresponding to 0.01, 0.1, and 1 cubic foot of sampled air.

Photometry, ultraviolet (tuned to 253.7 nm)—Direct readout of mercury vapor; calibration filter is built into the meter. Other gases or vapors that interfere include acetone, aniline, benzene, ozone, and others that absorb radiation at 253.7 nm.

Photometry, visible (narrow-centered 394-nm band pass)—Continuous monitoring of SO_2, SO_3, H_2S, mercaptans, and total sulfur compounds in ambient air. Operates more than 3 days unattended.

Polarography—Monitors gaseous oxygen in flue gases, automobile exhausts, hazardous environments, and food storage atmospheres, as well as dissolved oxygen in wastewater samples. Battery operated, portable, sample temperature range 32° to 110°F, up to 95% relative humidity. Potentiometric recorder output. Maximum distance between sensor and amplifier is 1000 feet.

Radioactivity—Continuous monitoring of ambient gamma and x-radiation by measurement of ion chamber currents, averaging or integrating over a constant recycling time interval; sample temperature limits 32°F to 120°F and 0 to 95% relative humidity (weatherproof detector); up to 1000-foot remote sensing capability. Recorder and computer outputs. Complete with alert, scram, and failure alarm systems. All solid-state circuitry.

Radioactivity—Continuous monitoring of beta- or gamma-emitting radioactive materials within gaseous or liquid effluents; either a thin-wall Geiger–Müller tube or a gamma scintillation crystal detector is selected depending on the isotope of interest; gaseous effluent flow is 4 cfm; effluent sample temperature limits are 32°F to 120°F using a scintillation detector and −65°F to 165°F using a Geiger–Müller detector. Complete with high radiation, alert, and failure alarms.

Radioactivity—Continuous monitoring of radioactive airborne particulates collected on a filter tape transport system; rate of air flow is 10 scfm; scintillation and Geiger–Müller detectors optional but a beta-sensitive plastic scintillator is provided to reduce shielding requirements and offer greater sensitivity. Air sample temperature limits are 32°F to 120°F; weight is 550 pounds. Complete with high- and low-flow alarm and filter failure alarm.

Direct-Reading Colorimetric Devices

Direct-reading colorimetric devices are widely used, easy to operate, and inexpensive. They utilize the chemical properties of an atmospheric contaminant for the reaction of that substance with a color-producing reagent, revealing stain length or color intensity. Stain lengths or color intensities can be read directly to provide an instantaneous value of the concentration accurate within ±25%. Reagents used in detector kits may be in either a liquid or a solid phase or provided in the form of chemical-treated papers. The liquid and solid reagents are generally supported in sampling devices through which a measured amount of contaminated air is drawn. On the other hand, chemically treated papers are usually exposed to the atmosphere and the reaction time noted for a color change to occur (NIOSH, 2014).

Calibration of Direct-Reading Instruments

Two common methods used for calibrating direct-reading instruments are

1. *The static method*, which is easy to use and efficient. A known volume of gas is introduced into the instrument and sampling is performed for a limited period of time.
2. *The dynamic method* uses the instrument to monitor a known concentration of the contaminant to test its accuracy.

AIR MONITORING AND CONFINED SPACE ENTRY

When a confined space is to be entered, it is important to remember that you can never rely on your senses to determine if the air in the confined space is safe. You cannot see or smell many toxic gases and vapors, nor can you determine the level of oxygen present (Spellman, 1999). One of the most common and important functions that an environmental professional responsible for safety and health is called upon to perform is with regard to evaluation of confined spaces for safe entry. A *confined space* is defined as a space large enough and so configured that an employee can bodily enter and perform assigned work, has limited or restricted means for entry or exit, and is not designed for continuous employee occupancy. A *permit-required confined space* (a permit is a written or printed document provided by the employer to allow and control entry into a permit space) has one or more of the following characteristics: (1) contains or has the potential to contain a hazardous atmosphere, (2) contains a material that has the potential for engulfing an entrant, (3) has a configuration such that an entrant could be trapped or asphyxiated by inwardly converging walls or by a floor that slopes downward and tapers to a smaller cross-section, or (4) contains any recognized serious safety or health hazard.

To ensure the safety and health of a confined space entrant, atmospheric monitoring (testing) is required for two distinct purposes: evaluation of the hazards of the permit space and verification that acceptable entry conditions for entry into that space exist.

1. *Evaluation testing*—The atmosphere of a confined space should be analyzed using equipment of sufficient sensitivity and specificity to identify and evaluate any hazardous atmospheres that may exist or arise so appropriate permit entry procedures can be developed and acceptable entry conditions stipulated for that space. Evaluation and interpretation of these data and development of entry procedures should be done by, or reviewed by, a technically qualified industrial hygienist based on evaluation of all serious hazards.

2. *Verification testing*—The atmosphere of a permit space that may contain a hazardous substance should be tested for residues of all contaminants identified by evaluation testing using permit-specified equipment to determine that residual concentrations at the time of testing and entry are within the range of acceptable entry conditions. Results of testing (e.g., actual concentrations) should be recorded on the permit in the space provided adjacent to the acceptable entry condition.
3. *Duration of testing*—Measurement of values for each atmospheric parameter should be made for at least the minimum response time of the test instrument specified by the manufacturer.
4. *Testing stratified atmospheres*—When monitoring for entries involving a descent into an atmosphere that may be stratified, the atmospheric envelope should be tested a distance of approximately 4 feet in the direction of travel and to each side. If a sampling probe is used, the entrant's rate of progress should be slowed to accommodate the sampling speed and detector response.

NOISE AND VIBRATION

High noise levels in the workplace are a hazard to employees. High noise levels are a physical stress that may produce psychological effects by annoying, startling, or disrupting the worker's concentration, which can lead to accidents. High levels can also result in damage to the worker's hearing, resulting in hearing loss. In this section, we discuss the basics of noise, including those elements industrial hygienists need to know to ensure that their organization's hearing conservation program is in compliance with OSHA. We also discuss the basics of vibration and its control; vibration is closely related to noise.

OSHA NOISE CONTROL REQUIREMENTS

In 1983, OSHA adopted a Hearing Conservation Amendment to OSHA 29 CFR 1910.95 requiring employers to implement *hearing conservation programs* in any work setting where employees are exposed to an 8-hour time-weighted average of 85 dBA and above. Employers must monitor all employees whose noise exposure is equivalent to or greater than a noise exposure received in 8 hours where the noise level is constantly 85 dB. The exposure measurement must include all continuous, intermittent, and impulsive noise within an 80- to 130-dB range and must be taken during a typical work situation. This requirement is performance oriented because it allows employers to choose the monitoring method that best suits each individual situation. In addition to concerns over noise levels, the OSHA standard also addresses the issue of duration of exposure. LaBar (1989) explains the duration aspects of the regulation as follows:

> Duration is another key factor in determining the safety of workplace noise. The regulation has a 50 percent 5 dBA logarithmic tradeoff. That is, for every 5-decibel increase in the noise level, the length of exposure must be reduced by 50%. For example, at 90 decibels (the sound level of a lawnmower or shop tools), the limit on "safe" exposure is 8 hours. At 95 dBA, the limit on exposure is 4 hours, and so on. For any sound that is 106 dBA and above—this would include such things as a sandblaster, rock concert, or jet engine—exposure without protection should be less than 1 hour, according to OSHA's rule.

The basic requirements of OSHA's Hearing Conservation Standard are explained below (LaBar, 1989):

- *Monitoring noise levels.* Noise levels should be monitored on a regular basis. Whenever a new process is added, an existing process is altered, or new equipment is purchased, special monitoring should be undertaken immediately.

- *Medical surveillance.* The medical surveillance component of the regulation specifies that employees who will be exposed to high noise levels should be tested upon being hired and again at least annually.
- *Noise controls.* The regulation requires that steps be taken to control noise at the source. Noise controls are required in situations where the noise level exceeds 90 dBA. Administrative controls are sufficient until noise levels exceed 100 dBA. Beyond 100 dBA engineering controls must be used.
- *Personal protection.* Personal protective devices are specified as the next level of protection when administrative and engineering controls do not reduce noise hazards to acceptable levels. They are to be used in addition to rather than instead of administrative and engineering controls.
- *Education and training.* The regulation requires the provision of education and training to do the following: ensure that employees understand (1) how the ear works, (2) how to interpret the results of audiometric tests, (3) how to select personal protective devices that will protect them against the types of noise hazards to which they will be exposed, and (4) how to properly use personal protective devices.

NOISE AND HEARING LOSS TERMINOLOGY

There are many specialized terms used to express concepts in noise, noise control, and hearing loss prevention. The environmental practitioner responsible for ensuring compliance with OSHA's Hearing Conservation Program requirements must be familiar with these terms. The NIOSH (2005) definitions below were written in as non-technical a fashion as possible.

Acoustic trauma—A single incident that produces an abrupt hearing loss. Welding sparks (to the eardrum), blows to the head, and blast noise are examples of events capable of providing acoustic trauma.

Action level—The sound level which when reached or exceeded necessitates implementation of activities to reduce the risk of noise-induce hearing loss. OSHA currently uses an 8-hour time-weighted average of 85 dBA as the criterion for implementing an effective hearing conservation program.

Attenuate—Reduce the amplitude of sound pressure (noise).

Attenuation:

Real ear attenuation at threshold (REAT)—A standardized procedure for conducting psychoacoustic tests on human subjects designed to measure sound protection features of hearing protective devices. Typically, these measures are obtained in a calibrated sound field and represent the difference between subjects' hearing thresholds when wearing a hearing protector vs. not wearing the protector.

Real-world attenuation—Estimated sound protection provided by hearing protective devices as worn in "real-world" environments.

Audible range—The frequency range over which normal ears hear, approximately 20 Hz through 20,000 Hz.

Audiogram—A chart, graph, or table resulting from an audiometric test showing an individual's hearing threshold levels as a function of frequency.

Audiologist—A professional, specializing in the study and rehabilitation of hearing, who is certified by the American Speech–Language–Hearing Association or licensed by a state board of examiners.

Background noise—Noise from sources other than the particular noise sources being monitored.

Baseline audiogram—A valid audiogram against which subsequent audiograms are compared to determine if hearing thresholds have changed. The baseline audiogram is preceded by a quiet period so as to obtain the best estimate of the person's hearing at that time.

Continuous noise—Noise of a constant level as measured over at least one second using the "slow" setting on a sound level meter. Note that a noise that is intermittent (e.g., on for over a second and then off for a period) would be both variable and continuous.

Controls:

Administrative—Efforts, usually by management, to limit workers' noise exposure by modifying workers' schedule or location, or by modifying the operating schedule of noisy machinery.

Engineering—Any use of engineering methods to reduce or control the sound level of a noise source by modifying or replacing equipment, making any physical changes at the noise source or along the transmission path (with the exception of hearing protectors).

Criterion sound level—A sound level of 90 decibels.

dB (decibel)—The unit used to express the intensity of sound. The decibel was named after Alexander Graham Bell. The decibel scale is a logarithmic scale in which 0 dB approximates the threshold of hearing in the mid-frequencies for young adults and in which the threshold of discomfort is between 85 and 95 dB SPL and the threshold for pain is between 120 and 140 dB SPL.

Double hearing protection—A combination of both ear-plug and ear-muff types of hearing protection devices is required for employees who have demonstrated temporary threshold shift during audiometric examination and for those who have been advised to wear double protection by a medical doctor in work areas that exceed 104 dBA.

Dosimeter—When applied to noise, refers to an instrument that measures sound levels over a specified interval, stores the measures, and calculates the sound as a function of sound level and sound duration and describes the results in terms of, dose, time-weighted average, and (perhaps) other parameters such as peak level, equivalent sound level, sound exposure level, etc.

Equal-energy rule—The relationship between sound level and sound duration based on a 3-dB exchange rate; that is, the sound energy resulting from doubling or halving a noise exposure's duration is equivalent to increasing or decreasing the sound level by 3 dB, respectively.

Exchange rate—The relationship between intensity and dose. OSHA uses a 5-dB exchange rate. Thus, if the intensity of an exposure increases by 5 dB, the dose doubles. Sometimes this is also referred to as the doubling rate. The U.S. Navy uses a 4-dB exchange rate; the U.S. Army and Air Force use a 3-dB exchange rate. NIOSH recommends a 3-dB exchange rate. Note that the equal-energy rule is based on a 3-dB exchange rate.

Frequency—Rate in which pressure oscillations are produced; measured in hertz (Hz).

Hazardous noise—Any sound for which any combination of frequency, intensity, or duration is capable of causing permanent hearing loss in a specified population.

Hazardous task inventory—A concept based on using work tasks as the central organizing principle for collecting descriptive information on a given work hazard. It consists of a list of specific tasks linked to a database containing the prominent characteristics relevant to the hazard of interest which are associated with each task.

Hearing conservation record—Employee's audiometric record, which includes name, age, job classification, TWA exposure, date of audiogram, and name of the audiometric technician. It is to be retained for the duration of employment for OSHA purposes and indefinitely for workers' compensation purposes.

Hearing damage risk criteria—A standard that defines the percentage of a given population expected to incur a specified hearing loss as a function of exposure to a given noise exposure.

Hearing handicap—A specified amount of permanent hearing loss usually averaged across several frequencies that negatively impacts employment and/or social activities. Handicap is often related to an impaired ability to communicate. The degree of handicap will also be related to whether the hearing loss is in one or both ears and whether the better ear has normal or impartial hearing.

Hearing loss—Hearing loss is often characterized by the area of the auditory system responsible for the loss. For example, when injury or a medical condition affects the outer ear or middle ear (i.e., from the pinna, ear canal, and ear drum to the cavity behind the ear drum—which includes the ossicles) the resulting hearing loss is referred to as a *conductive* loss. When an injury or medical condition affects the inner ear or the auditory nerve that connects the inner ear to the brain (i.e., the cochlea and the VIIIth cranial nerve) the resulting hearing loss is referred to as a *sensorineural* loss. Thus, a welder's spark that damages the ear drum causes a conductive hearing loss. When noise damages the tiny hair cells located in the cochlea, sensorineural hearing loss occurs.

Hearing loss prevention program audit—An assessment performed prior to putting a hearing loss prevention program into place or before changing an existing program. The audit should be a top-down analysis of the strengths and weaknesses of each aspect of the program.

Hearing threshold level (HTL)—The hearing level, above a reference value, at which a specified sound or tone is heard by an ear in a specified fraction of the trials. Hearing threshold levels have been established so that 0 dB HTL reflects the best hearing of a group of persons.

Hz (hertz)—The unit of measurement for audio frequencies. The frequency range for human hearing lies between 20 Hz and approximately 20,000 Hz. The sensitivity of the human ear drops off sharply below about 500 Hz and above 4000 Hz.

Impulsive noise—Used to generally characterize impact or impulse noise which is typified by a sound that rapidly rises to a sharp peak and then quickly fades. The sound may or may not have a "ringing" quality (such as a striking a hammer on a metal plate or a gunshot in a reverberant room). Impulsive noise may be repetitive or may be a single event (as with a sonic boom). If impulses are occurring in very rapid succession (such as with some jack hammers), the noise would not be described as impulsive.

Loudness—The subjective attribute of a sound by which it would be characterized along a continuum from soft to loud. Although this is a subjective attribute, it depends primarily upon sound pressure level and, to a lesser extent, the frequency characteristics and duration of the sound.

Material hearing impairment—As defined by OSHA, a material hearing impairment is an average hearing threshold level of 25 dB HTL at the frequencies of 1000, 2000, and 3000 Hz.

Medical pathology—A disorder or disease. For the purposes of this program, a condition or disease affecting the ear that a physician specialist should treat.

Noise—Any unwanted sound.

Noise dose—The noise exposure expressed as a percentage of the allowable daily exposure. For OSHA, a 100% dose would equal an 8-hour exposure to a continuous 90-dBA noise; a 50% dose would equal an 8-hour exposure to an 85-dBA noise or a 4-hour exposure to a 90-dBA noise. If 85 dBA is the maximum permissible level, then an 8-hour exposure to a continuous 85-dBA noise would equal a 100% dose. If a 3-dB exchange rate is used in conjunction with an 85-dBA maximum permissible level, a 50% dose would equal a 2-hour exposure to 88 dBA or an 8-hour exposure to 82 dBA.

Noise dosimeter—An instrument that integrates a function of sound pressure over a period of time to directly indicate a noise dose.

Noise hazard area—Any area where noise levels are equal to or exceed 85 dBA. OSHA requires employers to designate work areas, post warning signs, and warn employees when work practices exceed 90 dBA as a "Noise Hazard Area." Hearing protection must be worn whenever 90 dBA is reached or exceeded.

Noise hazard work practice—Performing or observing work where 90 dBA is equaled or exceeded. Some work practices will be specified; however, as a rule of thumb, whenever attempting to hold normal conversation with someone who is 1 foot away and shouting must be employed to be heard one can assume that a 90-dBA noise level or greater exists and hearing protection is required. Typical examples of work practices where hearing protection is required are jack hammering, heavy grinding, heavy equipment operations, and similar activities.

Noise-induced hearing loss—A sensorineural hearing loss that is attributed to noise and for which no other etiology can be determined.

Noise level measurement—Total sound level within an area; includes workplace measurements indicating the combined sound levels of tool noise (from ventilation systems, cooling compressors, circulation pumps, etc.).

Noise reduction rating (NRR)—The NRR is a single-number rating method that attempts to describe a hearing protector based on how much the overall noise level is reduced by the hearing protector. When estimating A-weighted noise exposures, it is important to remember to first subtract 7 dB from the NRR and then subtract the remainder from the A-weighted noise level. The NRR theoretically provides an estimate of the protection that should be met or exceeded by 98% of the wearers of a given device. In practice, this does not prove to be the case, so a variety of methods for "de-rating" the NRR have been discussed.

Ototoxic—A term typically associated with the sensorineural hearing loss resulting from therapeutic administration of certain prescription drugs.

Ototraumatic—A broader term than ototoxic. As used in hearing loss prevention, refers to any agent (e.g., noise, drugs, industrial chemicals) that has the potential to cause permanent hearing loss subsequent to acute or prolong exposure.

Presbycusis—The gradual increase in hearing loss that is attributable to the effects of aging and not related to medical causes or noise exposure.

Sensorineural hearing loss—A hearing loss resulting from damage to the inner ear (from any source).

Sociacusis—A hearing loss related to nonoccupational noise exposure.

Sound intensity (I)—Sound intensity at a specific location is the average rate at which sound energy is transmitted through a unit area normal to the direction of sound propagation.

Sound level meter (SLM)—A device that measures sound and provides a readout of the resulting measurement. Some provide only A-weighted measurements, others provide A- and C-weighted measurements, and some can provide weighted, linear, and octave (or narrower) band measurements. Some SLMs are also capable of providing time-integrated measurements.

Sound power—The total sound energy radiated by a source per unit time. Sound power cannot be measured directly.

Sound pressure level (SPL)—A measure of the ratio of the pressure of a sound wave relative to a reference sound pressure. Sound pressure level in decibels is typically referenced to 20 mPa. When used alone (e.g., 90 dB APL) a given decibel level implies an unweighted sound pressure level.

Standard threshold shift (STS)—(1) OSHA uses the term to describe a change in hearing threshold relative to the baseline audiogram of an average of 10 dB or more at 2000, 3000, and 4000 Hz in either ear. It is used by OSHA to trigger additional audiometric testing and related follow-up. (2) NIOSH uses this term to describe a change of 15 dB or more at any frequency, 5000 through 6000 Hz, from baseline levels that is present on an immediate retest in the same ear and at the same frequency. NIOSH recommends a confirmation audiogram within 30 days with the confirmation audiogram preceded by a quiet period of at least 14 hours.

Threshold shift—Audiometric monitoring programs will encounter two types of changes in hearing sensitivity threshold shifts: permanent threshold shift (PTS) and temporary threshold shift (TTS). As the names imply, any change in hearing sensitivity that is persistent is considered a PTS. Persistence may be assumed if the change is observed on a 30-day follow-up exam. Exposure to loud noise may cause a temporary worsening in hearing sensitivity (i.e., a TTS) that may persist for 14 hours (or even longer in cases where the exposure duration exceeded 12 to 16 hours). Hearing health professionals need to recognize that not all threshold shifts represent decreased sensitivity, and not all temporary or permanent threshold shifts are due to noise exposure. When a permanent threshold shift can be attributable to noise exposure, it may be referred to as a noise-induced permanent threshold shift (NIPTS).

Velocity—The speed at which the regions of sound producing pressure changes move away from the sound source.

Wavelength—The distance required for one complete pressure cycle to be completed (1 wavelength), measured in feet or meters.

Weighted measurements—Two weighting curves are commonly applied to measures of sound levels to account for the way the ear perceives the loudness of sounds.

A-weighting—A measurement scale that approximates the loudness of tones relative to a 40-db SPL 1000-Hz reference tone. A-weighting has the added advantage of being correlated with annoyance measures and is most responsive to the mid-frequencies of 500 to 4000 Hz.

C-weighting—A measurement scale that approximates the loudness of tones relative to a 90-dB SPL 1000-Hz reference tone. C-weighting has the added advantage of providing a relatively flat measurement scale that includes very low frequencies.

OCCUPATIONAL NOISE EXPOSURE

Noise is commonly defined as any unwanted sound. Noise literally surrounds us every day and is with us just about everywhere we go. However, the noise we are concerned with here is that produced by industrial processes. Excessive amounts of noise in the work environment (and outside of it) cause many problems for workers, including increased stress levels, interference with communication, disrupted concentration, and, most importantly, varying degrees of hearing loss. Exposure to high noise levels also adversely affects job performance and increases accident rates. One of the major problems with attempting to protect workers' hearing acuity is the tendency of many workers to ignore the dangers of noise. Because hearing loss, like cancer, is insidious, it is easy to ignore. It can sneak up slowly and not be apparent (in many cases) until after the damage is done. Alarmingly, hearing loss from occupational noise exposure has been well documented since the 18th century, yet since the advent of the industrial revolution the number of exposed workers has greatly increased. Today, however, the picture of hearing loss is not as bleak as it has been in the past, as a direct result of OSHA's requirements. Now that noise exposure must be controlled in all industrial environments, that well-written and well-managed hearing conservation programs must be put in place, and that employee awareness must be raised with regard to the dangers of exposure to excessive levels of noise, job-related hearing loss is coming under control.

DETERMINING WORKPLACE NOISE LEVELS

The unit of measurement for sound is the decibel. *Decibels* are the preferred unit for measuring sound, and the name is derived from the bel, a unit of measure in electrical communications engineering. The decibel is a dimensionless unit used to express the logarithm of the ratio of a measured quantity to a reference quantity. With regard to noise control in the workplace, the industrial hygienist's primary concern is first to determine if any noise producers in the facility exceed the OSHA limits for worker exposure—exactly which machines or processes produce noise at unacceptable levels. Making this determination is accomplished by conducting a noise level survey of the plant or facility. Sound measuring instruments are used to make this determination. These include noise dosimeters, sound level meters, and octave-band analyzers. The uses and limitations of each kind of instrument are discussed below:

1. *Noise dosimeter*—The noise dosimeters used by OSHA meet the American National Standards Institute (ANSI) Standard S1.25-1978, "Specifications for Personal Noise Dosimeter," which set performance and accuracy tolerances. For OSHA use, the dosimeter must have a 5-dB exchange rate, use a 90-dBA criterion level, be set at slow response, and use either an 80-dBA or 90-dBA threshold gate, or a dosimeter that has both capabilities, whichever is appropriate for evaluation.
2. *Sound level meter (SLM)*—When conducting the noise level survey, the industrial hygienist or survey technician should use an ANSI-approved sound level meter, a device used most commonly to measure sound pressure. The SLM measures in decibels. One decibel is one-tenth of a bel and is the minimum difference in loudness that is usually perceptible.
3. *Octave-band noise analyzers*—Several Type 1 sound level meters (such as the GenRad 1982 and 1983 and the Quest 155) used by OSHA have built-in octave band analysis capability. These devices can be used to determine the feasibility of controls for individual noise sources for abatement purposes and to evaluate hearing protectors. Octave-band analyzers segment noise into its component parts. The octave-band filter sets provide filters with the following center frequencies: 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000, and 16,000 Hz. The special signature of a given noise can be obtained by taking sound level meter readings at each of these settings (assuming that the noise is fairly constant over time). The results may indicate those octave bands that contain the majority of the total radiated sound power. Octave-band noise analyzers can assist industrial hygienists in determining the adequacy of various types of frequency-dependent noise controls. They can also be used to select hearing protectors because they can measure the amount of attenuation offered by the protectors in the octave bands responsible for most of the sound energy in a given situation.

ENGINEERING CONTROL FOR INDUSTRIAL NOISE

When environmental professionals investigate the possibility of using engineering controls to control noise, the first thing they recognize is that reducing or eliminating all noise is virtually impossible, and this should not be the focus in the first place. Instead, eliminating or reducing hazards is the goal. Although the primary hazard may be the possibility of hearing loss, the distractive effect (or its interference with communication) must also be considered. The distractive effect of excessive noise can certainly be classified as hazardous whenever the distraction might affect the attention of the worker. The obvious implication of noise levels that interfere with communications is emergency response. If ambient noise is at such a high level that workers cannot hear fire or other emergency alarms, this is obviously an unacceptable situation.

So what does all this mean? Environmental professionals must determine the acceptable level of noise. They can then look into applying the appropriate noise control measures. These include making alterations in engineering design (which obviously can only be accomplished in the design phase) or making modifications after installation. Unfortunately, this latter method is the one environmental professionals are usually forced to apply—and also the most difficult, depending on circumstances. Let's assume that the environmental professional is trying to reduce noise levels generated by an installed air compressor to a safe level. The first place to start is at the *source*: the air compressor. Several options are available to employ at the source. First, the safety engineer would look at the possibility of modifying the air compressor to reduce its noise output. One option might be to install resilient vibration mounting devices. Another might be to change the coupling between the motor and the compressor.

If the options described for use at the source of the noise are not feasible or are only partially effective, the next component the environmental professional would look at is the *path* along which the sound energy travels. Increasing the distance between the air compressor and the workers could be a possibility. (Sound levels decrease with distance.) Another option might be to install acoustical treatments on ceilings, floors, and walls. The best option available (in this case) probably is to enclose the air compressor, so that the dangerous noise levels are contained within the enclosure, and the sound leaving the space is attenuated to a lower, safer level. If total enclosure of the air compressor is not practicable, then erecting a barrier or baffle system between the compressor and the open work area might be an option.

The final engineering control component the environmental professional might incorporate to reduce the air compressor's noise problem is to consider the *receiver* (the worker/operator). An attempt should be made to isolate the operator by providing a noise reduction or soundproof enclosure or booth for the operator.

AUDIOMETRIC TESTING

Audiometric testing monitors an employee's hearing acuity over time. It also provides an opportunity for employers to educate employees about their hearing and the need to protect it. The employer must establish and maintain an audiometric testing program. The important elements of the program include baseline audiograms, annual audiograms, training, and follow-up procedures. Employers must make audiometric testing available at no cost to all employees who are exposed to an action level of 85 dB or above, measured as an 8-hour TWA. The audiometric testing program follow-up should indicate whether the employer's hearing conservation program is preventing hearing loss. A licensed or certified audiologist, otolaryngologist, or other physician must be responsible for the program. Both professionals and trained technicians may conduct audiometric testing. The professional in charge of the program does not have to be present when a qualified technician conducts tests. The professional's responsibilities include overseeing the program and the work of the technicians, reviewing problem audiograms, and determining whether referral is necessary.

The employee needs a referral for further testing when test results are questionable or when related medical problems are suspected. If additional testing is necessary or if the employer suspects a medical pathology of the ear that is caused or aggravated by wearing hearing protectors, the employer must refer the employee for a clinical audiological evaluation or otological exam, as appropriate. There are two types of audiograms required in the hearing conservation program: baseline and annual audiograms.

The *baseline audiogram* is the reference audiogram against which future audiograms are compared. Employers must provide baseline audiograms within 6 months of an employee's first exposure at or above an 8-hour TWA of 85 dB. An exception is allowed when the employer uses a mobile test van for audiograms. In these instances, baseline audiograms must be completed within 1 year after an employee's first exposure to workplace noise at or above a TWA of 85 dB. Employees, however, must be fitted with, issued, and required to wear hearing protectors whenever they are exposed to noise levels above a TWA of 85 dB or any period exceeding 6 months after their first exposure until the baseline audiogram is conducted. Baseline audiograms taken before the hearing conservation program took effect in 1983 are acceptable if the professional supervisor determines that the audiogram is valid. Employees should not be exposed to workplace noise for 14 hours before the baseline test or be required to wear hearing protectors during this time period.

Employers must provide annual audiograms within 1 year of the baseline. It is important to test workers' hearing annually to identify deterioration in their hearing acuity as early as possible. This enables employers to initiate protective follow-up measures before hearing loss progresses. Employers must compare annual audiograms to baseline audiograms to determine whether the audiogram is valid and whether the employee has lost hearing acuity or experienced a standard threshold shift (STS). An STS is an average shift in either ear of 10 dB or more at 2000, 3000, and 4000 hertz.

The employer must fit or refit any employee showing an STS with adequate hearing protectors, show the employee how to use them, and require the employee to wear them. Employers must notify employees within 21 days after the determination that their audiometric test results show an STS. Some employees with an STS may need further testing if the professional determines that their

TABLE 11.3
Permissible Noise Exposures per 29 CFR 1910.95

Duration per Day (hours)	Sound Level dBA Slow Response
8	90
6	92
4	95
3	97
2	100
1.5	102
1	105
0.5	110
0.25 or less	115

Note: When the daily noise exposure is composed of two or more periods of noise exposure of different levels, their combined effect should be considered, rather than the individual effect of each. If the sum of the fractions $C_1/T_1 + C_2/T_2 + C_n/T_n$ exceeds unity, then the mixed exposure should be considered to exceed the limit value. C_n indicates the total time of exposure at a specified noise level, and T_n indicates the total time of exposure permitted at that level. Exposure to impulsive or impact noise should not exceed the 140-dB peak sound pressure level.

test results are questionable or if they have an ear problem thought to be caused or aggravated by wearing hearing protectors. If the suspected medical problem is not thought to be related to wearing hearing protection, the employer must advise the employee to see a physician. If subsequent audiometric tests show that the STS identified on a previous audiogram is not persistent, employees whose exposure to noise is less than a TWA of 90 dB may stop wearing hearing protectors.

The employer may substitute an annual audiogram for the original baseline audiogram if the professional supervising the audiometric program determines that the employee’s STS is persistent. The employer must retain the original baseline audiogram, however, for the length of the employee’s employment. This substitution will ensure that the same shift is not repeatedly identified. The professional also may decide to revise the baseline audiogram if the employee’s hearing improves. This will ensure that the baseline reflects actual hearing thresholds to the extent possible. Employers must conduct audiometric tests in a room meeting specific background levels and with calibrated audiometers that meet American National Standard Institute (ANSI) specifications of SC-1969.

Any company’s written hearing conservation program should provide the effects of noise exposure when the sound levels exceed those shown in Table 11.3 (when measured on the A scale of a standard sound level meter at slow response).

NOISE UNITS, RELATIONSHIPS, AND EQUATIONS

A number of noise units, relationships, and equations that are important to industrial hygienists involved with controlling noise hazards in the workplace are discussed below.

Sound Power

Sound power of a source is the total sound energy radiated by the source per unit time. It is expressed in terms of the sound power level (L_w) in decibels referenced to 10^{-12} watts (w_0). The relationship to decibels is shown below:

$$L_w = 10 \log_{10} w/w_0$$

where

L_w = Sound power level (decibels).
$\log_{10}$ = Logarithm to the base 10.
w = Sound power (watts).
w_0 = Reference power (10^{-12} watts).

Sound Pressure

Units used to describe sound pressures are

$$1\ \mu\text{bar} = 1\ \text{dyne/cm}^2 = 0.1\ \text{N/cm}^2 = 0.1\ \text{Pa}$$

Sound Pressure Level

$$\text{SPL (decibels)} = 10 \log(p^2/p_0)$$

where

p = Measured rms sound pressure (N/m^2, µbars).[*]
p_0 = Reference rms sound pressure (20 µPa, N/m^2, µbars).

Speed of Sound

$$c = f_1$$

Wavelength

$$\lambda = c/f$$

Octave Band Frequencies

$$\text{Upper frequency band} = f_2 = 2f_1$$

where

f_2 = Upper frequency band.
f_1 = Lower frequency band.

$$\text{One-half octave band} = f_2 = \sqrt{2(f_1)}$$

where

f_2 = 1/2 octave band.
f_1 = Lower frequency band.

$$\text{One-third octave band} = f_2 = \sqrt[3]{2(f_1)}$$

where

f_2 = 1/3 octave band.
f_1 = lower frequency band.

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[*] The root-mean-square (rms) value of a changing quantity, such as sound pressure, is the square root of the mean of the squares of the instantaneous values of the quantity.

Adding Noise Sources

When sound power is known:

$$L_w = 10\log\left(\frac{w_1 + w_2}{w_0 + w_0}\right)$$

where

L_w = Sound power (watts).
w_1 = Sound power of noise source 1 (watts).
w_2 = Sound power of noise source 2 (watts).
w_0 = Reference sound power (reference 10^{-12}) (watts).

Sound Pressure Additions

When sound pressure is known:

$$SPL\text{ (decibels)} = 10\log\left(\frac{p^2}{p_0^2}\right)$$

where

$p^2/p_0^2 = 10^{SPL/10}$.
p = Measured root-mean-square (rms) sound pressure (N/m^2, μbars).
p_0 = Reference rms sound pressure (20 μPa, N/m^2, μbars).

For three sources, the equation becomes

$$SPL = 10\ \log\left[\left(10^{SPL_1/10}\right) + \left(10^{SPL_2/10}\right) + \left(10^{SPL_3/10}\right)\right]$$

When adding any number of sources, whether or not the sources are identical, the equation becomes

$$SPL = 10\ \log\left[\left(10^{SPL_1/10}\right) + \cdots + \left(10^{SPL_n/10}\right)\right]$$

To determine the sound pressure level from multiple identical sources, use the following equation:

$$SPL_f = SPL_i + 10\log(n)$$

where

SPL_f = Total sound pressure level (dB).
SPL_i = Individual sound pressure level (dB).
n = Number of identical sources.

Noise Levels in a Free Field

$$SPL = L_w - 20\log(r) - 0.5$$

where

SPL = Sound pressure (reference 0.00002 N/m^2).
L_w = Sound power (reference 10^{-12} watts).
r = Distance (feet).

Noise Levels with Directional Characteristics

$$SPL = L_w - 20\log(r) - 0.5 + \log(Q)$$

where

SPL = Sound pressure (reference 0.00002 N/m^2).

L_w = Sound power (reference 10^{-12} watts).

r = Distance (feet).

Q = Directivity factor.

= 2 for one reflecting plane.

= 4 for two reflecting planes.

= 8 for three reflecting planes.

Noise Level at a New Distance from the Noise Source

$$SPL = SPL_1 + 20\log(d_1/d_2)$$

where

SPL = Sound pressure level at new distance (d_2).

SPL_1 = Sound pressure level at d_1.

d_n = Distance from source.

Daily Noise Dose

The following formula combines the effects of different sound pressure levels and allowable exposure times:

$$\text{Daily noise dose} = \frac{C_1 + C_2 + C_3 + \cdots + C_n}{T_1 + T_2 + T_3 + \cdots + T_n}$$

where

C_i = Number of hours exposed at given SPL_i.

T_i = Number of hours exposed at given SPL_i.

OSHA Permissible Noise Levels

$$T_{SPL} = 8/2^{(SPL-90)/5}$$

where

T_{SPL} = Time at given SPL (hours).

SPL = Sound pressure level (dBA).

Equivalent Eight-Hour TWA

$$TWA_{eq} = 16.61\log\left(\frac{D}{100}\right) + 90$$

where

TWA_{eq} = Eight-hour equivalent TWA (dBA).

D = Noise dosimeter reading (%).

INDUSTRIAL VIBRATION CONTROL

Vibration is often closely associated with noise but is frequently overlooked as a potential occupational health hazard. Vibration is defined as the oscillatory motion of a system around an equilibrium position. The system can be in a solid, liquid, or gaseous state, and the oscillation of the system can be periodic or random, steady state or transient, continuous or intermittent (NIOSH, 1973). Vibrations of the human body (or parts of the human body) are not only annoying but also affect worker performance and sometimes cause blurred vision and loss of motor control. Excessive vibration can cause trauma, which results when external vibrating forces accelerate the body or some part so that amplitudes and restraining capacities by tissues are exceeded. Vibration results in the mechanical shaking of the body or parts of the body. These two types of vibration are called *whole-body vibration* (affecting vehicle operators) and *segmental vibration* (occurring in foundry operations, mining, stonecutting, and a variety of assembly operations, for example). Vibration originates from mechanical motion, generally occurring at some machine or series of machines. This mechanical vibration can be transmitted directly to the body or body part or it may be transmitted through solid objects to a worker located at some distance away from the actual vibration.

The effect of vibration on the human body is not totally understood; however, we do know that vibration of the chest may create breathing difficulties, and that an inhibition of tendon reflexes is a result of vibration. Excessive vibration can cause reduced ability on the part of the worker to perform complex tasks, and indications of potential damage to other systems of the body also exist.

More is known about the results of segmental vibration (typically transmitted through hand to arm), and a common example is the vibration received when using a pneumatic hammer—jackhammer. One recognized indication of the effect of segmental vibration is impaired circulation to the appendage, a condition known as *Raynaud's syndrome*, also known as "dead fingers" or "white fingers." Segmental vibration can also result in the loss of the sense of touch in the affected area. Some indications that decalcification of the bones in the hand can result from vibration transmitted to that part of the body exist. In addition, muscle atrophy has been identified as a result of segmental vibration.

As with noise, the human body can withstand short-term vibration, even though this vibration might be extreme. The dangers of vibration are related to certain frequencies that are resonant with various parts of the body. Vibration outside these frequencies is not nearly as dangerous as vibration that results in resonance. Control measures for vibration include substituting some other device (one that does not cause vibration) for the mechanical device that causes the vibration. An important corrective measure (often overlooked) that helps in reducing vibration is proper maintenance of tools, or support mechanisms for tools, including coating the tools with materials that attenuate vibrations. Another engineering control often employed to reduce vibration is the application of balancers, isolators, and damping devices or materials that help to reduce vibration.

RADIATION

The type of radiation that most of us are familiar with is *ionizing radiation*. Very few people have difficulty in recognizing the potential destructive power of this type of radiation. However, fewer individuals are aware of another type of radiation, *non-ionizing radiation*, to which we are exposed each day. Even fewer people can differentiate between the two types. Industrial hygienists must be familiar with the nature of radiation and understand the detection of radiation, permissible exposure limits, biological effects of radiation, monitoring techniques, and control measures and procedures.

Radiation Safety Program Acronyms and Definitions*

Abbreviations Typically Used in Radiation Safety Programs

ALARA—As low as reasonably achievable
ALI—Annual limit on intake
AU—Authorized user
^{14}C—Carbon-14
CDC—Centers for Disease Control and Prevention
10 CFR 19—NRC's Title 10, Chapter 1, Code of Federal Regulations, Part 19
10 CFR 20—NRC's Title 10, Chapter 1, Code of Federal Regulations, Part 20

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* This list of acronyms and definitions typically included in radiation safety programs is adapted from CDC, *Radiation Safety Manual*, Centers for Disease Control and Prevention, Atlanta, GA, 1999.

Ci—Curie
cm^2—Square centimeters
^{60}Co—Cobalt-60
cpm—Counts per minute
^{51}Cr—Chromium-51
^{137}CS—Iodine-137
DAC—Derived air concentration
dpm—Disintegrations per minute
GM—Geiger–Müller
^{3}H—Tritium (hydrogen-3)
^{125}I—Iodine-125
^{129}I—Iodine-129
^{131}I—Iodine-131
kg—Kilogram
lfm—Linear feet per minute
LSC—Liquid scintillation counter
mCi—milliCurie
mL—milliliters
MeV—mega electron-volts
mrem—millirem (0.001 rem)
NaI—Sodium iodide
NRC—Nuclear Regulatory Commission
OHC—Occupational Health Clinic
OHS—Office of Health and Safety
^{32}P—Phosphorus-32
^{33}P—Phosphorus-33
PSA—Physical security activity
RIA—Radioimmunoassay
RSC—Radiation Safety Committee
RSO—Radiation Safety Officer
^{35}S—Sulfur-35
TLD—Thermoluminescent dosimeter

Typical Radiation Program Definitions

Absorbed dose is the energy imparted by ionizing radiation per unit mass of irradiated material. The units of absorbed dose are the rad and the gray (Gy).

Activity is the rate of disintegration (transformation) or decay of radioactive material. The units of activity are the curie (Ci) and the becquerel (Bq).

Alpha particle is a strongly ionizing particle emitted from the nucleus of an atom during radioactive decay, containing two protons and neutrons and having a double positive charge.

Alternate authorized user serves in the absence of the authorized user and can assume any duties as assigned.

Authorized user is an employee who is approved by the radiation safety officer and radiation safety committee and is ultimately responsible for the safety of those who use radioisotopes under his or her supervision.

Beta particle is an ionizing charge particle emitted from the nucleus of an atom during radioactive decay, equal in mass and charge to an electron.

Bioassay means the determination of kinds, quantities or concentrations, and, in some cases, the locations of radioactive material in the human body, whether by direct measurement (*in vivo* counting) or by analysis and evaluation of materials excreted or removed from the human body.

Biological half-life is the length of time required for one-half of a radioactive substance to be biologically eliminated from the body.

Bremsstrahlung is electromagnetic (x-ray) radiation associated with the deceleration of charged particles passing through matter.

Contamination is the deposition of radioactive material in any place where it is not wanted.

Controlled area means an area, outside of a restricted area but inside the site boundary, access to which can be limited by the licensee for any reason.

Counts per minute (cpm) is the number of nuclear transformations from radioactive decay able to be detected by a counting instrument in a one-minute time interval.

Curie (Ci) is a unit of activity equal to 37 billion disintegrations per second.

Declared pregnant woman means a woman who has voluntary informed her employer, in writing, of her pregnancy and the estimated date of conception.

Disintegrations per minute (dpm) is the number of nuclear transformation from radioactive decay in a one minute time interval.

Dose equivalent is a quantity of radiation dose expressing all radiation on a common scale for calculating the effective absorbed dose. The units of dose equivalent are the rem and sievert (SV).

Dosimeter is a device used to determine the external radiation dose a person has received.

Effective half-life is the length of time required for a radioactive substance in the body to lose one-half of its activity present through a combination of biological elimination and radioactive decay.

Exposure means the amount of ionization in air from x-rays and gamma rays.

Extremity means hand, elbow, and arm below the elbow, foot, knee, or leg below the knee.

Gamma rays are very penetrating electromagnetic radiations emitted from a nucleus and an atom during radioactive decay.

Half-life is the length of time required for a radioactive substance to lose one-half of its activity by radioactive decay.

Limits (dose limits) means the permissible upper bounds of radiation doses.

Permitted worker is a laboratory worker who does not work with radioactive materials but works in a radiation laboratory.

Photon means a type of radiation in the form of an electromagnetic wave.

Rad is a unit of radiation absorbed dose. One rad is equal to 100 ergs per gram.

Radiation (ionizing radiation) means alpha particles, beta particles, gamma rays, x-rays, neutrons, high-speed electrons, high-speed protons, and other particles capable of producing ions.

Radiation workers are those personnel listed on the Authorized User Form of the supervisor to conduct work with radioactive materials.

Radioactive decay is the spontaneous process of unstable nuclei in an atom disintegrating into stable nuclei, releasing radiation in the process.

Radioisotope is a radioactive nuclide of a particular element.

Rem is a unit of dose equivalent. One rem is approximately equal to one rad of beta, gamma, or x-ray radiation, or 1/20 of alpha radiation.

Restricted area means an area access to which is limited by the licensee for the purpose of protecting individuals against undue risks from exposure to radiation and radioactive materials.

Roentgen is a unit of radiation exposure. One roentgen is equal to 0.00025 Coulombs of electrical charge per kilogram of air.

Thermoluminescent dosimeter (TLD) is a dosimeter worn by radiation workers to measure their radiation dose. The TLD contains crystalline material which stores a fraction of the absorbed ionizing radiation and releases this energy in the form of light photons when heated.

Total effective dose equivalent (TEDE) is the sum of the deep-dose equivalent (for external exposures) and the committed effective dose equivalent (for internal exposures).

Unrestricted area refers to an area access to which is neither limited nor controlled by the licensee.

X-rays are a penetrating type of photon radiation emitted from outside the nucleus of a target atom during bombardment of a metal with fast electrons.

IONIZING RADIATION

Ionization is the process by which atoms are made into ions by the removal or addition of one or more electrons; they produce this effect by the high kinetic energies of the quanta (discrete pulses) they emit. Simply, ionizing radiation is any radiation capable of producing ions by interaction with matter. Direct ionizing particles are charged particles (e.g., electrons, protons, alpha particles) having sufficient kinetic energy to produce ionization by collision. Indirect ionizing particles are uncharged particles (e.g., photons, neutrons) that can liberate direct ionizing particles. Sources of ionizing radiation can be found in a wide range of occupational settings, including healthcare facilities, research institutions, nuclear reactors and their support facilities, nuclear weapon production facilities, and various other manufacturing settings, to name just a few. These sources of ionizing radiation can pose a considerable health risk to affected workers if they are not properly controlled. Ionization of cellular components can lead to functional changes in the tissues of the body. Alpha, beta, and neutron particles; x-rays; gamma rays; and cosmic rays are all ionizing radiations.

Three mechanisms for external radiation protection include time, distance, and shielding. A shorter time in a radiation field means less dose. From a point source, dose rate is reduced by the square of the distance and expressed by the inverse square law:

$$I_1(d_1)^2 = I_2(d_2)^2$$

where

I_1 = Dose rate or radiation intensity at distance d_1.
I_2 = Dose rate or radiation intensity at distance d_2.

Radiation is reduced exponentially by thickness of shielding material.

EFFECTIVE HALF-LIFE

The half-life is the length of time required for one-half of a radioactive substance to disintegrate. The formula depicted below is used when the industrial hygienist is interested in determining how much radiation is left in a worker's stomach after a period of time. Effective half-life is a combination of radiological and biological half-lives and is expressed as

$$T_{eff} = \frac{T_b \times T_r}{T_b + T_r}$$

where

T_{eff} = Effective half-life.
T_b = Biological half-life.
T_r = Radiological half-life.

It is important to point out that T_{eff} will always be shorter than either T_b or T_r. T_b may be modified by diet and physical activity.

ALPHA RADIATION

Alpha radiation is used for air ionization—elimination of static electricity (polonium-210), clean room applications, and smoke detectors (americium-241). It is also used in air density measurement, moisture meters, nondestructive testing, and oil well logging. Naturally occurring alpha particles are also used for physical and chemical properties, including uranium (coloring of ceramic glaze, shielding) and thorium (high-temperature materials). The characteristics of alpha radiation are listed below:

- Alpha (α) radiation is a particle composed of two protons and neutrons.
- Alpha radiation is not able to penetrate skin.
- Alpha-emitting materials can be harmful to humans if the materials are inhaled, swallowed, or absorbed through open wounds.
- A variety of instruments have been designed to measure alpha radiation. Special training in use of these instruments is essential for making accurate measurements.
- A civil defense instrument (CDV-700) cannot detect the presence of radioactive materials that produce alpha radiation unless the radioactive materials also produce beta and/or gamma radiation.
- Instruments cannot detect alpha radiation through even a thin layer of water, blood, dust, paper, or other material, because alpha radiation is not penetrating.
- Alpha radiation travels a very short distance through air.
- Alpha radiation is not able to penetrate turnout gear, clothing, or a cover on a probe. Turnout gear and dry clothing can keep alpha emitters off of the skin.

Alpha Radiation Detectors

The types of high-sensitivity portable equipment used to evaluate alpha radiation in the workplace include

- Geiger–Müller counter
- Scintillators
- Solid-state analysis
- Gas proportional devices

BETA RADIATION

Beta radiation is used for thickness measurements for coating operations, radioluminous signs, tracers for research, and for air ionization (gas chromatograph, nebulizers). The characteristics of beta radiation are listed below:

- Beta (β) is a high energy electron particle.
- Beta radiation may travel meters in air and is moderately penetrating.
- Beta radiation can penetrate human skin to the “germinal layer,” where new skin cells are produced. If beta-emitting contaminants are allowed to remain on the skin for a prolonged period of time, they may cause skin injury.
- Beta-emitting contaminants may be harmful if deposited internally.
- Most beta emitters can be detected with a survey instrument (such as a CDV-700, provided the metal probe cover is open). Some beta emitters, however, produce very low energy, poorly penetrating radiation that may be difficult or impossible to detect. Examples of these are carbon-14, tritium, and sulfur-35
- Beta radiation cannot be detected with an ionization chamber such as CDV-715.

- Clothing and turnout gear provide some protection against most beta radiation. Turnout gear and dry clothing can keep beta emitters off of the skin.
- Exposure to beta radiation can be external or internal. External beta radiation hazards are primarily skin burns. Internal beta radiation hazards are similar to alpha emitters.

Beta Detection Instrumentation

The types of equipment used to evaluate beta radiation in the workplace include

- Geiger–Müller counter
- Gas proportional devices
- Scintillators
- Ion chambers
- Dosimeters

Shielding for Beta Radiation

Shielding for beta radiation is best accomplished by using materials with a low atomic number (low z materials) to reduce Bremsstrahlung radiation (i.e., secondary x-radiation produced when a beta particle is slowed down or stopped by a high-density surface). The thickness is critical to stopping the maximum energy range and varies with the type of material used. Typical shielding materials include lead, water, wood, plastics, cement, Plexiglas, and wax.

GAMMA RADIATION AND X-RAYS

Gamma radiation and x-rays are used for sterilization of food and medical products; radiography of welds, castings, and assemblies; gauging of liquid levels and material density; oil well logging; and material analysis. The characteristics of gamma radiation and x-rays are listed below:

- Gamma (γ) radiation and x-rays are highly penetrating elecromagnetic radiation.
- X-rays are composed of photons (generated by electrons leaving an orbit).
- Gamma radiation and x-rays are electromagnetic radiation like visible light, radiowaves, and ultraviolet light. These various types of electromagnetic radiation differ only in the amount of energy they have. Gamma rays and x-rays are the most energetic of these.
- Gamma radiation is able to travel many meters in air and many centimeters in human tissue. It readily penetrates most materials and is sometimes called *penetrating radiation*.
- X-rays are also penetrating radiation.
- Radioactive materials that emit gamma radiation and x-rays constitute both an external and internal hazard to humans.
- Dense materials are needed for shielding from gamma radiation. Clothing and turnout gear provide little shielding from penetrating radiation but will prevent contamination of the skin by radioactive materials.
- Gamma radiation is detected with survey instruments, including civil defense instruments. Low levels can be measured with a standard Geiger counter, such as the CDV-700. High levels can be measure with an ionization chamber, such as the CDV-715.
- Gamma radiation or x-rays frequently accompany the emission of alpha and beta radiation.
- Instruments designed solely for alpha detection (such as an alpha scintillation counter) will not detect gamma radiation.
- Pocket chamber (pencil) dosimeters, film badges, thermoluminescent, and other types of dosimeters can be used to measure accumulated exposure to gamma radiation.
- The principal health concern associated with gamma radiation is external exposure by penetrating radiation and physically strong source housing. Sensitive organs include the lens of the eye, the gonads, and damage to the bone marrow.

Gamma Detection Instrumentation

The types of equipment used to evaluate gamma radiation in the workplace include the following:

- Ion chambers
- Gas proportional devices
- Geiger–Müller counter

Shielding for Gamma and X-Rays

Shielding gamma and x-radiation depends on energy level. Protection follows an exponential function of shield thickness. At low energies, absorption can be achieved with millimeters of lead. At high energies, shielding can attenuate gamma radiation.

RADIOACTIVE DECAY EQUATIONS

Radioactive materials emit alpha particles, beta particles, and photon energy and lose a proportion of their radioactivity with a characteristic half-life. This is known as radioactive decay. To calculate the amount of radioactivity remaining after a given period of time, use the following basic formulae for decay calculations:

$$\text{Later activity} = (\text{Earlier activity}) \times e^{-\lambda} \times (\text{Elapsed time})$$

$$A = A_i \times e^{-\lambda} \times t$$

where

A = New or later radioactivity level.
A_i = Initial radioactivity level.
λ = Decay constant (probability of an atom decaying in a unit time) = $\ln 2/T$.
t = Time.
$\ln 2 = 0.693$.
T = Radioactive half-life (time period in which half of a radioactive isotope decays).

Use the following to determine the time required for a radioactive material to decay (A_o to A):

$$t = (-\ln A/A_i)(T/\ln 2)$$

where

t = Time.
A = New or later radioactivity level.
A_i = Initial radioactivity level.
T = Radioactive half-life (time period in which half of a radioactive isotope decays).
$\ln 2 = 0.693$.

Basic rule of thumb: In 7 half-lives, radioactivity is reduced to <1%; in 10 half-lives, to <0.1%.

To determine the rate of radioactive decay, keep in mind that radioactive disintegration is directly proportional to the number of nuclei present. Thus, the radioactive decay rate is expressed in nuclei disintegrated per unit time:

$$A_i = (0.693/T)(N_i)$$

where

A_i = Initial rate of decay.
N_i = Initial number of radionuclei.
T = Half-life.

Half-life is defined as the time it takes for a material to lose 50% of its radioactivity. The following equation can be used to determine half-life:

$$A = A_i(0.5)^{t/T}$$

where

A = Activity at time t.
A_i = Initial activity.
t = Time.
T = Half-life.

RADIATION DOSE

In the United States, radiation *absorbed dose*, *dose equivalent*, and *exposure* are often measured and stated in the traditional units called *rad, rem*, or *roentgen*. For practical purposes with gamma and x-rays, these units of measurement for exposure or dose are considered equal. This exposure can be from an external source irradiating the whole body, an extremity, or other organ or tissue resulting in an *external radiation dose*. Alternatively, internally deposited radioactive material may cause an *internal radiation dose* to the whole body or to an organ or tissue.

A prefix is often used for smaller measured fractional quantities; for example, milli- (m) means 1/1000 and 1 rad = 1000 mrad. Micro- (μ) means 1/1,000,000, so 1,000,000 μrad = 1 rad, or 10 μR = 0.000010 R. The SI system for radiation measurement is the official system of measurement and uses the gray (Gy) and sievert (Sv) for absorbed dose and equivalent dose, respectively. Conversions are as follows:

1 Gy = 100 rad
1 mGy = 100 mrad
1 Sv = 100 rem
1 mSv = 100 mrem

Radioactive transformation events (radiation counting systems) can be measured in units of disintegrations per minute (dpm) and, because instruments are not 100% efficient, counts per minute (cpm). Background radiation levels are typically less than 10 μR per hour, but due to differences in detector size and efficiency the cpm reading on fixed monitors and various handheld survey meters will vary considerably.

NON-IONIZING RADIATION

Non-ionizing radiation is described as a series of energy waves composed of oscillating electric and magnetic fields traveling at the speed of light. Non-ionizing radiation includes those electromagnetic regions extending from ultraviolet to radiowaves—and usually refers to the portion of the spectrum commonly known as the radiofrequency range. Non-ionizing radiation does not cause ionization. In this text, we are concerned with the following types of non-ionizing radiation that can cause injury: ultraviolet, visible light, infrared, laser, microwave, and radiofrequency. Adverse effects on humans range from ultraviolet radiation causing problems that range from serious sunburns (sometimes ultimately causing skin cancers) to photochemical damage to the eyes; high-intensity visible light damaging the eyes; infrared radiation leading to skin burns, dehydration, and eye damage; and microwave radiation causing thermal damage to body tissues and internal organs, leading to cataracts or other eye injury. In comparison to ionizing radiation, non-ionizing radiation is incapable of dislodging orbital electrons but may leave the atom in an excited state. All lower energy (frequency) radiation is non-ionizing. Non-ionizing radiation is expressed as a relationship of frequency, wavelength, and the speed of light. The higher the frequency, the higher the energy.

Non-ionizing radiation is found in a wide range of occupational settings and can pose a considerable health risk to potentially exposed workers if not properly controlled. The various types of non-ionizing radiation sources are listed below:

Extremely low-frequency radiation (ELF)—ELF radiation at 60 Hz is produced by power lines, electrical wiring, and electrical equipment. Common sources of intense exposure include ELF induction furnaces and high-voltage power lines. Wavelengths are in the range of 50 to 60 Hz. ACGIH exposure standards are based on understood, verifiable health effects (e.g., magnetophosphenes, induced currents, and potential interference with electronic devices, such as pacemakers). ELF radiation applied to the surfaces of the body induces electric currents and fields inside the body and excite cells.

Radiofrequency (RF)/microwave radiation (MW)—Microwave radiation is absorbed near the skin, whereas RF radiation may be absorbed throughout the body. At high enough intensities both will damage tissue through heating. Sources of RF and MW radiation include radio emitters and cell phones. Microwave and radiofrequency radiation includes frequencies ranging from 0.1 cm to 300 meters or 1 mHz to 300,000 MHz. Microwaves create heat by causing water molecules to vibrate and heat up. Microwaves are reflected by metal but pass through glass, paper, and plastic. Materials containing water absorb them.

Infrared radiation (IR)—All objects emit infrared radiation to other objects that have a lower surface temperature. Infrared radiation has a wavelength of from 700 nm to 1 mm. The skin and eyes absorb infrared radiation as heat. Workers normally notice excessive exposure through heat sensation and pain. Sources of IR radiation include furnaces, glass blowing, heat lamps, and IR lasers. Infrared light is heat. Exposure standards can be found in the ACGIH TLV booklet. To use this information, the wavelength, geometry of source, and length of exposure must be known.

Visible light radiation—The different visible frequencies of the electromagnetic (EM) spectrum are seen by our eyes as different colors. Good lighting is conducive to increased production and can help prevent incidents related to poor lighting conditions. Excessive visible radiation can damage the eyes and skin. Visible light wavelength ranges from 400 to 700 nm. Lasers, compact arc lamps, quartz–iodide–tungsten lamps, gas and vapor discharge tubes, and flash lamps are all sources of visible light. Visible light exposure standards are outlined in the ACGIH TLV booklet and depend on wavelength and exposure duration.

Ultraviolet radiation (UV)—Ultraviolet radiation has a high photon energy range and is particularly hazardous because there are usually no immediate symptoms of excessive exposure. Sources of UV radiation include the sun, black lights, fluorescent lamps, welding arcs, and UV lasers. The wavelength range of UV extends from 100 to 400 nm. The ozone layer only allows wavelengths greater than 290 nm to reach the Earth. Exposure standards for UV are wavelength dependent: UV-A, 1 mW/cm^2 for 10^3 seconds measuring UV-A at the source; UV-B and UB-C, wavelength depends on action spectrum but is most active at 200 nm. Sunglasses, clothing, sunblock, and enclosing the source provide the best protection against UV.

Laser hazards—Laser is an acronym for "light amplification by stimulated emission of radiation." The photon of one atom can cause an excited electron of a neighboring atom to drop to the same energy level, thus causing the emission of another identical photon. Lasers typically emit optical (UV, visible, IR) radiations and are primarily an eye and skin hazard. Common lasers include the carbon dioxide IR laser; helium–neon, neodymium YAG, and ruby visible lasers; and nitrogen UV laser. ANSI has classified lasers into specific categories ranging from I to IV. Class I is less hazardous than Class IV:

- Class I lasers (e.g., laser printers) are considered to be incapable of producing damaging radiation levels and are therefore exempt from most control measure or other forms of surveillance.

- Class II lasers emit radiation in the visible portion of the spectrum, and protection is normally afforded by the normal human aversion response (blink reflex) to bright radiant sources. They may be hazardous if viewed directly for extended periods of time. Laser printers are an example.
- Class IIIa lasers are those that normally would not produce injury if viewed only momentarily with the unaided eye. They may present a hazard if viewed using collecting optics (e.g., telescopes, microscopes, binoculars). Examples are HeNe lasers above 1 milliwatt but not exceeding 5 milliwatts radiant power.
- Class IIIb lasers can cause severe eye injuries if beams are viewed directly or specular reflections are viewed. Class III lasers are not normally fire hazards. Examples include visible HeNe lasers above 5 milliwatts but less than 500 milliwatts radiant power. Class IIIa and IIIb lasers require "Caution" signs and well-lighted areas to decrease pupil size.
- Class IV lasers are a hazard to the eye from the direct beam and specular reflections and sometimes even from diffuse reflections. Class IV lasers can also start fires and can damage skin. Class IV lasers require "Danger" signs.

Optical Density

Optical density (OD) is a parameter for specifying the attenuation afforded by a given thickness of any transmitting medium. Because laser beam intensities may be a factor of a thousand or a million above safe exposure levels, percent transmission notation can be unwieldy and is not used. As a result, laser protective filter eyewear is specified in terms of the logarithmic units of optical density. Because of the logarithmic factor, a filter attenuating a beam by a factor of 1000 (or 10^3) has an optical density of 3, and one attenuating a beam by 1,000,000 or (10^6) has an optical density of 6. The required optical density is determined by the maximum laser beam intensity to which the individual could be exposed. The optical density of two highly absorbing filters when stacked together is essentially the linear sum of two individual optical densities. The optical density for welding goggles may be 14. A pair of specific protective goggles may have an OD of 7. The formula for calculating optical density is shown below:

$$OD = \log(I_o/I)$$

where

OD = Optical density.
I_o (or I_1) = Initial beam intensity.
I (or I_2) = Final beam intensity.

Finally, as with ionizing radiation (and all other workplace hazards), environmental practitioners must understand the principles of electromagnetic radiation, its uses in the workplace, its hazards, and effective control measures. Environmental professionals will usually find themselves responsible for the radiation safety program, if one is needed in the organization.

OSHA RADIATION SAFETY REQUIREMENTS

OSHA has standards for both ionizing radiation (29 CFR 1910.96) and non-ionizing radiation (29 CFR 1910.97). In order to understand the hazards associated with radiation, environmental engineers need to understand the basic terms and concepts summarized in the following list, adapted from 29 CFR 1910.96:

Radiation consists of energetic nuclear particles and includes alpha rays, beta rays, gamma rays, x-rays, neutrons, high-speed electrons, and high-speed protons.

Radioactive material is material that emits corpuscular or electromagnetic emanations as the result of spontaneous nuclear disintegration.

Restricted area is any area to which access is restricted in an attempt to protect employees from exposure to radiation or radioactive materials.

Unrestricted area is any area to which access is not controlled because there is no radioactivity hazard present.

Dose is the amount of ionizing radiation absorbed per unit of mass by part of the body or the whole body.

Rad is a measure of the dose of ionizing radiation absorbed by body tissues stated in terms of the amount of energy absorbed per unit of mass of tissue. One rad equals the absorption of 100 ergs per gram of tissue.

Rem is a measure of the dose of ionizing radiation to body tissue stated in terms of its estimated biological effect relative to a dose of 1 roentgen of x-rays.

Air dose means that the dose is measured by an instrument in air at or near the surface of the body in the area that has received the highest dosage.

Personal monitoring devices are devices worn or carried by an individual to measure radiation doses received. Widely used devices include film badges, pocket chambers, pocket dosimeters, and film rings.

Radiation area is any accessible area in which radiation hazards exist that could deliver doses as follows: (1) within 1 hour a major portion of the body could receive more than 5 millirem, or (2) over 5 consecutive days a major portion of the body could receive more than 100 millirem.

High-radiation area is any accessible area in which radiation hazards exist that could deliver a dose in excess of 100 millirem within 1 hour.

The OSHA requirements regarding ionizing radiation (according to 29 CFR 1910.96) include the following:

- The employer must ensure that no individual in a restricted area receives higher levels of radiation than those summarized in Table 11.4.
- The employer is responsible for ensuring that no employee under 18 years of age receives, in one calendar year, a dose of ionizing radiation in excess of 10% of the values shown in Table 11.4.
- The employer is responsible for the provision and use of radiation and the use of radiation monitoring devices such as film badges.
- Where a potential for exposure to radioactive materials exists, appropriate warning signs must be posted.

For normal environmental conditions, OSHA requirements for non-ionizing radiation (according to 29 CFR 1910.97) include guidelines for electromagnetic energy of frequencies between 10 MHz and 100 GHz: power density, 10 mW/cm^2 for periods of 0.1 hour or more, and energy density, 1 Mw-hr/cm^2 during any 0.1-hour period. Note that this guideline applies whether the radiation is continuous or intermittent. Appropriate warning signs must also be posted.

TABLE 11.4
Levels of Radiation per 29 CFR 1900–1910

Part of Body	Dose (rems/quarter)
Whole body: head and trunk; active, blood-forming organs; lens of eyes; gonads	1.25
Hands and forearms; feet and ankles	18.75
Skin of whole body	7.5

TABLE 11.5
Controls for Ionizing Radiation per 29 CFR 1910.96

Types of Controls	Accomplished by
Limit radiation emissions at the source.	Limit the quantity of ionizing material.
Limit time exposure.	Limit employees' time of exposure. Prevent access to locations where radiation sources exist. Have written procedures in place to limit exposures.
Extend distance from the source.	Increased distance tends to dilute airborne particulates and gases; radiation levels decrease with the square of the distance—the inverse square law.
Provide shielding.	Reduce radiation levels with shielding made of concrete, lead, steel, or water.
Provide barriers.	Walls or fences will keep people out who should not be near or around radiation sources.
Post warnings.	Radiation areas should be clearly marked.
Evacuate.	If a significant release of radioactive material occurs, the site should have a well thought out evacuation plan that employees are familiar with.
Provide security.	Physical monitoring and security procedures can be utilized.
Provide training	Employees who work with or around radiation must be trained on the hazards of ionizing radiation.

RADIATION EXPOSURE CONTROLS

Controls, both engineering and administrative, are an important element in any radiation safety program. Environmental practitioners can employ some controls (depending on the situation) to protect employees and the public. Again, as we have stated throughout this text, engineering controls are the preferred methodology when they are appropriate and possible. Tables 11.5 and 11.6 list the kinds of engineering and other control methods that can be employed to protect people from ionizing radiation, as well as the controls for non-ionizing radiation. The information contained in these tables comes primarily from publications by the American National Standards Institute (ANSI); readers should refer to a complete listing of ANSI standards.

TABLE 11.6
Controls for Non-Ionizing Radiation per 29 CFR 1910.97

Source	Controls
Microwaves	Limit the intensity of microwaves (frequency or wavelength workers are exposed to) or limit the duration of exposure. Increasing the distance from a source and shielding can also limit the intensity of exposure. Post signs to warn of radiation hazard or dangers. Employees should handle equipment near microwave sources with insulated gloves to minimize shock and burn hazards. Microwave equipment must be properly grounded to reduce hazards.
Ultraviolet radiation	Limit exposure to most harmful wavelengths. Use absorbing materials to shield skin and eyes.
Infrared radiation	Limit duration of exposure and the intensity of exposure. Looking into infrared sources must be avoided. Shielding (eyewear that absorbs and reflects infrared radiation) reduces the intensity of exposure.
Lasers	Depending on the class of laser, the Food and Drug Administration has standards for the classification and safety design features of lasers. Controls may include enclosure of the laser source, control of potentially reflective surfaces, interlocks on doors to locations where lasers are used, fail-safe pulsing controls to prevent accidental actuation, remote firing room and controls, use of baffles to limit location of beams, and wearing suitable protective eyewear and clothing.

RADIATION EXPOSURE TRAINING

Rationalizing the need for extensive employee training is not at all difficult when it comes to working with or around ionizing radiation sources and materials. However, to date, not enough emphasis has been placed on training employees on the hazards involved with nonionizing radiation sources. Safety engineers must ensure that training becomes a key component of the organizational radiation safety program.

THERMAL STRESS

Appropriately controlling the temperature, humidity, and air distribution in work areas is an important part of providing a safe and healthy workplace. A work environment in which the temperature is not properly controlled can be uncomfortable. Outdoor work areas where extremes of either heat or cold are beyond human control can be more than uncomfortable—they can be dangerous. Heat stress and cold stress are major concerns of modern health and environmental practitioners responsible for worker safety and health in the workplace. This section provides information on how to recognize and overcome the hazards associated with extreme temperatures.

THERMAL COMFORT

Thermal comfort in the workplace is a function of a number of different factors. Temperature, humidity, air distribution, personal preference, and acclimatization are all determinants of comfort in the workplace. Determining optimum conditions, however, is not a simple process. To fully understand the hazards posed by temperature extremes, industrial hygienists must be familiar with several basic concepts related to thermal energy and comfort. The most important of these are summarized here:

- *Convection* is the transfer of heat from one location to another by way of a moving medium (a gas or a liquid). Convection ovens use this principle to transfer heat from an electrode by way of gases in the air to whatever is being baked.
- *Metabolic heat*, a byproduct of the body's activity, is produced within a body as a result of activity that burns energy. All humans produce metabolic heat. This is why a room that is comfortable when occupied by just a few people may become uncomfortable when it is crowded. Unless the thermostat is lowered to compensate, the metabolic heat of a crowd will cause the temperature of a room to rise to an uncomfortable level.
- *Environmental heat* is produced by external sources. Gas or electric heating systems produce environmental heat, as do sources of electricity and a number of industrial processes.
- *Radiant heat* is the result of electromagnetic nonionizing energy that is transmitted through space without the movement of matter within that space.

Some standard terminology is also important:

- *Heat* is a measure of energy in terms of quantity.
- A *calorie* is the amount of energy in terms of quantity.
- *Evaporative cooling* takes place when sweat evaporates from the skin. High humidity reduces the rate of evaporation and thus reduces the effectiveness of the body's primary cooling mechanism.

HEAT INDEX

The heat index (see Table 11.7) combines temperature and humidity levels to determine how the combined conditions affect individuals. The formula for calculating the heat index is

TABLE 11.7
Heat Index Chart (Temperature and Relative Humidity)

RH	Temperature (°F)															
(%)	**90**	**91**	**92**	**93**	**94**	**95**	**96**	**97**	**98**	**99**	**100**	**101**	**102**	**103**	**104**	**105**
90	119	123	128	132	137	141	146	152	157	163	168	174	180	186	193	199
85	115	119	123	127	132	136	141	145	150	155	161	166	172	178	184	190
80	112	115	119	123	127	131	135	140	144	149	154	159	164	169	175	180
75	109	112	115	119	122	126	130	134	138	143	147	152	156	161	166	171
70	106	109	112	115	118	122	125	129	133	137	141	145	149	154	158	163
65	103	106	108	111	114	117	121	124	127	131	135	139	143	147	151	155
60	100	103	105	108	111	114	116	120	123	126	129	133	136	140	144	148
55	98	100	103	105	107	110	113	115	118	121	124	127	131	134	137	141
50	96	98	100	102	104	107	109	112	114	117	119	122	125	128	131	135
45	94	96	98	100	102	104	106	108	110	113	115	118	120	123	126	129
40	92	94	96	97	99	101	103	105	107	109	111	113	116	118	121	123
35	91	92	94	95	97	98	100	102	104	106	107	109	112	114	116	118
30	89	90	92	93	95	96	98	99	101	102	104	106	108	110	112	114

Source: Weather Images, http://www.weatherimages.org/data/heatindex.html.
Note: Exposure to full sunshine can increase heat index values by up to 15°F.

$$\begin{aligned}\text{Heat index} = {} & 16.923 + ((1.85212 \times 10^{-1}) \times T) + (5.37941 \times RH) - ((1.00254 \times 10^{-1}) \times T \times RH) \\ & + ((9.41695 \times 10^{-3}) \times T^2) + ((7.28898 \times 10^{-3}) \times RH^2) + ((3.45372 \times 10^{-4}) \times T^2 \times RH) \\ & - ((8.14971 \times 10^{-4}) \times T \times RH^2) + ((1.02102 \times 10^{-5}) \times T^2 \times RH^2) - ((3.8646 \times 10^{-5}) \times T^3) \\ & + ((2.91583 \times 10^{-5}) \times RH^3) + ((1.42721 \times 10^{-6}) \times T^3 \times RH) + ((1.97483 \times 10^{-7}) \times T \times RH^3) \\ & - ((2.18429 \times 10^{-8}) \times T^3 \times RH^2) + ((8.43296 \times 10^{-10}) \times T^2 \times RH^3) - ((4.81975 \times 10^{-11}) \times T^3 \times RH^3)\end{aligned}$$

where
T = Temperature (°F).
RH = Relative humidity (%).

BODY'S RESPONSE TO HEAT

Operations involving high air temperatures, radiant heat sources, high humidity, direct physical contact with hot objects, or strenuous physical activities have a high potential for inducing heat stress in employees engaged in such operations. Industries that involve processes that create such environments include iron and steel foundries, nonferrous foundries, brick-firing and ceramic plants, glass product facilities, rubber product factories, electrical utilities (particularly boiler rooms), bakeries, confectioneries, commercial kitchens, laundries, food canneries, chemical plants, mining sites, smelters, and steam tunnels. Outdoor operations conducted in hot weather, such as construction, refining, asbestos removal, and hazardous waste site activities, especially those that require workers to wear semipermeable or impermeable protective clothing, are also likely to cause heat stress among exposed workers (OSHA, 2003). The human body is equipped to maintain an appropriate balance between the metabolic heat it produces and the environmental heat to which it is exposed. Sweating and subsequent evaporation of the sweat are the body's way of trying to maintain an acceptable temperature balance. This balance can be expressed as a function of the various factors in the following equation (Alpaugh and Hogan, 1988):

$$H = M \pm R \pm C - E$$

where

H = Body heat.
M = Internal heat gain (metabolic).
R = Radiant heat gain.
C = Convection heat gain.
E = Evaporation (cooling).

The ideal balance when applying the equation is no new heat gain. As long as heat gained from radiation, convection, and metabolic processes does not exceed that lost through the evaporation induced by sweating, the body experiences no stress or hazard. However, when heat gain from any source is more than the body can compensate for by sweating, the result is *heat stress*.

Heat stress involves several causal factors. Age, weight, degree of physical fitness, degree of acclimatization, metabolism, use of alcohol or drugs, and a variety of medical conditions (such as hypertension) all affect a person's sensitivity to heat. However, even the type of clothing worn must be considered. Prior heat injury predisposes an individual to additional injury. Predicting just who will be affected and when is difficult because individual susceptibility varies widely. In addition, environmental factors include more than the ambient air temperature. Radiant heat, air movement, conduction, and relative humidity all affect an individual's response to heat (OSHA, 2003). Workers should not be permitted to work when their deep body temperature exceeds 38°C (100.4°F) (ACGIH, 1992).

HEAT DISORDERS AND HEALTH EFFECTS

Heat stress can manifest itself in a number of ways, depending on the level of stress (OSHA, 2003). The most common types of heat stress are heat stroke, heat exhaustion, heat cramps, heat rash, transient heat fatigue, chronic heat fatigue, and sunburn. These various types of heat stress can cause a number of undesirable bodily reactions, including prickly heat, inadequate venous return to the heart, inadequate blood flow to vital body parts, circulatory shock, cramps, thirst, and fatigue.

Heat stroke occurs when the body's system of temperature regulation fails and body temperature rises to critical levels. This condition is caused by a combination of highly variable factors, and its occurrence is difficult to predict. Heat stroke is very dangerous and should be dealt with immediately because it can be fatal. The primary signs and symptoms of heat stroke are confusion, irrational behavior, loss of consciousness, convulsions, a lack of sweating (usually), hot dry skin, and an abnormally high body temperature (a victim of heat stroke will have a rectal temperature of 104.5°F or higher that will typically continue to climb). If a worker shows signs of possible heat stroke, professional medical treatment should be obtained immediately. The worker should be placed in a shady area and the outer clothing should be removed. The worker's skin should be wetted and air movement around the worker should be increased to improve evaporative cooling until professional methods of cooling are initiated and the seriousness of the condition can be assessed. Fluids should be replaced as soon as possible. The medical outcome of an episode of heat stroke depends on the victim's physical fitness and the timing and effectiveness of first aid treatment.

Heat exhaustion is a type of heat stress that occurs as a result of water and/or salt depletion. When people sweat in response to exertion and environmental heat, they lose water, salt, and electrolytes, the minerals needed for the body to maintain the proper metabolism and for cells to produce energy. Loss of electrolytes causes these functions to break down. Electrolyte imbalance is a problem with heat exhaustion and heat cramps. For this reason, using commercially produced drinks that contain water, salt, sugar, potassium, or electrolytes to replace those lost through sweating is important. Employees working in the heat should have water and electrolyte replacement drinks readily available and should drink them frequently.

Symptoms of heat exhaustion are headache, nausea, vertigo, weakness, thirst, and giddiness. Fortunately, this condition responds readily to prompt treatment. Heat exhaustion should not be dismissed lightly. One principal reason should be apparent to the safety engineer: fainting associated with heat exhaustion can be dangerous because the victim may be operating machinery, controlling an operation that should not be left unattended, or in physical danger from falling. A victim of heat exhaustion should be moved to a cool (but not cold) environment and should rest lying down. Give fluids slowly but steadily by mouth until the urine volume indicates that the body's fluid level is once again in balance.

Performing hard physical labor in a hot environment can cause heat cramps, a type of heat stress that occurs as a result of salt and potassium depletion. Primary observable symptoms are muscle spasms in the arms, legs, and abdomen. To prevent heat cramps, acclimatize workers to the hot environment gradually over a period of at least a week. Ensure that fluid replacement is accomplished with a commercially available carbohydrate–electrolyte replacement product that contains the appropriate amount of salt, potassium, and electrolytes.

Heat rashes are the most common problem in hot work environments. This type of heat stress manifests itself as small raised bumps or blisters that cover a portion of the body and give off a prickly sensation that can cause discomfort. Caused by prolonged exposure to hot, damp conditions in which the body is continuously covered with sweat that does not evaporate because of the high humidity, in most cases heat rashes will disappear when the affected individual returns to a cool environment.

The principle cause of heat fatigue is the victim's lack of acclimatization. Well-conditioned, properly acclimatized employees will suffer this form of heat stress less frequently and less severely than poorly conditioned employees. Consequently, preventing heat fatigue involves physical conditioning and acclimatization, because removing the heat stress before a more serious heat-related condition develops is the only treatment for heat fatigue available.

Whereas getting sunburned is not good for anyone, certain skin types are particularly susceptible to damage from the sun. High-level protection sunscreen (20 SPF); lightweight, long-sleeved protective clothing; and a hat are indicated for outdoor safety for these individuals. Workers should be reminded that the effects of over-exposure to the sun take time to develop. Often the real problem does not show up until the work day is over. Though the short-term consequences can be painful, safety measures should be taken to minimize the long-term consequences of sun exposure (such as skin cancer), and sun- and heat-related problems that cause symptoms must be addressed immediately.

COLD HAZARDS

Temperature hazards are generally thought of as relating to extremes of heat, because most workplace temperature hazards do relate to heat; however, temperature extremes at the other end of the spectrum—cold—can also be hazardous. Employees who work outdoors in colder climates and employees who work indoors in such jobs as meatpacking are subjected to cold hazards. Four factors contribute to cold stress: cold temperature, high or cold wind, dampness, and cold water. These factors, alone or in combination, draw heat away from the body (Greaney, 2000). A cold stress equation can be written as low temperature + wind speed + wetness = injuries and illness (OSHA, 1998). The major injuries associated with extremes of cold can be classified as being either generalized or localized. A generalized injury from extremes of cold is hypothermia. Localized injuries include frostbite, frostnip, and trenchfoot.

Hypothermia results when the body is unable to produce enough heat to replace the heat loss to the environment. It may occur at air temperatures up to 65°F. The body uses its defense mechanisms to help maintain its core temperature. Frostbite is an irreversible condition in which the skin freezes, causing ice crystals to form between cells. The toes, fingers, nose, ears, and cheeks are the most common sites of freezing cold injury. Frostnip is less severe than frostbite. It causes the skin to turn white and typically occurs on the face and other exposed parts of the body. No tissue damage

TABLE 11.8
Wind-Chill Chart

Wind (mph)	**Temperature (°F)**											
	30	**25**	**20**	**15**	**10**	**5**	**0**	**–5**	**–10**	**–15**	**–20**	**–25**
5	25	19	13	7	1	–5	–11	–16	**–22**	**–28**	**–34**	**–40**
10	21	15	9	3	–4	–10	–16	**–22**	**–28**	**–35**	**–41**	**–47**
15	19	13	3	0	–7	–13	**–19**	**–26**	**–32**	**–39**	**–45**	**–51**
20	17	11	4	–2	–9	–15	**–22**	**–29**	**–35**	**–42**	**–48**	**–55**
25	16	9	3	–4	–11	–17	**–24**	**–31**	**–37**	**–44**	**–51**	**–58**
30	15	8	1	–5	–12	**–19**	**–26**	**–33**	**–39**	**–46**	**–53**	**–60**
35	14	7	0	–7	–14	**–21**	**–27**	**–34**	**–41**	**–48**	**–55**	**–62**
40	13	6	–1	–8	–15	**–22**	**–29**	**–36**	**–43**	**–50**	**–57**	**–64**
45	12	5	–2	–9	–16	**–23**	**–30**	**–37**	**–44**	**–51**	**–58**	**–65**
50	12	4	–3	–19	–17	**–24**	**–31**	**–38**	**–45**	**–52**	**–60**	**–67**
55	11	4	–3	–11	**–18**	**–25**	**–32**	**–39**	**–46**	**–54**	**–61**	**–68**
60	10	3	–4	–11	**–19**	**–26**	**–33**	**–40**	**–48**	**–55**	**–62**	**–69**

Source: *USA Today*, http://usatoday30.usatoday.com/weather/winter/windchill/wind-chill-chart.htm.
Note: Bold numbers indicate that frostbite occurs in 15 minutes or less.

occurs; however, if the exposed area is not either covered or removed from exposure to the cold then frostnip can become frostbite. Trenchfoot is caused by continuous exposure to cold water. It may occur in wet, cold environments or through actual immersion in water

WIND-CHILL FACTOR

The wind-chill factor (see Table 11.8) increases the level of hazard posed by extremes of cold. Safety engineers need to understand this concept and how to make it part of their deliberations when developing strategies to prevent cold stress injuries.

COLD STRESS PREVENTION

Following are factors that contribute to cold-related stress, safe work practices, and engineering controls related to cold stress (OSHA, 1998).

Factors Contributing to Cold-Related Stress

- Inadequate or wet clothing increases the effects of cold on the body.
- Certain drugs or medications (including alcohol, nicotine, caffeine, and some kinds of over-the-counter and prescription medications) inhibit the body's response to cold or can impair judgment.
- A cold or certain medical conditions (including diabetes and heart, vascular, and thyroid issues) may make someone more susceptible to winter weather.
- Men are generally at higher risk from cold-related stress than women. Men experience far higher death rates from exposure to cold, for reasons that include performing more inherently risky activities, body-fat composition, and other physiological differences.
- Exhaustion or immobilization, especially due to injury or entrapment, can speed up cold weather's ill effects.
- In general, people are more vulnerable to the effects of harsh winter weather as they become older.

Safe Work Practices

- Allow employees a period of adjustment to the cold before embarking on a full work schedule.
- Always allow employees to work at their own pace and take extra work breaks when needed.
- Reduce the number of activities performed outdoors.
- Select the warmest hours of the day for outdoor winter work.
- Minimize activities that reduce circulation.
- Ensure that employees remain hydrated.
- Establish a buddy system for outdoor work.
- Learn the symptoms of cold-relate stresses, such as heavy shivering, uncomfortable coldness, severe fatigue, drowsiness, or euphoria.

Engineering Controls

- Use onsite heat sources (air jets, radiant heaters, contact warm plates).
- Shield work areas from drafty or windy conditions.
- Provide a heated shelter for employees who experience prolonged exposure to equivalent wind-chill temperatures of 20°F (–6°C) or less.
- Use thermal insulating material on equipment handles when temperatures drop below 30°F (–1°C).

VENTILATION

Simply put, ventilation is the classic method and most powerful environmental engineering tool to control airborne environmental hazards. Experience has shown that the proper use of ventilation as a control mechanism can ensure that workplace air remains free of potentially hazardous levels of airborne contaminants. To accomplish this, ventilation works in two ways: (1) by physically removing the contaminated air from the workplace, or (2) by diluting the workplace atmospheric environment to a safe level by the addition of fresh air.

A ventilation system is all very well and good (virtually essential, actually), but an improperly designed ventilation system can make the hazard worse. This essential point cannot be over-emphasized. At the heart of a proper ventilation system are proper design, proper maintenance, and proper monitoring. The environmental engineer plays a critical role in ensuring that installed ventilation systems operate at their optimum level.

Because of the importance of ventilation in the workplace, the environmental engineer must be well versed in the general concepts of ventilation, the principles of air movement, and monitoring practices. The environmental engineer must be properly prepared (through training and experience) to evaluate existing systems and design new systems for control of the workplace environment. The next few sections present the general principles and concepts of ventilation system design and evaluation. This material should provide the basic concepts and principles necessary for the proper application of industrial ventilation systems. It also serves to refresh the knowledge of practitioners in the field. Probably the best source of information on ventilation is the current edition of ACGIH's *Industrial Ventilation: A Manual of Recommended Practice*, a must-have reference for every safety engineer.

CONCEPTS OF VENTILATION

The purpose of industrial ventilation is essentially to recreate what would occur in natural ventilation but under controlled conditions. Natural ventilation results from differences in pressure. Air moves from high-pressure areas to low-pressure areas. This difference in pressure is the result of thermal conditions. We know that hot air rises, which, for example, allows smoke to escape from the smokestack in an industrial process rather than disperse into areas where workers operate the process. Hot air rises because air expands as it is heated, becoming lighter. The same principle is in effect when air in the atmosphere becomes heated. The air rises and is replaced by air from a higher pressure area. Thus, convection currents cause a natural ventilation effect through the resulting winds.

What does all of this have to do with industrial ventilation? Simply put, industrial ventilation is installed in a workplace to circulate the air within and to provide a supply of fresh air to replace air with undesirable characteristics. Couldn't this be accomplished simply by natural workplace ventilation? That is, couldn't we just heat the air in the workplace so it will rise and escape through natural ports, such as windows, doors, cracks in walls, or mechanical ventilators (e.g., wind-powered turbines) in the roof? Yes, a natural system like this could be designed, but in such a system the air does not circulate fast enough to remove contaminants before a hazardous level is reached, which defeats the purpose of providing a ventilation system in the first place. Thus, fans are used to provide an artificial, mechanical means of moving the air.

Along with controlling or removing toxic airborne contaminants from the air, installed ventilation systems perform several other functions within the workplace:

- *Maintain an adequate oxygen supply in an area.* In most workplaces, this is not a problem because natural ventilation usually provides an adequate volume of oxygen; however, in some work environments (deep mining and thermal processes that use copious amounts of oxygen for combustion) the need for oxygen is the major reason for an installed ventilation system.
- *Remove odors from a given area.* This type of system has applications in such places as athletic locker rooms, restrooms, and kitchens. The noxious air may be replaced with fresh air or odors may be masked with a chemical-masking agent.
- *Provide heat, cooling, and humidity control.*
- *Remove undesirable contaminants at their source*, before they enter the workplace air (e.g., from a chemical dipping or stripping tank). Obviously, this technique is an effective way to ensure that certain contaminants never enter the breathing zone of the worker—exactly the kind of function safety engineering is intended to accomplish.

Earlier we stated that installed ventilation is able to perform its designed function via the use of a mechanical fan. Actually, a mechanical fan is the heart of any ventilation system, but like the human heart, certain ancillaries are required to make it function as a system. Ventilation is no different. Four major components make up a ventilation system: (1) the fan, which forces the air to move; (2) an inlet or some type of opening that allows air to enter the system; (3) an outlet that allows air to leave the system; and (4) a conduit or pathway (ducting) that not only directs the air in the right direction but also limits the amount of flow to a predetermined level.

An important concept regarding ventilation systems is the difference between exhaust and supply ventilation. An exhaust ventilation system removes air and airborne contaminants from the workplace. Such a system may be designed to exhaust an entire work area, or it may be placed at the source to remove the contaminant prior to its release into the workplace air. The second type of ventilation system is the supply system, which adds air to the work area, usually to dilute work area contaminants to lower the concentration of these contaminants. A supplied-air system does much more, though. It also provides movement to air within the space, especially when an area is equipped with both an exhaust and supply system, a usual practice that allows movement of air from the inlet to the outlet and is important in replenishing exhausted air with fresh air.

Air movement in a ventilation system is a result of differences in pressure. Note that pressures in a ventilation system are measured in relation to atmospheric pressure. In the workplace, the existing atmospheric pressure is assumed to be the zero point. In the supply system, the pressure created by the system is in addition to the atmospheric pressure that exists in the workplace (i.e., a positive pressure). In an exhaust system, the objective is to lower the pressure in the system below the atmospheric pressure (i.e., a negative pressure). When we speak of increasing and decreasing pressure levels within a ventilation system, what we are really talking about is creating small differences in pressure—small when compared to the atmospheric pressure of the work area. For this reason, these differences are measured in terms of inches of water or water gauge, which provides the desired sensitivity of measurement. Air can be assumed to be incompressible, because of the small-scale differences in pressure. Because 1 pound per square inch of pressure is equal to 27 inches of water, 1 inch of water is equal to 0.036 pounds pressure, or 0.24% of standard atmospheric pressure. Remember that the potential for error introduced by considering air to be incompressible is very small at the pressures that exist within a ventilation system.

Environmental engineers must be familiar with the three pressures important in ventilation: velocity pressure, static pressure, and total pressure. To understand these three pressures and their function in ventilation systems, it is necessary to be familiar with the concept of pressure itself. In fluid mechanics, the energy of a fluid (air) that is flowing is termed *head*. Head is measured in terms of unit weight of the fluid or in foot-pounds/pound of fluid flowing.

Note: The usual convention is to describe head in terms of feet of fluid that is flowing.

So what is pressure? Pressure is the force per unit area exerted by the fluid. In the English system of measurement, this force is measured in pounds per square foot (lb/ft^2). Because we are considering the fluid in a ventilation system to be incompressible, the pressure of the fluid is equal to the head.

Velocity pressure (VP) is created as air travels at a given velocity through a ventilation system. Velocity pressure is only exerted in the direction of airflow and is always positive (i.e., above atmospheric pressure). When you think about it, velocity pressure has to be positive, and obviously the force or pressure that causes it also must be positive.

The velocity of the air moving within a ventilation system is directly related to the velocity pressure of the system. This relationship can be derived into the standard equation for determining velocity (clearly demonstrating the relationship between the velocity of moving air and the velocity pressure):

$$\text{Velocity} = \frac{4005}{\sqrt{\text{Velocity pressure}}}$$

Static pressure (SP) is the pressure that is exerted in all directions by the air within the system, which tends to burst or collapse the duct. It is expressed in inches of water gauge (in. wg). A simple example may help illustrate the concept of static pressure. Consider a balloon that is inflated at a given pressure. The pressure within the balloon is exerted equally on all sides of the balloon. No air velocity exists within the balloon itself. The pressure in the balloon is totally the result of static pressure. Note that static pressure can be both negative and positive with respect to the local atmospheric pressure.

Total pressure (TP) is defined as the algebraic sum of the static and velocity pressures, or

$$\text{TP} = \text{SP} + \text{VP}$$

The total pressure of a ventilation system can be either positive or negative (i.e., above or below atmospheric pressure). Generally, the total pressure is positive for a supply system and negative for an exhaust system.

Environmental engineers evaluating the performance of any installed ventilation system must make measurements of pressures in the ventilation system. Measurements are normally made using instruments such as a manometer or a Pitot tube. The manometer is often used to measure the static pressure in the ventilation system. It is a simple, U-shaped tube, open at both ends, and usually constructed of clear glass or plastic so the fluid level within can be observed. To facilitate measurement, a graduated scale is usually present on the surface of the manometer. The manometer is filled with a liquid (water, oil, or mercury). When pressure is exerted on the liquid within the manometer, the pressure causes the level of liquid to change as it relates to the atmospheric pressure external to the ventilation system. The pressure measured, therefore, is relative to atmospheric pressure as the zero point. When manometer measurements are used to obtain positive pressure readings in a ventilation system, the leg of the manometer that opens to the atmosphere will contain the higher level of fluid. When a negative pressure is being read, the leg of the tube open to the atmosphere will be lower, thus indicating the difference between the atmospheric pressure and the pressure within the system.

The Pitot tube is another device used to measure static pressure in ventilation systems. The Pitot tube is constructed of two concentric tubes. The inner tube forms the impact portion, while the outer tube is closed at the end and has static pressure holes normal to the surface of the tube. When the inner and outer tubes are connected to opposite legs of a single manometer, the velocity pressure is obtained directly. If the engineer wishes to measure static pressure separately, two manometers can be used. Positive and negative pressure measurements are indicated on the manometer as above.

LOCAL EXHAUST VENTILATION

Local exhaust ventilation is the most predominant method of controlling workplace air. It is used to control air contaminants by trapping and removing them near the source. In contrast to dilution ventilation, which allows the contamination to spread throughout the workplace, later to be diluted by exhausting quantities of air from the workspace, local exhaust ventilation surrounds the point of emission with an enclosure and attempts to capture and remove the emissions before they are released into the worker's breathing zone. The contaminated air is usually drawn through a system of ducting to a collector, where it is cleaned and delivered to the outside through the discharge end of the exhauster. A typical local exhaust system consists of a hood, ducting, an air-cleaning device, a fan, and a stack. A local exhaust system is usually the proper method of contaminant control if (Hazard, 1988)

- The contaminant in the workplace atmosphere constitutes a health, fire, or explosion hazard.
- National or local codes require local exhaust ventilation at a particular process.
- Maintenance of production machinery would otherwise be difficult.
- Housekeeping or employee comfort will be improved.
- Emission sources are large, few, fixed, or widely dispersed.
- Emission rates vary widely by time.
- Emission sources are near the worker breathing zone.

Environmental engineers must remember that determining beforehand precisely the effectiveness of a particular system is often difficult; thus, it is essential to measure exposures and evaluate how much control has been achieved after a system is installed. A good system may collect from 80% to over 90%, but a poor system may capture only 50% or less.

A phenomenon that many practitioners in the environmental engineering field forget (or never knew in the first place) is that ventilation, when properly designed, installed, and maintained, can go a long way toward ensuring a healthy working environment. Ventilation does have limitations, though. For example, the effects of blowing air from a supply system and removing air through an exhaust system are different. To better understand the difference and its significance, let's look at an example of air supplied through a standard exhaust duct.

When air is exhausted through an opening, it is gathered equally from all directions around the opening. This includes the area behind the opening itself. Thus, the cross-sectional area of airflow approximates a spherical form rather than the conical form that is typical when air is blown out of a supply system. To correct this problem, a flange is usually placed around the exhaust opening, which reduces the air contour from a large spherical contour to that of a hemisphere. As a result, this increases the velocity of air at a given distance from the opening. This basic principle is used in designing exhaust hoods. Remember that the closer the exhaust hood is to the source, and the less uncontaminated air it gathers, the more efficient the hood's percentage of capture will be. Simply put, it is easier for a ventilation system to blow air than it is for one to exhaust it. Keep this in mind whenever dealing with ventilation systems or problems.

GENERAL AND DILUTION VENTILATION

In addition to local exhaust ventilation there are two other major categories of ventilation systems: *general ventilation* and *dilution ventilation*. Each of these systems has a specific purpose, and finding all three types of these systems installed in a given workplace location is not uncommon. General ventilation systems (sometimes referred to as *heat control ventilation* systems) are used to control indoor atmospheric conditions associated with hot industrial environments (such as those found in foundries, laundries, bakeries, and other workplaces that generate excess heat) for the purpose of preventing acute discomfort or injury. General ventilation also functions to control the comfort level of the worker in just about any indoor working environment. Along with the removal of air that has become process-heated beyond a desired temperature level, a general ventilation system supplies air to the work area to condition (by heating or cooling) the air or to make up for the air that has been exhausted by dilution ventilation in a local exhaust ventilation system.

A dilution ventilation system dilutes contaminated air with uncontaminated air to reduce the concentration below a given level (usually the threshold limit value of the contaminant) to control potential airborne health hazards, fire and explosive conditions, odors, and nuisance-type contaminants. This is accomplished by removing or supplying air, causing the air in the workplace to move and, as a result, mixing the contaminated air with incoming uncontaminated air. This mixing operation is essential. To mix the air there must be, of course, air movement. The simplest type of air movement is created by natural drafts caused by prevailing winds moving through open doors and windows of the work area.

Thermal drafts can also move air. Whether the thermal draft is the result of natural causes or is generated from process heat, the heated air rises, carrying any contaminant present upward with it. Vents in the roof allow this air to escape into the atmosphere. Makeup air is supplied to the work area through doors and windows. A mechanical air-moving device provides the most reliable source for air movement in a dilution ventilation system. Such a system is rather simple. It requires a source of exhaust for contaminated air, a source of air supply to replace the air mixture that has been removed with uncontaminated air, and a duct system to supply or remove air throughout the workplace. Dilution ventilation systems often are equipped with filtering systems to clean and temper the incoming air.

PERSONAL PROTECTIVE EQUIPMENT

Although the goal of environmental practitioners responsible for workplace safety and health is certainly to engineer out all workplace hazards, this goal is virtually impossible to achieve in every case. Even in this age of robotics, computers, and other automated equipment and processes, the man–machine–process interface still exists. When people are included in the work equation, the opportunity for their exposure to hazards is very real; as injury statistics make clear, injuries occur. Experience has shown that when some workers put on their personal protective equipment (PPE), they also sometimes assume a "superperson" mentality. When workers use eye, hand, foot, head, hearing, or respiratory protection, they often think they have somehow become invincible. They feel safe, as if the PPE somehow magically protects them from the hazard, and they act accordingly. Nothing could be further from the truth, though. Hazards are all workers' kryptonite.

OSHA PPE STANDARD

In the past, many OSHA standards have included PPE requirements, ranging from very general to very specific. It may surprise the reader to know, however, that not until fairly recently (1993–1994) did OSHA incorporate a stand-alone PPE standard into its 29 CFR 1910/1926 guidelines.

This relatively new personal protective equipment standard is covered under 1910.132–138, but you can find PPE requirements elsewhere in the General Industry Standards. For example, 29 CFR 1910.156, OSHA's Fire Brigade Standard, has requirements for firefighting gear. In addition, 29 CFR 1926.95–106 cover the construction industry. The PPE standard focuses on head, feet, eye, hand, respiratory, and hearing protection. Common PPE classifications and examples include the following:

1. Head protection (hard hats, welding helmets)
2. Eye protection (safety glasses, goggles)
3. Face protection (face shields)
4. Respiratory protection (respirators)
5. Arm protection (protective sleeves)
6. Hearing protection (ear plugs, muffs)
7. Hand protection (gloves)
8. Finger protection (cots)
9. Torso protection (aprons)
10. Leg protection (chaps)
11. Knee protection (kneeling pads)
12. Ankle protection (boots)
13. Foot protection (boots, metatarsal shields)
14. Toe protection (safety shoes)
15. Body protection (coveralls, chemical suits)

Respiratory and hearing protection have their own standards. Respiratory protection is covered under 29 CFR 1910.134 and hearing protection under 1910.95. Using PPE is often essential, but it is generally the last line of defense after engineering controls, work practices, and administrative controls. Engineering controls involve physically changing a machine or work environment. Administrative controls involve changing how or when employees do their jobs, such as scheduling work and rotating employees to reduce exposures. Work practices involve training workers how to perform tasks in ways that reduce their exposure to workplace hazards.

OSHA PPE Standard Requirements

Several requirements for both the employer and the employee are mandated under OSHA's personal protective equipment standard. OSHA's requirements include the following:

1. Employers are required to provide employees with PPE that is sanitary and in good working condition.
2. The employer is responsible for examining all PPE used on the job to ensure that it is of a safe (and approved) design and in proper condition.
3. The employer must ensure that employees use PPE.
4. The employer must provide a means for obtaining additional and replacement equipment; defective or damaged PPE is not to be used.
5. The employer must ensure that PPE is inspected on a regular basis.
6. The employee must ensure that he or she dons PPE when required.
7. Where employees provide their own PPE, the employer must ensure that it is adequate and that it is properly maintained and sanitized.

Although the employer must ensure that employees wear PPE when required, both employers and employees should factor in three things: (1) the PPE used must not degrade performance unduly, (2) it must be reliable, and (3) it must be suitable for the hazard involved.

PPE Hazard Assessment

How does a safety official determine when and where an employer should provide PPE and when the employee should use it? This can be determined in three ways:

1. From the manufacturer's guidance. When it comes to equipment and processes produced by a manufacturer, the manufacturer is considered the expert on that equipment or process and is normally best suited to determine the hazards associated with them.
2. If the process or equipment involves chemicals, the Material Safety Data Sheets (MSDSs) for the chemicals involved list the required PPE to be used.
3. OSHA mandates that the employer perform a hazard assessment of the workplace. The purpose of the hazard assessment is to determine if hazards are present or likely to be present that necessitate the use of PPE. If a facility presents such hazards, the employer is required to (a) select and have each affected employee use the types of PPE that will protect the affected employee from the hazards identified in the hazard assessment; (b) communicate selection decisions to each affected employee; and (c) select PPE that properly fits each affected employee. The employer is required to verify that the workplace hazard assessment has been conducted through a written certification of hazard assessment that identifies the workplace evaluated, the person certifying that the evaluation has been performed, and the date of the hazard assessment.

PPE Training Requirement

The employer must provide training to each employee required to use PPE. This training must instruct the employee on when the PPE is necessary; what PPE is necessary; how to properly don, doff, adjust, and wear PPE; the limitations of the PPE; and the proper care, maintenance, useful life, and disposal of the PPE. Per OSHA's PPE employee training requirements, employees must be trained to

- Use PPE properly.
- Be aware of when PPE is necessary.
- Know what kind of PPE is necessary.
- Understand the limitations of PPE in protecting employees from injury.
- Don, adjust, wear, and doff PPE.
- Maintain PPE properly.

During an OSHA audit, each employee must demonstrate his or her understanding of their training on PPE. This is usually best accomplished by demonstration (e.g., wearing and operating self-contained breathing apparatus, or SCBA) and through written or oral examination. If the employer has reason to believe that any affected employee who has already been trained on PPE does not have the understanding and skill required, the employer must retrain such an employee. In this retraining requirement, remember that everything in life is constantly changing, including the workplace and work assignments. OSHA understands this dynamic trend and thus requires the employer to retrain employees on new processes, equipment, or requirements—any new element in a job task that might render previous training obsolete. Changes also occur in PPE itself. When a new type or model of PPE is introduced and used in the workplace, the employer must ensure that employees using such PPE are fully trained on the new equipment.

HEAD PROTECTION

Employers are required by OSHA to ensure that employees are protected from head injury whenever they work in areas where there is a possible danger of head injury from impact, from falling or flying objects, or from electrical shock and burns. According to 29 CFR 1926.100(b), helmets for the protection of workers against impact and penetration of falling and flying objects must meet the specifications contained in the ANSI standard Z89.1-1969, Safety Requirements for Industrial Head Protection. Helmets for the head protection of employees exposed to high-voltage electrical shock and burns must meet the specifications contained in the ANSI standard Z89.2-1971 (OSHA 29 CFR 1926.100(c)).

HAND PROTECTION

Under general requirements listed in 29 CFR 1910.138(a), Hand Protection, OSHA mandates that employers must select and require employees to use appropriate hand protection when employees' hands are exposed to hazards such as those from skin absorption of harmful substances, severe cuts or lacerations, severe abrasions, punctures, chemical burns, thermal burns, or harmful temperature extremes. For the selection of protective gloves, 29 CFR 1910.100(b) mandates employers to base the selection of the appropriate hand protection on an evaluation of the performance characteristics of the hand protection relative to the tasks to be performed, conditions present, duration of use, and the hazards and potential hazards identified.

EYE AND FACE PROTECTION

Eye and face protection requirements are outlined in OSHA 29 CFR 1910.133. The ANSI publication *Practice for Occupational and Educational Eye and Face Protection* (ANS Z87.1989) specifies the use and construction of protective eyewear. Eye and face protection includes safety glasses, chemical goggles, and face shields. Appropriate selection is based on the type of hazard. *Face shields* or chemical splash goggles are appropriate whenever a worker may be subject to splashing from chemicals. They are excellent for use when workers are dipping parts into open-surface tanks containing plating baths, cleaning solutions, organic chemicals, or corrosive chemicals. They are also appropriate whenever a worker may be subject to flying particles, such as when using a portable or pedestal grinder. Face shields are designed only to prevent direct splash exposures to the face and not to provide complete eye protection; they serve as secondary eye protection only. *Safety glasses* are necessary when working with hazardous materials, when operating machinery or air guns, or when there is reasonable probability of injury that can be prevented by use of such equipment. Safety glasses should be affixed with side-shields.

FOOT PROTECTION

In 29 CFR 1910.136, Occupational Foot Protection, OSHA states that the employer must ensure that each affected employee wears protective footwear when working in areas where there is a danger of foot injuries due to falling or rolling objects or objects piercing the sole and where such employee's feet are exposed to electrical hazards. Protective footwear is required to be durable and comfortable and designed for expected exposures. Footwear deemed unacceptable in most work settings includes any footwear that allows direct contact between the foot and a foreign agent. Examples include open-toed shoes, open-heel shoes, and soft shoes (e.g., canvas athletic shoes). Canvas athletic safety shoes are not recommended for those who handle or work around corrosive chemical substances. Steel-toed safety shoes are required whenever there is the potential for items to be dropped onto the foot.

FULL BODY PROTECTION: CHEMICAL PROTECTIVE CLOTHING

The purpose of chemical protective clothing and equipment is to shield or isolate individuals from the chemical, physical, and biological hazards that may be encountered during hazardous materials operations (OSHA, 2005). During chemical operations it is not always apparent when exposure occurs. Many chemicals pose invisible hazards and offer no warnings. The guidelines provided in this section describe the types of clothing that are appropriate for use in various chemical operations and provide recommendations in their selection and use. It is important that protective clothing users realize that no single combination of protective equipment and clothing is capable of providing protection against all hazards. Thus, protective clothing should be used in conjunction with other protective methods. For example, engineering or administrative controls to limit chemical contact with personnel should always be considered as an alternative measure for preventing chemical exposure. The use of protective clothing can itself create significant wearer hazards, such as heat stress, physical stress, and psychological stress, in addition to impaired vision, mobility, and communication. In general, the greater the level of chemical protective clothing required, the greater the associated risks. For any given situation, equipment and clothing should be selected that provide an adequate level of protection. Over-protection as well as under-protection can be hazardous and should be avoided.

DESCRIPTION OF PROTECTIVE CLOTHING

Protective Clothing Applications

Protective clothing must be worn whenever the wearer faces potential hazards arising from chemical exposure, including

- Emergency response
- Chemical manufacturing and process industries
- Hazardous waste site cleanup and disposal
- Asbestos removal and other particulate operations
- Agricultural application of pesticides

Within each application are several operations that require chemical protective clothing; for example, in emergency response, the following activities dictate chemical protective clothing use:

- *Site survey*, the initial investigation of a hazardous materials incident. These situations are usually characterized by a large degree of uncertainty and mandate the highest levels of protection.
- *Rescue*, entering a hazardous materials area for the purpose of removing an exposure victim. Special considerations must be given to how the selected protective clothing may affect the ability of the wearer to carry out rescue and to contamination of the victim.
- *Spill mitigation*, entering a hazardous materials area to prevent a potential spill or to reduce the hazards form an existing spill (e.g., applying a chlorine repair kit on a railroad tank car). Protective clothing must accommodate the required tasks without sacrificing adequate protection.
- *Emergency monitoring*, outfitting personnel in protective clothing for the primary purpose of observing a hazardous materials incident without entry into the spill site. This may be applied to monitoring contract activity for spill cleanup.
- *Decontamination*, applying decontamination procedures to personnel or equipment leaving the site. In general, a lower level of protective clothing is used by personnel involved in decontamination.

Clothing Ensemble

The approach in selecting personal protective clothing must encompass an ensemble of clothing and equipment items that are easily integrated to provide both an appropriate level of protection and still allow one to carry out activities involving chemicals. In many cases, simple protective clothing by itself may be sufficient to prevent chemical exposure, such as wearing gloves in combination with a splash apron and face shield (or safety goggles). The following is a checklist of components that may form the chemical protective ensemble:

- Protective clothing (suit, coveralls, hoods, gloves, boots)
- Respiratory equipment (SCBA, combination SCBA/supplied-air respirator, air-purifying respirator)
- Cooling system (ice vest, air circulation, water circulation)
- Communication device
- Head protection
- Eye protection
- Ear protection
- Inner garment
- Outer protection (overgloves, overboots, flashcover)

Factors that affect the selection of ensemble components include the following:

- How each item accommodates the integration of other ensemble components, as some components may be incompatible due to how they are worn (e.g., some SCBA may not fit within a particular chemical protective suit or allow acceptable mobility when worn)
- The ease of interfacing ensemble components without sacrificing required performance (e.g., a poorly fitting overglove that greatly reduces wearer dexterity)
- Limiting the number of equipment items to reduce donning time and complexity (e.g., some communications devices are built into SCBA which as a unit are not NIOSH certified)

Levels of Protection

Personal protective equipment is categorized into levels A through D. Level A is the most complete and comprehensive level, and level D is the lowest level of protection. The PPE levels listed below can be used as the starting point for creating ensembles; however, each ensemble must be tailored to the specific situation in order to provide the most appropriate level of protection. For example, if an emergency response activity involves a highly contaminated area or if the potential contamination is high, it may be advisable to wear a disposable covering, such as Tyvek coveralls or PVC splash suits, over the protective ensemble.

Level A protection includes the following:

- Vapor protective suit
- Two-way radio
- Pressure demand, self-contained breathing apparatus (SCBA)
- Hard hat
- Two pair of gloves
- Chemical-resistant steel-toe/steel-shank boots and disposable booties

Use Level A protection

- When the chemical concentration is known to be above a safe level
- During a confined space entry
- In the presence of extremely hazardous substances (e.g., cyanide)
- In the presence of skin destructive substances

Limitations of Level A protection include the following:

- Protective clothing must resist permeation by the chemical or mixture present.
- Ensemble items must allow integration without loss of performance.

Level B protection includes the following:

- Two-piece liquid splash-protective suit with hood or disposable suit
- Pressure-demand, full-facepiece SCBA
- Hard hat
- Two pairs of gloves
- Chemical-resistant steel-toe/steel-shank boots and disposable booties

Use Level B protection when

- Immediately dangerous to life or health (IDLH) conditions exist.
- Concentrations are above the protection factors provided by a full-mask, air-purifying respirator.
- Oxygen levels are less than 19.5%.
- Skin contact is unlikely to the head and neck.
- An unidentified vapor is suspected.

Limitations of level B protection include the following:

- Protective clothing must resist penetration by the chemicals or mixtures present.
- Ensemble items must allow integration without loss of performance.

Level C protection includes the following:

- Full-face air-purifying respirator
- Hard hat
- Two pairs of gloves
- Chemical-resistant steel-toe/steel-shank boots and disposable booties
- Two-piece suit or disposable suit

Use Level C protection when

- The air concentration is known.
- Assigned protective factors offer control with an air-purifying respirator.
- There is no threat of IDLH conditions.
- There is no skin hazard.
- There is no unidentified vapor present.

Limitations of Level C protection include the following:

- Protective clothing items must resist penetration by the chemical or mixtures present.
- Chemical airborne concentration must be less than IDLH levels.
- The atmosphere must contain at least 19.5%% oxygen.

Level D protection includes the following:

- Safety glasses
- Hard hat
- One pair of gloves
- Safety shoes
- Coveralls

Use Level D protection when

- There is no measurable concentration.
- No exposure to splash or inhalation will occur.

Limitations of Level D protection include the following:

- This level should not be worn in a hot zone.
- The atmosphere must contain at least 19.5% oxygen.
- It is not acceptable for chemical emergency responses.

The type of equipment used and the overall level of protection should be evaluated periodically as the amount of information about the chemical situation or process increases and when workers are required to perform different tasks. Personnel should upgrade or downgrade their level of protection only with concurrence with site supervisors, safety officers, or plant industrial hygienists. The recommendations listed above serve only as guidelines. It is important to realize that selecting items by how they are designed or configured alone is not sufficient to ensure adequate protection. In other words, just having the right components to form an ensemble is not enough. These levels of protection do not define what performance the selected clothing or equipment must offer.

Clothing Selection Factors

Chemical hazards—Chemicals present a variety of hazards such as toxicity, corrosiveness, flammability, reactivity, and oxygen deficiency. Depending on the chemicals present, any combination of hazards may exist.

Physical environment—Chemical exposure can happen anywhere: in industrial settings, on the highways, or in residential areas. It may occur either indoors or outdoors. The environment may be extremely hot, cold, or moderate. The exposure site may be relatively uncluttered or rugged, presenting a number of physical hazards. Chemical handling activities may involve entering confined spaces, heavy lifting, climbing a ladder, or crawling on the ground. The choice of ensemble components must account for these conditions.

Duration of exposure—The protective qualities of ensemble components may be limited to certain exposure levels (e.g., material chemical resistance, air supply). The decision for ensemble use time must be made assuming the worst-case exposure so that safety margins can be applied to increase the protection available to the worker.

Protective clothing or equipment available—Ideally, an array of different clothing or equipment is available to workers to meet all intended applications. Reliance on one particular clothing or equipment item may severely limit a facility's ability to handle a broad range of chemical exposures. In its acquisition of equipment and clothing, the safety department or other responsible authority should attempt to provide a high degree of flexibility when choosing protective clothing and equipment that is easily integrated and provides protection against each conceivable hazard.

Classification of Protective Clothing

Personal protective clothing includes the following:

- Fully encapsulating suits
- Nonencapsulating suits
- Gloves, boots, and hoods
- Firefighter's protective clothing
- Proximity or approach clothing
- Blast or fragmentation suits
- Radiation-protective suits

Firefighter turnout clothing, proximity gear, blast suits, and radiation suits by themselves are not acceptable for providing adequate protection from hazardous chemicals.

Material Chemical Resistance

Ideally, the chosen materials must resist permeation, degradation, and penetration by the respective chemicals. *Permeation* is the process by which a chemical dissolves in or moves through a material on a molecular basis. In most cases, there will be no visible evidence of chemicals permeating a material. Permeation breakthrough time is the most common result used to assess material chemical compatibility. The rate of permeation is a function of several factors such as chemical concentration, material thickness, humidity, temperature, and pressure. Most material testing is done with 100% chemical over an estimated exposure period. The time it takes the chemical to permeate through the material is the *breakthrough time*. An acceptable material is one where the breakthrough time exceeds the expected period of garment use; however, temperature and pressure effects may enhance permeation and reduce the magnitude of this safety factor. For example, small increases in ambient temperature can significantly reduce breakthrough time and the protective barrier properties of a protective clothing material. *Degradation* involves physical changes in a material as the result of a chemical exposure, use, or ambient conditions (e.g., sunlight). The most common observations of material degradation are discoloration, swelling, loss of physical strength, or deterioration. *Penetration* is the movement of chemicals through zippers, seams, or imperfections in a protective clothing material. It is important to note that no material protects against all chemicals and combinations of chemicals and that no currently available material is an effective barrier to any prolonged chemical exposure.

Decontamination Procedures

Decontamination is the process of removing or neutralizing contaminants that have accumulated on personnel and equipment. This process is critical to health and safety at hazardous material response sites. Decontamination protects end users from hazardous substances that may contaminate and eventually permeate the protective clothing, respiratory equipment, tools, vehicles, and other equipment used in the vicinity of the chemical hazard; it protects all plant or site personnel by minimizing the transfer of harmful material into clean areas, it helps prevent mixing of incompatible chemicals, and it protects the community by preventing uncontrolled transportation of contaminants from the site. The two types of decontamination are

1. *Gross decontamination*, which allows the end user to safely exist or doff the chemical protective clothing.
2. *Decontamination*, which allows reuse of the chemical protective clothing.

The first step in decontamination is to establish standard operating procedures that minimize contact with chemicals and thus the potential for contamination; for example,

- Stress work practices that minimize contact with hazardous substances (e.g., do not walk through areas of obvious contamination; do not directly touch potentially hazardous substances).
- Use remote sampling, handling, and container-opening techniques (e.g., drum grapples, pneumatic impact wrenches).
- Protect monitoring and sampling instruments by bagging. Make openings in the bags for sample ports and sensors that must contact site materials.
- Wear disposable outer garments and use disposable equipment where appropriate.
- Cover equipment and tools with a strippable coating that can be removed during decontamination.

- Encase the source of contaminants (e.g., with plastic sheeting or overpacks).
- Be sure all closures and ensemble component interfaces are completely secured and that no open pockets are present that could serve to collect contaminants.

Types of Contamination

Surface contaminants may be easy to detect and remove. *Permeated contaminants* are contaminants that are difficult or impossible to detect or remove. If contaminants that have permeated a material are not removed by decontamination, they may continue to permeate the material and cause an unexpected exposure. Four major factors affect the extent of permeation:

1. *Contact time*—The longer a contaminant is in contact with an object, the greater the probability and extent of permeation. For this reason, minimizing contact time is one of the most important objectives of a decontamination program.
2. *Concentration*—Molecules flow from areas of high concentration to areas of low concentration. As the concentrations of chemicals increase, the potential for permeation of personal protective clothing increases.
3. *Temperature*—An increase in temperature generally increases the permeation rate of contaminants.
4. *Physical state of chemicals*—As a rule, gases, vapors, and low-viscosity liquids tend to permeate more readily than high-viscosity liquids or solids.

Decontamination Methods

Decontamination methods include (1) physically removing contaminants, (2) inactivating contaminants by chemical detoxification or disinfection/sterilization, or (3) removing contaminants by a combination of both physical and chemical means.

INSPECTION, STORAGE, AND MAINTENANCE OF PROTECTIVE CLOTHING

When donning protective clothing and equipment, workers must take all necessary steps to ensure that the ensemble will perform as expected. During emergencies is not the time to discover discrepancies in protective clothing. Employers should teach how to care for the clothing and other protective equipment in much the same manner as parachutists care for parachutes. Following a standard program for inspection, proper storage, and maintenance, along with realizing the limitations of protective clothing and equipment, is the best way to avoid chemical exposure during emergency response.

Inspection

An effective chemical protective clothing inspection program should feature five different inspections:

1. Inspection and operational testing of equipment received as new from the factory or distributor
2. Inspection of equipment as it is selected for a particular chemical operation
3. Inspection of equipment after use or training and prior to maintenance
4. Periodic inspection of stored equipment
5. Periodic inspection when a question arises concerning the appropriateness of selected equipment or when problems with similar equipment are discovered

Storage

Clothing must be stored properly to prevent damage or malfunction from exposure to dust, moisture, sunlight, damaging chemicals, extreme temperatures, and impact. Procedures are needed for both the initial receipt of equipment and after use or exposure of that equipment. Many manufacturers specify recommended procedures for storing their products. These should be followed to avoid equipment failure resulting from improper storage.

Maintenance

Manufacturers frequently restrict the sale of certain protective suit parts to individuals or groups who are specially trained, equipped, or authorized by the manufacturer to purchase them. Explicit procedures should be adopted to ensure that the appropriate level of maintenance is performed only by those individuals who have this specialized training and equipment. In no case should an attempt be made to repair equipment without checking with the person in the facility responsible for chemical protective clothing maintenance.

RESPIRATORY PROTECTION

Wearing respiratory protective devices to reduce exposure to airborne contaminants is widespread in industry. An estimated 5 million workers wear respirators, either occasionally or routinely. Although it is preferred industrial hygiene practice to use engineering controls to reduce contaminant emissions at their source, there are operations where this type of control is not technologically or economically feasible or is otherwise inappropriate. Respirators are devices that can allow workers to safely breathe without inhaling particles or toxic gases. Two basic types are (1) *air-purifying*, which filter dangerous substances from the air; and (2) *air-supplying*, which deliver a supply of safe breathing air from a tank (SCBA), from a group of tanks (cascade system), or from an uncontaminated area nearby via a hose or airline attached to the mask.

Because respirators are not as consistently reliable as engineering and work practice controls and may create additional problems, they are not the preferred method of reducing exposures below the occupational exposure levels. Accordingly, their use as a primary control is restricted to certain circumstances. When engineering and work practice controls cannot be used to reduce airborne contaminants below their occupational exposure levels (e.g., certain maintenance and repair operations, emergencies, or during periods when engineering controls are being installed), the use of respirators could be justified to reduce worker exposure. In other cases, where work practices and engineering controls alone cannot reduce exposure levels to below the occupational exposure level, the use of respirators would be essential for supplemental protection. When environmental professionals responsible for safety and health in the workplace determine that respiratory protection is required, it is incumbent upon them to implement written respiratory protection programs in compliance with OSHA's Respiratory Protection Standard (29 CFR 1910.134).

Respirators can only provide adequate protection if they are properly selected for the task, are fitted to the wearer and consistently donned and worn properly, and are properly maintained so they continue to provide the protection required for the work situation. These variations can only be controlled if a comprehensive respiratory protection program is developed and implemented in each workplace where respirators are used. When respirator use is augmented by an appropriate respiratory protection program, it can prevent fatalities and illnesses from both acute and chronic exposures to hazardous substances.

We have stressed the vital need to first attempt to engineer out any hazard, but when engineering and other methods of control are not feasible then proper selection and use of respiratory protection can be used to protect against airborne hazards. Unlike past practices, where respiratory protection entailed nothing more than providing respirators to workers who could be exposed to airborne hazards and expecting workers to use the respirator to protect themselves, supplying respirators today without the proper training, paperwork, and testing is illegal. Employers are sometimes unaware that by supplying respirators to their employees without having a comprehensive respiratory protection program they are making a serious mistake, because by issuing respirators they have implied that a hazard actually exists. In a lawsuit, they could then become fodder for the lawyers. OSHA mandates that an effective program must be put in place. This respiratory protection program not only must follow OSHA's guidelines but must also be well planned and properly managed. A well-planned, well-written respiratory protection program must include the elements listed below:

- Procedures for selecting respirators for use in the workplace
- Medical evaluations of employees required to use respirators
- Fit testing procedures for tight-fitting respirators
- Use of respirators in routine and reasonably foreseeable emergency situations
- Procedures and schedules for cleaning, disinfecting, storing, inspecting, repairing, and otherwise maintaining respirators
- Procedures to ensure adequate air quality, quantity, and flow of breathing air for atmosphere-supplying respirators
- Training of employees in the respiratory hazards to which they are potentially exposed
- Training of employees in the proper use of respirators, including putting on and removing them, any limitations on their use, and maintenance procedures
- Procedures for regularly evaluating the effectiveness of the program

> ***Note:*** For permit-required confined space entry operations, respiratory protection is a key piece of safety equipment, one always required for entry into an immediately dangerous to life or health (IDLH) space and one that must be readily available for emergency use and rescue if conditions change in a non-IDLH space. Remember, however, that *only air-supplying respirators should be used in confined spaces where there is not enough oxygen.*

Selecting the proper respirator for the job, the hazard, and the worker is very important, as is thorough training in the use and limitations of respirators. Compliance with OSHA's Respiratory Standard begins with developing written procedures covering all applicable aspects of respiratory protection.

ENGINEERING DESIGN AND CONTROLS FOR SAFETY

> An engineer is charged with the responsibility for designing a new seatbelt that is comfortable, functional, inexpensive, and easy for factory workers to install. He designs a belt that meets all these requirements and it is installed in 10,000 new cars. As the cars are bought and accidents begin to occur, it becomes apparent that the new seatbelt fails in crashes involving speeds over 36 miles per hour. The engineer that designed the belt took all factors into consideration except one: safety.
>
> **Goetsch (1996)**

> The cost-effectiveness of safety is open to constant debate. What IS the most cost-effective way? "Dependent upon the individual situation" is often the answer. But in most cases, for the best long-term results, putting engineered controls into place at the earliest possible stage is the most cost-effective approach, in terms of dollars and in terms of worker health and safety.
>
> **Spellman (1996)**

An enduring question is "What is the best way employers can ensure the safety and health of their employees?" The most common answer is probably to provide as much safety protective equipment as possible. But what type of safety protective equipment? We generally hear the same thing over and over again: "You know, safety protective equipment … like eye and face protection, head protection, hand protection, respiratory protection, fall protection, electrical protection." Notwithstanding the efficacy of PPE in protecting employees on the job, PPE is the protection of last resort. Engineering and administrative controls are always the preferred and recommended methods of protecting workers on the job. PPE should be used only when the other two methods are not feasible or are impossible to implement because PPE does not eliminate the hazardous condition. Instead, PPE is used to establish a barrier between the exposed employee and the hazard to reduce the probability and severity of an injury. The real work of safety engineering is in ensuring worker safety and health by identifying and implementing engineering and administrative controls and safe work practices.

So, what *is* the best way to ensure the safety and health of workers? Following the guidelines provided in OSHA's standards is the best way, but let's take a broad overview of the problems involved. Because most companies operate with one primary goal in mind—to make a profit—they try to operate in the most cost-effective manner possible. What is the most cost-effective manner possible? Some would answer, quite simply, cut costs, cut costs, cut costs—because, obviously, costs are the steady state of concern of the business world. Typically, the cost of ensuring the safety of a workforce is seen as an add-on cost, one that does not contribute to the bottom line. Although this view is shortsighted, it is a view commonly held in industry today. Why do managers feel that safety is a burden, analogous to taking money and dumping it down an endless drain? This is not a simple question to answer, and it becomes even more complicated when you factor in other issues. For example, laws regulate the safety and health of workers, so should the company manager think strictly in terms of OSHA and other regulations or take a broader view?

Because workplace environments have become more technologically complex, protecting workers from safety and health hazards has become more pressing, complex, and necessary. Managers must take the broader view and make choices and decisions requiring a broad background and greater level of knowledge. Fortunately, most company executives eventually come to share the broader view, either of their own volition or as a result of regulatory pressure, and are aware of the importance of employee safety and health. When this occurs (if it does), the focus shifts from a need to comply to ensure the safety and health of workers to figuring out the best way to ensure the safety and health of employees. This question naturally leads to other questions: "Should we adopt elaborate engineering controls or trust to the effectiveness of personal protective equipment?" or "Should we undergo complete process or hardware redesign, or simple modification of existing systems?" The point is that costs are still the main factor (the bottom line), and the question naturally changes to "What are the costs and benefits?" Others would take this question a step further and ask, "What are the limitations and risks of each possible approach?"

This section attempts to answer some of these questions for managers and safety engineers by concentrating on plant design and layout for safety, using engineering controls instead of personal protective equipment to ensure the safety and health of workers. Effective safety and health engineering begins long before the worker appears in the workplace, a critical fact that astute planners, managers, design engineers, and safety engineers must remember. It is less costly (remember, reducing costs is the bottom line) and more efficient to correct safety and health hazards by engineering them out and eliminating them before they exist and before they become part of the workplace.

Does it ever happen this way in the real world? Sure. Proper attention to safety and health in the design phase is key. The environmental engineer's primary function in the workplace is to reduce or eliminate hazards, which can be accomplished through the proper design and layout of the plant or facility. For an environmental engineer working for a company that is building or renovating a facility, this is a golden opportunity to do just that. The following discussion addresses codes and standards, physical plant layout, illumination, high hazard areas, personal services and sanitation facilities, and the concept of system engineering—all of which are important in the planning and design phase but are especially important in ensuring effective accident prevention.

CODES AND STANDARDS

Probably the first known written admonition regarding the need for accident prevention was contained in Hammurabi's Code, about 1750 BC: "If a builder constructs a house for a person and does not make it firm and the house collapses and causes the death of the owner, the builder shall be put to death." Today, some of us would say that the justice rendered in such a case is rather severe. Although the penalties have become less severe, the need for care has increased exponentially due to the growth of technology since Hammurabi's time. Countless pages have been written relating laws, standards, and codes regarding safety, health, and the environment since Hammurabi's Code. The fact of the matter is that codes and standards have become essential tools in any plan of operations and in the design of any workplace. The primary intent of standards and codes is to prescribe minimum requirements and controls to safeguard life and property and to protect the public from hazards. To understand codes and standards used in accident control, a few pertinent definitions are necessary (Hammer, 1989):

Code—A collection of laws, standards, or criteria relating to a particular subject, such as the National Electric Code (NEC), Uniform Fire Code (UFC), Building Officials and Code Administrators (BOCA) codes, and National Fire Prevention Association (NFPA) codes.
Criterion—Any rule or set of rules that might be used for control, guidance, or judgment.
Design handbooks, guide, or manuals—Manuals offering nonmandatory practices, general concepts, and examples to assist a designer or operator.
Practice—A series of recommended methods, rules, or designs, generally on a single subject.
Regulation—A set of orders issued to control the conduct of persons within the jurisdiction of the regulatory authority.
Specification—A detailed description of requirements, usually technical.
Standard—A set of criteria, requirements, or principles.

Local or state laws also have many ordinances governing specific requirements that cover such items or systems as fire sprinklers, fire alarms, exhaust and ventilation systems, emergency lighting, and means of egress. City, county, state, and federal agencies may have specific standards for sanitation, building construction, and pollution control and prevention requirements. Criteria contained in such standards and other work rules and in building and operating permits can be extremely beneficial in accident prevention. Written standards aid in making a designer's or safety engineer's job easier by providing useful technical information and promoting consistency to establish a basic level of safety in similar operations, materials, and equipment.

A large number of standards and voluntary safety codes (consensus standards) have been incorporated into law. The best known example of this practice is the American National Standards Institute (ANSI); many of the original OSHA standards originated from ANSI standards. ANSI has a wide range of standards for such items as ladders, stairs, sanitation, building load design, floor and wall openings, marking hazards, accident prevention signs, and many others. Design and safety engineers must keep in mind that standards provided by ANSI, NEC, NFPA, ASME, and others are only recommendations—a starting point for safe workplace design. Design engineers, safety engineers, and environmental engineers who do not pay attention to various codes, standards, and local requirements are setting themselves up for admonitions that may not be quite as severe as the ones recommended by Hammurabi but a headache generator at the very least.

PLANT LAYOUT

During the design phase for a plant or facility, and especially for general working areas, several elements must be taken into consideration. With safe and efficient use of materials in various process and methods as the primary goal, the location, size, shape, and layout of worksite buildings should be determined. Designers and safety or environmental engineers have learned from experience (generally from past mistakes) that when the worksite functions to produce a finished product, designing the worksite so that raw materials enter at one end of the worksite and the finished product is shipped at the other is more efficient, and sometimes safer. What we have basically described here is process flow—an important consideration that should not be overlooked. For example, consider the following: If a certain process calls for robotic welding to be conducted during a product's assembly phase, a process flow diagram should indicate this to ensure that hazardous materials such as flammable cleaning solvents, gasoline, and/or explosives are not staged or stored in such an area. Obviously, this is critical to ensuring safe operations. Process flow diagrams also aid in the proper positioning of equipment; electrical apparatus; heating, ventilation, and air conditioning (HVAC); storage spaces; and other appurtenances or add-ons.

TABLE 11.9
Minimum Levels for Industrial Lighting

Area	Foot-Candles
Assembly–rough, easy seeing	0
Assembly–medium	100
Building construction–general	10
Corridors	20
Drafting rooms–detailed	200
Electrical equipment, testing	100
Elevators	20
Garages–repair areas	100
Garages–traffic areas	20
Inspection, ordinary	50
Inspection, highly difficult	200
Loading platforms	20
Machine shops–medium work	100
Materials–loading, trucking	20
Offices–general areas	100
Paint dipping, spraying	50
Service spaces–wash rooms	30
Sheet metal–presses, shears	50
Storage rooms–inactive	5
Storage rooms–active, medium	20
Welding–general	50
Woodworking–rough sawing	30

ILLUMINATION

Care must be taken with lighting design, not only to ensure that enough lighting is provided for workers to perform their work tasks safely and efficiently but also to ensure that the lighting does not interfere with work or cause visual fatigue. To be sure that the proper quantity or amount of illumination (usually measured in foot-candles) is installed in the worksite, it is necessary to determine exactly what kind of work is to be performed in the space. The amount of illumination will vary with the job function. A lack of proper illumination for various industrial areas (including office areas) is listed as a common cause of accidents. The ANSI Practice for Office Lighting standard (ANSI/IESNA RP-7-01) lists the minimum levels of illumination for various industrial areas and tasks (see Table 11.9). One aspect of lighting that is often overlooked in the design phase is emergency lighting. No one doubts that an emergency of just about any size is apt to involve the loss of electrical power, which, of course, would mean that shutdown of equipment and processes, evacuation of workers, and rescue must be performed in darkness—unless emergency lighting is provided. Design engineers should at least incorporate into the workplace design standby sources of light that come on automatically when the power fails, if only to allow for safe evacuation. Whatever type of emergency lighting system is chosen, remember that it must be designed to operate from an independent connection at the point where the main service line enters the workplace.

HIGH-HAZARD WORK AREAS

Work areas involved with process operations typically include some areas or operations that have an inherently high hazard potential. Obviously, such areas may require special precautionary measures and planning, such as the need for sprinkler systems, containment dikes, alarms, electrical interlocks, and other precautionary measures. These areas include the following:

- Spray-painting areas
- Explosives manufacturing, use, or storage
- Manufacturing, use, or storage of flammable materials
- Areas with process equipment of high-energy movement through a power source, such as steam, electrical, hydraulic, pneumatic, or mechanical
- Radiation areas
- Confined spaces
- Chemical mixing areas

PERSONAL AND SANITATION FACILITIES

In addition to designing the facility for easy and correct housekeeping activities, design engineers must also factor into any workplace design several sanitation and personal hygiene requirements, including provisions for potable water for drinking and washing; sewage, solid waste, and garbage disposal; sanitary food services; drinking fountains; washrooms; locker rooms; toilets; and showers. Housekeeping and sanitation are closely related. Control of health hazards requires sanitation, and control is usually put into place through good housekeeping practices. Disease transmission and ingestion of toxic or hazardous materials are controlled through a variety of sanitation practices, but if the workplace is not properly designed with correct sanitary and storm sewers and ready availability of safe drinking water and sanitary dispensing equipment, then it becomes much more difficult to include sound sanitary practices within the workplace.

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Glossary

Abiotic: The nonliving part of the physical environment (e.g., light, temperature, and soil structure).

Absorption: (1) Movement of a chemical into a plant, animal, or soil. (2) Any process by which one substance penetrates the interior of another substance; in chemical spill cleanup, this process applies to the uptake of chemical by capillaries within certain sorbent materials.

Absorption units: Devices or units designed to transfer the contaminant from a gas phase to a liquid phase.

Accidental spills: The unintended release of chemicals and hazardous compounds or materials into the environment.

Acid: A hydrogen-containing corrosive compound that reacts with water to produce hydrogen ions; a proton donor; a liquid compound with a pH less than or equal to 2.

Acid mine drainage: The dissolving and transporting of sulfuric acid and toxic metal compounds from abandoned underground coal mines to nearby streams and rivers when surface water flows through the mines.

Acid rain: Precipitation made more acidic from falling through air pollutants (primarily sulfur dioxide) and dissolving them.

Acidic deposition: See *Acid rain*.

Adiabatic: Without loss or gain of heat; when air rises, air pressure decreases and expands adiabatically in the atmosphere. Because the air can neither gain nor lose heat, its temperature falls as it expands to fill a larger volume.

Adiabatic lapse rate: The temperature profile, or lapse rate, used as a basis for comparison for actual temperature profiles (from ground level) and hence for predictions of stack gas dispersion characteristics.

Adsorption: (1) Process by which one substance is attracted to and adheres to the surface of another substance without actually penetrating its internal structure. (2) Process by which a substance is held (bound) to the surface of a soil particle or mineral in such a way that the substance is only available slowly.

Adsorption site density: The concentration of sorptive surface available from the mineral and organic contents of soils. An increase in adsorption sites indicates an increase in the ability of the soils to immobilize hydrocarbon compounds in the soil matrix.

Advanced wastewater treatment: Any treatment that follows primary and secondary wastewater treatment.

Advective wind: The horizontal air movements resulting from temperature gradients that give rise to density gradients and subsequently pressure gradients.

Aerobic: Living in the air; opposite of *anaerobic*.

Aerobic processes: Biotechnology production and effluent treatment processes that are dependent on microorganisms that require oxygen for their metabolism. For example, water in an aerobic stream contains dissolved oxygen; therefore, organisms using this can oxidize organic wastes to simple compounds.

Afterburners: A device that includes an auxiliary fuel burner and combustion chamber to incinerate combustible gas contaminants.

Aggregate: Clusters of soil particles.

Agricultural sources: Both organic and inorganic contaminants usually produced by pesticides, fertilizers, and animals wastes, all of which enter water bodies via runoff and groundwater absorption in areas of agricultural activity.

Air: The mixture of gases that constitutes the Earth's atmosphere.

Air currents: Air moving upward and downward.

Air mass: A large body of air with particular characteristics of temperature and humidity. An air mass forms when air rests over an area long enough to pick up the conditions of that area.

Air pollutants: Generally includes sulfur dioxide, hydrogen sulfide, hydrocarbons, carbon monoxide, ozone, and atmospheric nitrogen but can include any gaseous substance that contaminates air.

Air pollution: Contamination of the atmosphere with any material that can cause damage to life or property.

Air stripping: A mass transfer process in which a substance in solution in water is transferred to solution in a gas.

Airborne contaminants: Any contaminant capable of dispersion in air or capable of being carried by air to other locations.

Airborne particulate matter: Fine solids or liquid droplets suspended and carried in the air.

Albedo: The fraction of received radiation reflected by a surface.

Algae: A large and diverse assemblage of eucaryotic organisms that lack roots, stems, and leaves but have chlorophyll and other pigments for carrying out oxygen-producing photosynthesis.

Aliphatic hydrocarbon: Compound comprised of straight-chain molecules as opposed to a ring structure.

Alkalinity: (1) The concentration of hydroxide ions. (2) The capacity of water to neutralize acids because of the bicarbonate, carbonate, or hydroxide content. Usually expressed in milligrams per liter of calcium carbonate equivalent.

Alkanes: A class of hydrocarbons (gas, solid, or liquids depending on carbon content). The solids (paraffins) are a major constituent of natural gas and petroleum. Alkanes are usually gases at room temperature (methane) when containing less than 5 carbon atoms per molecule.

Alkenes: A class of hydrocarbons (also called *olefins*) common in petroleum products; they are sometimes gaseous at room temperature but usually liquid. Alkenes are generally more toxic than alkanes and less toxic than aromatics.

Alkynes: A class of hydrocarbons (formerly known as *acetylenes*) comprised of unsaturated compounds characterized by one or more triple bonds between adjacent carbon atoms. Lighter alkenes, such as ethylene, are gases; heavier ones are liquids or solids.

Amoebae (pl.), amoeba (sing.): One of the simplest living animals, consisting of a single cell and belonging to the protozoa group. The body consists of colorless protoplasm. Its activities are controlled by the nucleus, and it feeds by flowing around and engulfing organic debris. It reproduces by binary fission. Some species of amoebae are harmless parasites.

Anabolism: The process of building up cell tissue, promoted by the influence of certain hormones; the constructive side of metabolism as opposed to catabolism.

Anaerobic: Not requiring oxygen.

Anaerobic process: Any process (usually chemical or biological) carried out without the presence of air or oxygen, such as in a heavily polluted watercourse with no dissolved oxygen present.

Analysis: The separation of an intellectual or substantial whole into its constituent parts for individual study.

Animal feedlots: A confined area where hundreds or thousands of livestock animals are fattened for sale to slaughterhouses and meat producers.

Animal wastes: The dung (fecal matter) and urine of animals.

Anthropogenic sources: Generated by human activity.

Anticyclone: High-atmosphere areas characterized by clear weather and the absence of rain and violent winds.

Apoenzyme: The protein part of an enzyme.

Aqueous solution: Solution in which the solvent is water.

Aquifer: Any rock formation containing water. The rock of an aquifer must be porous and permeable to absorb water.

Aromatic hydrocarbons: Class of hydrocarbons considered to be the most immediately toxic; found in oil and petroleum products; soluble in water (antonym, *aliphatic*).

Asphalt incorporation: Soil remediation/recycling process whereby contaminated soil is removed from the site and fed into an asphalt-making process as part of the aggregated filler substance.

Atmosphere: The layer of air surrounding the Earth's surface.

Atom: A basic unit of physical matter indivisible by chemical means; the fundamental building block of chemical elements composed of a nucleus of protons and neutrons surrounded by electrons.

Atomic number: Number of protons in the nucleus of an atom. Each chemical element has been assigned a number in a complete series from 1 to over 100.

Atomic orbitals/electron shells: The region around the nucleus of an atom in which an electron is most likely to be found.

Atomic weight: The mass of an element relative to its atoms.

Auger: A tool used to bore holes in soil to capture a sample.

Automatic samplers: Devices that automatically take samples from a waste stream.

Autotrophic: An organism that can synthesize organic molecules needed for growth from inorganic compounds using light or another source of energy.

Autotrophs: See *Autotrophic*.

Avogadro's number: The number of carbon atoms in 12 g of the carbon-12 isotope (6.022045×10^{23}). The relative atomic mass of any element, expressed in grams, contains this number of atoms.

Bacilli (pl.), bacillus (sing.): Members of a group of rodlike bacteria that occur everywhere in soil and air. Some are responsible for diseases such as anthrax or cause food spoilage.

Bacteria: One-celled microorganisms.

Bacteriophage: A virus that infects bacteria; often called a *phage*.

Baghouse filter: A closely woven bag for removing dust from dust-laden gas streams. The fabric allows passage of the gas with retention of the dust.

Bare rock succession: An ecological succession process whereby rock or parent material is slowly degraded to soil by a series of bioecological processes.

Base: A substance that when dissolved in water generates hydroxide (OH^-) ions or is capable of reacting with an acid to form a salt.

Beneficial reuse: The practice of reusing a typical waste product in a beneficial manner, such as, for example, wastewater biosolids to compost.

Benthic (benthos): A term originating from the Greek word for "bottom" that broadly includes aquatic organisms living on the bottom or on submerged vegetation.

Best available technology (BAT): Essentially, a refinement of best practicable means whereby a greater degree of control over emissions to land, air, and water may be exercised using currently available technology.

Binomial system of nomenclature: A system used to classify organisms; organisms are generally described by a two-word scientific name comprised of the *genus* and *species*.

Bioaccumulation: Biological concentration mechanism whereby filter feeders such as limpets, oysters, and other shellfish concentrate heavy metals or other stable compounds present in dilute concentrations in seawater or freshwater.

Biochemical oxygen demand (BOD): The amount of oxygen required by bacteria to stabilize decomposable organic matter under aerobic conditions.

Biodegradable: A material capable of being broken down, usually by microorganisms, into basic elements.

Biodegradation: The ability of natural decay processes to break down manmade and natural compounds to their constituent elements and compounds for assimilation in, and by, the biological renewal cycles. Wood, for example, is decomposed to carbon dioxide and water.

Biogeochemical cycles: *Bio* refers to living organisms and *geo* to water, air, rocks, or solids. *Chemical* is concerned with the chemical composition of the Earth. Biogeochemical cycles are driven by energy, directly or indirectly, from the sun.

Biological oxygen demand (BOD): The amount of dissolved oxygen taken up by microorganisms in a sample of water.

Biological treatment: Process by which hazardous waste is rendered nonhazardous or reduced in volume by the actions of microorganisms.

Biological treatment process: Includes such treatment processes as activated sludge, aerated lagoon, trickling filters, waste stabilization ponds, and anaerobic digestion.

Biology: The science of life.

Biosolids: A term that refers to water or sewage sludge. The biosolids treatment process normally includes conditioning, thickening, dewatering, disposal by incineration, composting, land application, or land burial.

Biosphere: The region of the Earth and its atmosphere in which life exists, an envelope extending from up to 6000 meters above to 10,000 meters below sea level that embraces all life from alpine plant life to the ocean depths.

Biostimulant: A chemical that can stimulate growth, such as phosphates or nitrates in a water system.

Biota: The animal and plant life of a particular region considered as a total ecological entity.

Biotic: Pertaining to life or specific life conditions.

Biotic index: The diversity of species in an ecosystem is often a good indicator of the presence of pollution: The greater the diversity, the lower the degree of pollution. The biotic index is a systematic survey of invertebrate aquatic organisms that is used to correlate with river quality. It is based on two principles: (1) Pollution tends to restrict the variety of organisms present at a point, although large numbers of pollution-tolerant species may persist, and (2) in a polluted stream, as the degree of pollution increases, key organisms tend to disappear in the order of stoneflies, mayflies, caddisflies, freshwater shrimp, bloodworms, and tubificid worms.

Blastospore: Fungi spores formed by budding.

Blowby: In an internal combustion engine, blowby occurs as gases from the piston ring area pass into the crankcase.

Boiling point: The temperature at which a substance changes from a liquid to a gas.

Brackish water: Water (nonpotable) containing between 100 and 10,000 ppm of total dissolved solids.

Brick manufacturing process: In this text, contaminated soil recycling/remediation process whereby contaminated soil is added to the mix used to make brick.

Brine: Water containing more than 100,000 ppm of total dissolved solids that can yield salt (NaCl) after evaporation.

Btu: British thermal unit, a measuring unit of heat.

Budding: Type of asexual reproduction in which an outgrowth develops from a cell to form a new individual. Most yeasts reproduce in this way.

Calorie: The amount of heat required to raise the temperature of 1 gram of water 1°C.

Capsules, bacterial: Organized accumulations of gelatinous material on cell walls.

Carbon adsorption: Process whereby activated carbon, known as the sorbent, is used to remove certain wastes from water by preferentially holding them on the carbon surface.

Carbon cycle: The atmosphere is a reservoir of gaseous carbon dioxide, but to be of use to life this carbon dioxide must be converted into suitable organic compounds, or *fixed*, as in the production of plant stems by the process of photosynthesis. The productivity of an area of vegetation is measured by the rate of carbon fixation. The carbon fixed by photosynthesis is eventually returned to the atmosphere as plants and animals die and the dead organic matter is consumed by the decomposer organisms.

Carbon dioxide: A colorless, odorless inert gas; a byproduct of combustion.

Carbon monoxide: A highly toxic and flammable gas that is a byproduct of incomplete combustion; very dangerous even in very low concentrations.

Carbonate hardness: Temporary hard water caused by the presence of bicarbonates; when water is boiled, the bicarbonates are converted to insoluble carbonates that precipitate as scale.

Catabolism: In biology, the destructive part of metabolism where living tissue is changed into energy and waste products.

Catalysis: The acceleration (or retardation) of chemical or biochemical reactions by a relatively small amount of a substance (the catalyst), which itself undergoes no permanent chemical change and which may be recovered when the reaction has finished.

Catalyst: A substance or compound that speeds up the rate of chemical or biochemical reactions.

Catalytic combustion: Operates by passing a preheated contaminant-laden gas stream through a catalyst bed that promotes the oxidation reaction at lower temperatures. The metal catalyst (usually platinum) is used to initiate and promote combustion at much lower temperatures than those required for thermal combustion.

Catalytic converter: A device fitted to the exhaust system of a motor vehicle to reduce toxic emissions from the engine. It converts harmful exhaust products to relatively harmless ones by passing the exhaust gases over a mixture of catalysts coated on a metal or ceramic honeycomb, a structure that increases the surface area and therefore the amount of active catalyst with which the exhaust gases will contact.

Catchment: The natural drainage area for precipitation; the collection area for water supplies or a river system. The notional line, or watershed, on surrounding high land defines the area.

Cell: The basic biological unit of plant and animal matter.

Cell membrane (cytoplasmic membrane): The lipid- and protein- containing, selectively permeable membrane that surrounds the cytoplasm in procaryotic and eucaryotic cells; in most types of microbial cell, the cell membrane is bordered externally by the cell wall. In microbial cells, the precise composition of the cell membrane depends on the species, on growth conditions, and on the age of the cell.

Cell nucleus: Contained within a eucaryotic cell, a membrane-lined body that contains chromosomes.

Cell wall: The permeable, rigid outermost layer of a plant cell composed mainly of cellulose.

Cement production process: A recycling/remediation technology for contaminated soil whereby the contaminated soil is added to the mix in cement production.

CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act of 1980; Superfund): Provides for cleanup and compensation and assigns liability for the release of hazardous substances into the air, land, or water.

Chemical bond: A chemical linkage that holds atoms together to form molecules.

Chemical change: A transfer that results from chemical bonds being made or broken.

Chemical equation: A shorthand method for expressing a reaction in terms of written chemical formulas.

Chemical extraction: Process in which excavated contaminated soils are washed to remove contaminants of concern.

Chemical formula: In the case of substances that consist of molecules, the chemical formula indicates the kinds of atoms present in each molecule and the actual number of them.

Chemical oxygen demand (COD): A means of measuring the pollution strength of domestic and industrial wastes based on the fact that all organic compounds, with few exceptions, can be oxidized by the action of strong oxidizing agents under acid conditions to carbon dioxide and water.

Chemical precipitation: Process by which inorganic contaminants (heavy metals from groundwater) are removed by the addition of carbonate, hydroxide, or sulfide chemicals.

Chemical process audit/survey: A procedure used to gather information on the type, composition, and quantity of waste produced.

Chemical reaction: A substance undergoes a chemical change and is no longer the same substance; it becomes one or more new substances.

Chemical weathering: A form of weathering brought about by a chemical change in the rocks affected; involves the breakdown of the minerals within a rock and usually produces a claylike residue.

Chemosynthesis: A method of making protoplasm using energy from chemical reactions, in contrast to the use of light energy employed for the same purpose in photosynthesis.

Chlorofluorocarbons (CFCs): Synthetic chemicals that are odorless, nontoxic, nonflammable, and chemically inert. CFCs have been used as propellants in aerosol cans, as refrigerants in refrigeration and air conditioners, and in the manufacture of foam packaging. They are partly responsible for the destruction of the ozone layer.

Chlorophyll: A combination of green and yellow pigments present in all "green" plants which captures light energy and enables the plants to form carbohydrate material from carbon dioxide and water in the process known as *photosynthesis*. Chlorophyll is found in all algae, phytoplankton, and almost all higher plants.

Chloroplasts: A structure (or organelle) found with a plant cell containing the green pigment chlorophyll.

Cilia: Small threadlike organs on the surface of some cells, composed of contractile fibers that produce rhythmic waving movements. Some single-celled organisms move by means of cilia. In multicellular animals, they keep lubricated surfaces clear of debris. They also move food in the digestive tracts of some invertebrates.

Clarification: The process of removing solids from water.

Clay content: The amount of clay (fine-grained sedimentary rock) within a soil.

Clean Air Act: Act passed by the U.S. government. Originally passed in 1963, it dealt with the control of smoke from industrial and domestic sources. It was extended in 1968 to control gas cleaning and heights of stacks of installations in which fuels are burned to deal with smoke from open industrial bonfires. The 1990 revision introduced wide-ranging reforms for all kinds of pollution from large or small mobile or stationary sources, including routine and toxic emissions ranging from power plants to consumer products.

Clean Water Act (CWA): A keystone environmental law credited with significantly cutting the amount of municipal and industrial pollution fed into the nation's waterways. More formally known as the Federal Water Pollution Control Act Amendments, passed in 1972, it stems originally from a much-amended 1948 law aiding communities in building sewage treatment plants and has itself been much amended, most notably in 1977 and 1987.

Clean zone: That point in a river or stream upstream before a single point of pollution discharge.

Climate: The composite pattern of weather conditions that can be expected in a given region. Climate refers to yearly cycles of temperature, wind, rainfall, and so on, not to daily variations.

Coal gasification process: The conversion of coal (via destructive distillation or heated out) to gaseous fuel.

Cocci (pl.), coccus (sing.): Member of group of globular bacteria, some of which are harmful to humans.

Cofactor: Nonprotein activator that forms a functional part of an enzyme.

Cold front: The leading portion of a cold atmospheric air mass moving against and eventually replacing a warm air mass.

Cold-mix asphalt process: A mobile or in-place process whereby contaminated soils are recycled or remediated by serving as the fine-grained component in the asphalt-making process.

Collector: See *Cyclone collector.*

Colloidal material: A constituent of total solids in wastewater that consists of particulate matter with an approximate diameter range of from 1 millimicron to 1 micron.

Color: A physical characteristic of water often used to judge water quality; pure water is colorless.

Combined wastewater: The combination of sanitary wastewater and stormwater runoff.

Combustion: In chemical terms, the rapid combination of a substance with oxygen, accompanied by the evolution of heat and usually light. In air pollution control, combustion or incineration is a beneficial pollution control process in which the objective is to convert certain contaminants to innocuous substance such as carbon dioxide and water.

Commercial chemical products: USEPA category listing of hazardous wastes (also called *P* or *U* listed wastes because their code numbers begin with these letters); includes specific commercial chemical products or manufacturing chemical intermediates.

Commercial sources of municipal solids waste (MSW): Solids generated in restaurants, hotels, stores, motels, service stations, repair shops, markets, office buildings, and print shops.

Community Right-to-Know Act: A part of SARA Title III under CERCLA that stipulates that a community located near a facility storing, producing, or using hazardous materials has a right to know about the potential consequences of a catastrophic chemical spill or release of chemicals from the site.

Composite sample: A sample formed by mixing discrete samples taken at periodic points in time or a continuous proportion of the flow. The number of discrete samples that make up the composite depends on the variability of pollutant concentration and flow.

Composting: A beneficial reuse biological process whereby waste (e.g., yard trimmings or wastewater biosolids) is transformed into a harmless humus-like substance used as a soil amendment.

Compound: A substance composed of two or more elements, chemically combined in a definite proportion.

Concentrated solution: Contains a relatively large proportion of solute relative to the solvent.

Condensation: Air pollution control technology used to remove gaseous pollutants from the waste stream; a process in which the volatile gases are removed from the contaminant stream and changed into a liquid.

Condenser: Air pollution control device used in a condensation method to condense vapors to a liquid phase by either increasing the system pressure without a change in temperature or by decreasing the system temperature to its saturation temperature without a pressure change.

Conduction: Flow of heat energy through a material without the movement of any part of the material itself.

Confined aquifer: Consists of a water-bearing layer sandwiched between two less permeable layers; water flow is restricted to vertical movement only.

Conidia: The asexual spores borne on aerial mycelia (actinomycetes bacteria).

Construction and demolition sources of MSW: Generated at new construction sites, by the razing of old buildings, and at road repair and renovation sites (e.g., broken pavement).

Consumers: Organisms that cannot produce their own food and eat by engulfing or predigesting the fluids, cells, tissues, or waste products of other organisms.

Contact condenser: Similar to a simple spray scrubber, it cools vapor stream by spraying liquid directly on the vapor stream.

Control of disposal: A system of controls and restrictions governing the disposal of hazardous wastes onto, or into, the land; a key element of RCRA's goal of protecting groundwater supplies.

Convection: Method of heat transfer whereby the heated molecules circulate through the medium (gas or liquid).

Cooling tower method: A treatment method used to treat thermally polluted water by spraying the heated water into the air and allowing it to cool by evaporation.

Corrosive: Refers to a substance that attacks and eats away other materials by strong chemical action.

Covalent bond: A chemical bond produced when two atoms share one or more pairs of electrons.

Cradle-to-Grave Act: See *RCRA*.

Crustacean: One of a class of arthropods that includes crabs, lobsters, shrimps, woodlice, and barnacles.

Cultural eutrophication: Overnourishment of aquatic ecosystems with plant nutrients resulting from human activities, including agriculture, urbanization, and industrial discharge.

Cyclone collector: In air pollution control, used to remove particles from a gas stream by centrifugal force.

Cytochrome: A class of iron-containing proteins important in cell metabolism.

Cytoplasm: The jelly-like matter within a cell.

Decomposers: Organisms such as bacteria, mushrooms, and fungi that obtain nutrients by breaking down complex matter in the wastes and dead bodies of other organisms into simpler chemicals, most of which are returned to the soil and water for reuse by producers.

Decomposition: Process whereby a chemical compound is reduced to its component substances; in biology, the destruction of dead organisms either by chemical reduction or by the action of decomposers.

Deep-well injection: In waste control technology, the ultimate disposal of liquid hazardous waste under pressure to underground strata isolated by impermeable rock strata to a depth of about 700 meters.

Density: The ratio of the weight of a mass to the unit of volume.

Depletion: In evaluating ambient air quality, pertains to the fact that pollutants emitted into the atmosphere do not remain there forever.

Desertification: Creation of deserts by changes in climate or by human-aided processes.

Detoxification: Biological conversion of a toxic substance to one less toxic.

Dewatering: The physical or chemical process of removing water from sludge or biosolids.

Diatoms: Microscopic single-celled algae found in all parts of the world.

Diffusion: (1) Mixing of substances, usually gases and liquids, from molecular motion. (2) The spreading out of a substance to fill a space.

Dilute solutions: A solution weakened by the addition of water, oil, or other liquid or solid.

Dinoflagellates: Unicellular, photosynthetic protistan algae.

Direct flame combustion (flaring): Used in air pollution control technology to burn off process off-gases (e.g., methane).

Disinfection: Chemical or physical processes that effectively kill all organisms capable of causing infectious disease (e.g., chlorination is commonly employed for disinfection in wastewater treatment processes).

Dispersion: The dilution and reduction of concentration of pollutants in either air or water. Air pollution dispersion mechanisms are a function of the prevailing meteorological conditions.

Dissolved oxygen (DO): The amount of oxygen dissolved in a stream, river, or lake which indicates the degree of health of the body of water and its ability to support a balanced aquatic ecosystem.

DNAPLs (dense nonaqueous-phase liquids): Liquids such as carbon tetrachloride, creosote, trichloroethane, dichlorobenzene, and others that can contaminate groundwater supplies.

Domestic wastewater: Consists mainly of human and animal wastes, household wastes, small amounts of groundwater infiltration, and perhaps small amounts of industrial wastes.

Dose–response curve: A visual means of determining, based on collected data, the percent mortality compared to dose administered.

Dose–response evaluation: Toxicological evaluation of the potency of a chemical.

Dose–response relationship: Used by toxicologists as the basis for their toxicological considerations. A dose is administered to test animals and, depending on the outcome, is increased or decreased until a range is found where at the upper end all animals die and at the lower end all animals survive.

Drainage basin: The geographical region drained by a river or stream.

Dry adiabatic lapse rate: When a dry parcel of air is lifted in the atmosphere, it undergoes adiabatic expansion and cooling that result in a lapse rate (cooling) of 1°C/100 meters.

Dry tower method: A thermal pollution treatment technique whereby heated water is pumped through tubes and the heat is released into the air (similar to the performance of an automobile radiator).

Dumps: An open location where refuse and other waste materials are disposed of in a manner that does not protect the environment, is susceptible to open burning, or is exposed to the elements, vermin, or scavengers.

Dystrophic: Defective nutrition.

Ecological toxicology: The branch of toxicology that addresses the effect of toxic substances, not only on the human population but also on the environment in general, including air, soil, surface water, and groundwater.

Ecology: The study of the interrelationship of an organism or a group of organisms with their environment.

Ecosystem: A self-regulating natural community of plants and animals interacting with one another and with their nonliving environment.

Ecotoxicology: See *Ecological toxicology.*

Electrolytic recovery technique: Used primarily for recovery of metals from process streams, to clean process waters, or to treat wastewaters prior to discharge; based on the oxidation–reduction reaction where electrode surfaces are used to collect the metals from the waste stream.

Electron: A component of an atom that travels in a distant orbit around a nucleus.

Electron transport system: In metabolic transfer, a series of electron carriers that operate together to transfer electrons from donors such as NADH and $FADH_2$ to acceptors such as oxygen.

Electrostatic precipitation: Process using a precipitator to remove dust or other particles from air and other gases by electrostatic means. An electric discharge is passed through the gas, giving the impurities a negative electric charge. Positively charged plates are then used to attract the charged particles and remove them from the fast flow.

Elements: The simplest substance that cannot be separated into more simple parts by ordinary means. There are more than 100 known elements.

Emergency response: Relates primarily to OSHA's requirement under 29 CFR 1910.120 for chemical, industrial, storage, and waste sites to have a written emergency response plan for any covered chemical release or spill to the environment that could jeopardize the good health and well-being of any worker. USEPA also requires an emergency response plan for facilities handling, producing, or using covered chemicals in its risk management plan requirements. Contingencies for fire, natural disasters, terrorist attacks, and medical emergencies should also be included in emergency response plans.

Emergent vegetation: A subdivision of the littoral zone of a pond that encompasses the shoreline soil area and the immediate shallow water area where emergent plant life can take root under water, grow, and surface above the waterline.

Emergents: See *Emergent vegetation.*

Endergonic: A reaction in which energy is absorbed.

Endoplasmic reticulum: Within a eucaryotic cell, a system of membranes ramifying the cytoplasmic region; it forms the limiting boundaries, compartments, and channels whose lumina are completely isolated from the cytoplasm. It is a protein-containing lipid bilayer.

Energy: A system capable of producing a physical change of state.

Entropy: A measure of the disorder of a system.

Environment: All the surroundings of an organism, including other living things, climate, soil, etc.; in other words, the conditions for development or growth.

Environmental degradation: All the limiting factors that act together to regulate the maximum allowable size or carrying capacity of a population.

Environmental factors: Factors that influence volatilization of hydrocarbon compounds from soils, such as temperature, wind, evaporation, and precipitation.

Environmental science: The study of the human impact on the physical and biological environment of an organism. In its broadest sense, it also encompasses the social and cultural aspects of the environment.

Environmental toxicology: The branch of toxicology that addresses the effect of toxic substances, not only on the human population but also on the environment in general, including air, soil, surface water, and groundwater.

Enzymes: Proteinaceous substances that catalyze microbiological reactions such as decay or fermentation. They are not used up in the process but speed it up greatly. They can promote a wide range of reactions, but a particular enzyme can usually only promote a reaction on a specific substrate.

Epilimnion: Upper layer of a lake; it is heated by the sun and is lighter and less dense than the underlying water.

Eucaryotic: An organism characterized by a cellular organization that includes a well-defined nuclear membrane.

Euphotic: The surface layer of an ocean, a lake, or other body of water through which sufficient sunlight reaches to allow photosynthesis.

Eutrophic lake: Lake with a large or excessive supply of plant nutrients (mostly phosphates and nitrates).

Eutrophication: Natural process in which lakes receive inputs of plant nutrients as a result of natural erosion and runoff from the surrounding land basin.

Evaporative emissions: The evaporative emission of fuel from internal combustion systems caused by diurnal loses, hot soak, and running losses.

Evapotranspiration: Combination of evaporation and transpiration that transforms liquid water in plant tissue and in the soil to water vapor in the atmosphere.

Excavation: The physical removal of soil to construct a burial site for contaminants (landfill) or the removal of contaminated soil by mechanical means.

Excavation and disposal: The removal of contaminated soil for treatment or ultimate disposal.

Exergonic: Releasing energy.

Exposure assessment: Measurement to estimate the magnitude of actual or potential human exposures, the frequency and duration of these exposures, and the pathways by which humans are potentially exposed.

Exposure pathways: Can be divided into the two categories of *direct human exposure pathways* and *environmental exposure pathways*. Each of these categories is further subdivided into primary and secondary exposure pathways. Primary pathways directly affect site operations and personnel (e.g., skin contact during soil sampling). Secondary exposure pathways occur as a minor component during site operations and exhibit significant decreases with time as treatment progresses (e.g., wind-blown dust).

Extraction procedure (EP): A standardized laboratory test used to test for toxicity; replaced in 1990 by the toxicity characteristics leaching procedure (TCLP).

Extraction well: Used to lower the water table, creating a hydraulic gradient that draws a plume of contamination to the well so the contaminant can be extracted.

Extremely hazardous substance: USEPA term for those chemicals that must be reported to the appropriate authorities if released above the threshold reporting quantity.

Facultative: Bacteria capable of growth under aerobic and anaerobic conditions.

Federal Water Pollution Control Act (Clean Water Act): Act concerned with controlling and regulating the amount of municipal and industrial pollution fed into the nation's water bodies.

Fermentation: The decomposition of organic substances by microorganisms or enzymes. The process is usually accompanied by the evolution of heat and gas and can be aerobic or anaerobic.

Fertilizer: Substance that adds essential nutrients to the soil and makes the land or soil capable of producing more vegetation or crops.

Filtration: Technique by which suspended solid particles in a fluid are removed by passing the mixture through a filter. The particles are retained by the filter to form a residue, and the fluid that passes through is known as the filtrate.

First law of thermodynamics: In any chemical or physical change, movement of matter from one place to another, or change in temperature, energy is neither created nor destroyed but merely converted from one form to another.

Flagella: A threadlike appendage that gives some bacteria motility; it extends outward from the plasma membrane and cell wall.

Flare: See *Direct flame combustion.*

Flexible-membrane liner (FML): Rubber or plastic liner used in sanitary landfills.

Floating leaf vegetation: Part of the littoral zone in a lake or pond where vegetation rooted under the surface allows stems to produce foliage that is able to reach and float on the water surface.

Fluoride: Fluoride salt is added to public drinking water supplies for improved resistance to dental caries.

Food chain: A sequence of transfers of energy in the form of food from organisms in one trophic level to organisms in another trophic level when one organism eats or decomposes another.

Food web: A complex network of many interconnected food chains and feeding interactions.

Formula weight: The sum of the atomic weight of all atoms that comprise one formula unit.

Friable: Readily crumbled in hand.

Front: In meteorology, the boundary between two air masses of different temperature or humidity.

Frustules: The distinctive two-piece wall of silica in diatoms.

Fumigation: Results when emissions from a smokestack that is under an inversion layer head downward, leading to greatly elevated downwind, ground-level concentrations of contamination.

Fungi: Saprophytic or parasitic organisms that may be unicellular or made up of tubular filaments and that lack chlorophyll.

Garbage: The generic name for waste emanating from households that contains mostly vegetable matter and paper.

Gas: In the widest sense, term applied to all aeriform bodies, the most minute particles of which exhibit the tendency to fly apart from each other in all directions. Normally, these gases are found in that state at ordinary temperature and pressure. They can only be liquefied or solidified by artificial means, either through high pressure or extremely low temperatures.

Gas laws: The physical laws concerning the behavior of gases. They include Boyle's law and Charles's law, which are concerned with the relationships among the pressure, temperature, and volume of an ideal (hypothetical) gas.

General biological succession: The process whereby communities of plant and animal species in a particular area are replaced over time by a series of different and usually more complex communities (also referred to as *ecological succession*).

Genome: A complete haploid set of chromosomes.

Genus: A group of species with many common characteristics.

Geology: The science of Earth, its origin, composition, structure, and history.

Geophysical testing: Used to evaluate the subsurface layers, locate the water table, and map contaminate contours using resistivity and conductivity meters.

Geosphere: Consists of the inorganic, or nonliving, portions of Earth which are home to all of the globe's organic, or living, matter.

Geothermal energy: The use of Earth's natural heat for human purposes; a form of alternative energy that is massive but difficult to tap.

Geothermal power: See *Geothermal energy.*

Global warming: The long-term rise in the average temperature of the Earth.

Glycolysis: One of three phases of the catabolism of glucose to carbon and water process.

Grab sample: An individual discrete sample collected over a period of time not exceeding 15 minutes.

Gram: The basic unit of weight in the metric system; equal to 1/1000th of a kilogram; approximately 28.5 grams equal 1 ounce.

Gravity: The force of attraction that arises between objects by virtue of their masses. On Earth, gravity is the force of attraction between any object in the Earth's gravitational field and the Earth itself.

Gravity settlers: Used for the removal of solid and liquid waste materials from gaseous streams. Consists of an enlarged chamber in which the horizontal gas velocity is slowed, allowing particles to settle out by gravity.

Greenhouse effect: Heat trapped in the atmosphere. Incoming short-wavelength solar radiation penetrates the atmosphere, but the longer wavelength outgoing radiation is absorbed by water vapor, carbon dioxide, ozone, and several other gases in the atmosphere and is reradiated to Earth, causing an increase in atmospheric temperature.

Greenhouse gases: The gases present in the Earth's atmosphere that cause the greenhouse effect.

Groundwater: Water collected underground in porous rock strata and soils; it emerges at the surface as springs and streams.

Grout curtain: Used in *in situ* isolation and containment; Portland cement or grout is injected under pressure to form a barrier against contaminant movement in soil.

Growth curve: A plot of bacterial growth cycles. The curve is divided into four phases designated as lag, exponential, stationary, and death. The lag phase, characterized by little or no growth, corresponds to an initial period of time when bacteria are first inoculated into a fresh medium. After the bacteria have adjusted to their new environment, a period of rapid growth (the exponential phase) follows; during this time, conditions are optimal, and the population doubles with great regularity. As the bacteria food supply begins to be depleted or as toxic metabolic products accumulate, the population enters the no-growth, or stationary, phase. Finally, as the environment becomes more and more hostile, the death phase is reached, and the population declines.

Guano: A substance composed chiefly of the dung of sea birds or bats; it accumulates along certain coastal areas or in caves and is used as fertilizer.

Habitat: The place or type of place where an organism or community of organisms naturally or normally thrives.

Hardness: A water quality parameter. Water that does not lather easily with soap and produces scale in pots, pans, and kettles contains certain salts of calcium and magnesium.

Hazardous and Solid Waste Act and Amendments: Part of RCRA that emphasizes the development and use of alternative and innovative treatment technologies that result in permanent destruction of wastes or reduction in toxicity, mobility, and volume. Land disposal is greatly restricted under the 1984 RCRA amendments.

Hazardous chemical: An explosive, flammable, poisonous, corrosive, reactive, or radioactive chemical requiring special care in handling because of hazards it poses to public health and the environment.

Hazardous material: A substance in a quantity or form posing an unreasonable risk to health, safety, or property when transported in commerce and that by its nature, containment, and reactivity has the capability for inflicting harm during an accident occurrence. Such a substance is characterized as toxic, corrosive, flammable, reactive, an irritant, or a strong sensitizer and thereby poisonous. It is a threat to health and the environment when improperly managed.

Hazardous substance: A USEPA term for certain listed chemicals; if they are released into the environment above a certain amount, the incident must be reported.

Hazardous waste: Waste materials or mixtures of waste that require special handling and disposal because of their potential to damage health and the environment.

Hazardous waste stream: A gaseous or liquid waste stream that contains any type of hazardous substance.

Heat: A condition of matter caused by the rapid movement of its molecules. Energy has to be applied to the material in sufficient amounts to create the motion and may be applied by mechanical or chemical means.

Heat balance: The constant trade-off that takes place when solar energy reaches the Earth's surface and is absorbed then must return to space to maintain Earth's normal heat balance.

Heat islands: Large metropolitan areas where the heat generated has an influence on the ambient temperature (adds heat) in and near the area.

Heavy metals: A group of elements whose compounds are toxic to humans when found in the environment; examples are cadmium, mercury, copper, nickel, chromium, lead, zinc, and arsenic.

Henry's law: Governs the behavior of gases in contact with water.

Heterotroph: See *Heterotrophic.*

Heterotrophic: Refers to organisms that obtain their energy by consuming the tissue of other organisms.

Holoenzyme: A complete enzyme consisting of an apoenzyme and a coenzyme.

Horizon: In soil, a layer of soil approximately parallel to the soil surface and differing in properties and characteristics from adjacent layers below or above it.

Hot-mix asphalt process: A remedial technology whereby a contaminant entrained in soil is used in beneficial applications to make asphalt. In the hot-mix process, the petroleum-laden soil is added as part of the aggregate to hot asphalt and then mixed to make the final product.

Hot soak: Evaporative emissions caused by heat from an internal combustion engine after the engine is shut off.

Humidity: The amount of water vapor in a given volume of the atmosphere (absolute humidity), or the ratio of the amount of water vapor in the atmosphere to the saturation value at the same temperature (relative humidity).

Humus: That more or less stable fraction of the soil organic matter remaining after the major portions of added plant and animal residues are decomposed; usually dark in color.

Hydraulic gradient: The difference in hydraulic head divided by the distance along the fluid flow path. Groundwater moves through an aquifer in the direction of the hydraulic gradient.

Hydrocarbon: A chemical containing only carbon and hydrogen atoms. Crude oil is a mixture largely of hydrocarbons.

Hydrological cycle: The means by which water is circulated in the biosphere. Cooling in the atmosphere and precipitation over both land and oceans counterbalance evapotranspiration from the land mass plus evaporation from the oceans.

Hydrosphere: The portion of the Earth's surface covered by the oceans, seas, and lakes.

Hypha (sing.), hyphae (pl.): In fungi, a tubular cell that grows from the tip and may form many branches.

Hypolimnion: The cold, relatively dense bottom layer of water in a stratified lake.

Ideal gas: A hypothetical gas that obeys the gas laws exactly with regard to temperature, pressure, and volume relationships.

Igneous: Refers to rock formed by the cooling and solidification of hot, molten material.

Ignitability: One of the characteristics used to classify a substance as hazardous.

Impaction: In air pollution control technology, a particle collection process whereby the center of mass of a particle diverging from a fluid strikes a stationary object and is collected by the stationary object.

Impoundment: A lake classification; an artificially manmade lake made by trapping water from rivers and watersheds.

***In situ* biodegradation:** Uses naturally occurring microorganisms in soil to degrade contaminants to another form.

***In situ* isolation/contamination:** In soil remediation, this method prevents the migration of liquid contaminant or leachates containing contaminants.

***In situ* leaching and chemical reaction:** Soil remediation process whereby water mixed with a surfactant is used to leach contaminants from the soil into the groundwater. The groundwater is then collected downstream of the leaching site through a collection system for treatment and/or disposal.

***In situ* passive remediation:** The easiest to implement and least expensive remediation methodology because it involves no action at the site; it lets nature takes its course but is not readily or normally accepted by regulators.

***In situ* technologies:** Remedial technologies performed in place at the site.

***In situ* vitrification:** Electrical current is passed through electrodes driven into the soil to produce extreme heat and convert the soil into a durable glassy material. The organic constituents are pyrolized in the melt and migrate to the surface, where they combust in the presence of oxygen. Inorganics in the soil are effectively bound in the solidified glass.

***In situ* volatilization:** Commonly known as air stripping, this process uses forced air or drawn air currents through in-place soil to remove volatile compounds.

Incineration: The application of high temperatures (800 to 3000°F) to break down organic wastes into simpler forms and to reduce the volume of waste requiring disposal. Energy can be recovered from the incineration heat.

Inclusions: Storage granules often seen within bacterial cells.

Industrial practices: Practices that can lead to soil contamination, including contaminants from USTs, oilfield sites, chemical sites, geothermal sites, manufactured gas plants, mining sites, and environmental terrorism.

Industrial wastewater: Liquid wastes produced by industry.

Infiltration galleries: Technique used in the *in situ* biodegradation process to reintroduce conditioned groundwater to the soil or aquifer.

Infrared radiation: Invisible electromagnetic radiation of wavelength between about 0.75 mm and 1 mm (between the limit of the red end of the visible spectrum and the shortest microwaves).

Injection well: In groundwater remediation, type of well used to raise the level of the water table and to push a contaminated plume away from a potable water system (well).

Innovative cleanup technology: Any new or developing soil remediation technology.

Inorganic substance: A substance that is mineral in origin that does not contain carbon compounds, except as carbonates, carbides, etc.

Insolation: The amount of direct solar radiation incident per unit of horizontal area at a given level.

Institutional sources of MSW: Hospitals, schools, jails and prisons, and government centers are among the sources of municipal solid waste.

Interception: In particle collection technology, interception occurs when the particle's center of mass closely misses the object, but, because of its finite size, the particle strikes the object and is collected.

Interstate Commerce Clause: The clause in the U.S. Constitution upon which the federal government based its enactment of the Rivers and Harbors Act of 1988, enabling the U.S. Army Corps of Engineers to regulate and in some cases prohibit private and municipal dumping practices.

Ionic bonds: A chemical bond in which electrons have been transferred from atoms of low ionization potential to atoms of high electron affinity.

Irrigation: Artificial water supply for dry agricultural areas created by means of dams and channels.

Isobar: A line drawn on maps and weather charts linking all places with the same atmospheric pressure (usually measured in millibars).

Jet stream: A narrow band of very fast wind found at altitudes of 6 to 10 miles, in the upper troposphere or lower stratosphere.

Kelvin: Temperature scale used by scientists that begins at absolute zero and increases by the same degree intervals as the Celsius scale; that is, 0°C is the same as 273 K and 100°C is 373 K.

Krebs cycle or citric acid cycle: The final part of the chain of biochemical reactions by which organisms break down food using oxygen to release energy (respiration).

Land farming: Another name for land treatment whereby various contaminants are spread on soil and worked into the surface and subsurface to allow biodegradation to take place.

Land treatment: See *Land farming.*

Landfill: Land waste disposal site located without regard to possible pollution of groundwater and surface water resulting from runoff and leaching; waste is covered intermittently with a layer of earth to reduce scavenger, aesthetic, disease, and air pollution problems.

Landfilling: An ultimate disposal technique whereby solid and hazardous wastes are disposed of in excavated sites.

Lapse rate: The rate of change of air temperature with increasing height.

Latent heat of fusion: The amount of heat required to change 1 gram of a substance from the solid to the liquid phase at the same temperature.

Latent heat of vaporization: The amount of heat required to change 1 gram of a substance from the liquid to the gas phase at the same temperature.

Law of conservation of mass: In any ordinary physical or chemical reaction, matter is neither created nor destroyed but merely changes from one form to another.

Laxative effect: The consumption of hardwater combined with the presence of magnesium sulfates sometimes leads to the development of a laxative effect on new consumers.

Leach liquors: Refers to liquid leached from a substance via water circulation through or over it.

Leachate: The liquid formed when rainwater percolates downward through landfilled wastes, picking up contaminants that might then enter the surrounding environment.

Lead: A heavy metal, the accumulation of which in the organic tissues of animals and humans could lead to behavioral changes, blindness, and ultimately death.

Lead-mine scale: Generally occurs in geothermal process equipment such as in piping where scale buildup leads to process equipment failure.

Leaking Underground Storage Tank (LUST) Trust Fund: The 1986 U.S. UST cleanup fund.

Lentic: Calm; refers to lakes, ponds, and swamps.

Limited: Refers to growth regulated by such nutrients such as carbon, nitrogen, and phosphorus.

Limiting factors: Factors such as temperature, light, water, or a chemical that limit the existence, growth, abundance, or distribution of an organism.

Limiting nutrient: See *Limited.*

Limnetic: The open water surface layer of a lake through which sufficient sunlight reaches for photosynthesis.

Limnology: The study of lakes and other bodies of open freshwater in terms of their plant and animal biology and their physical properties.

Liquid: A state of matter between a solid and a gas.

Liter: A metric unit of volume, equal to 1 cubic decimeter (1.76 pints).

Lithosphere: The Earth's crust; the layers of soil and rock that comprise the Earth's crust.

Litter: The intact and partially decayed organic matter lying on top of the soil; discards thrown about without regard to the environment.

Littoral: The shallow zone near the shore of a body of water.

LNAPLs: Light nonaqueous-phase liquids (e.g., gasoline, heating oil, kerosene).

Loam: The textural class name for soil with a moderate amount of sand, silt, and clay. Loam soils contain approximately 7 to 27% clay, 28 to 50% silt, and 23 to 52% sand.

Lotic: Running freshwater systems (e.g., rivers or streams).

Magma: Molten rock material within the Earth's core.

Management factors: Management techniques (e.g., fertilization, irrigation) employed in land and soil management that work to decrease leaching, increase soil surface contaminant concentrations, or maximize soil aeration against volatilization.

Manifest: See *Tracking system.*

Mass: The quantity of matter and a measurement of the amount of inertia that a body possesses.

Mass balance equations: Used to track pollutants from one place to another.

Materials balance: The law of conservation of matter says that everything has to go somewhere and is neither created nor destroyed in the process.

Mature pond: A pond that has reached maturity; characterized by being carpeted with rich sediment, having aquatic vegetation extending out into open water, and being home to a great diversity of plankton, invertebrates, and fishes.

Maximum contaminant levels (MCLs): Primary drinking water standard and maximum contaminant levels allowed based on health-related criteria.

Maximum sustainable yield: The highest rate at which a renewable resource can be used without impairing or damaging its ability to be fully renewed.

Melting point: The temperature at which a substance changes from solid to liquid.

Meromictic: Refers to chemically stratified lakes in which different dissolved chemicals are partly mixed.

Mesosome: A common intracellular structure found in the bacterial cytoplasm; an invagination of the plasma membrane in the shape of tubules, vesicles, or lamellae.

Mesosphere: An atmospheric layer that extends from the top of the stratosphere to about 56 miles above the Earth.

Mesotrophic lakes: Lakes intermediate in characteristics between oligotrophic and eutrophic lakes.

Metabolic transformation: Refers to the assembly-line of activities that occur in microorganisms during the processing of raw materials into finished products.

Metabolism: The chemical processes of living organisms; a constant alternation of building up and breaking down. Green plants, for example, build up complex organic substances from water, carbon dioxide, and mineral salts (photosynthesis). Also, digestion partially breaks down complex organic substances ingested as food by animals so they can be utilized by their bodies.

Metalloids: An element that exhibits the properties of both metals and nonmetals.

Metals: Elements that tend to lose their valence electrons.

Metamorphic: A type of rock that forms when rocks lying deep below the Earth's surface are heated to such a degree that their original crystal structure is lost. As the rock cools, a new crystalline structure is formed.

Meteorology: The scientific observation and study of the atmosphere used to forecast weather accurately.

Meter: The standard of length in the metric system, equal to 39.37 inches or 3.28 feet.

Methane (CH_4): The simplest hydrocarbon of the paraffin series. Colorless, odorless, and lighter than air, it burns with a bluish flame and explodes when mixed with air or oxygen. Methane is a greenhouse gas.

Microbial community: The community of microbes available to biodegrade contaminants in the soil.

Microbial degradation: The natural process whereby certain microbes in soil can degrade contaminants into harmless constituents.

Microbiology: The study of organisms that can only be seen under the microscope.

Middens: Primitive dunghills or refuse heaps.

Midnight dumping: Illegal dumping of solid or hazardous wastes into the environment.

Mining waste: The earth and rock (including minerals and chemicals within) taken from a mine and discarded because the mineral or fuel content is too low to warrant extraction. This waste is an environmental problem if toxic substances leach from it into a river, stream, groundwater, or the soil.

Mitochondria: A microscopic body found in the cells of almost all living organisms and containing enzymes responsible for the conversion of food to usable energy.

Mixture: In chemistry, a substance containing two or more compounds that still retain their separate physical and chemical properties.

Mobile sources: Nonstationary sources of gaseous pollutants, including locomotives, automobiles, ships, and airplanes.

Mobilization: The mobilizing of metals in soil by the acidity of precipitation.

Modeling: Refers to the use of mathematical representations of contaminant dispersion and transformation to estimate ambient pollutant concentrations.

Molar concentration (molarity): In chemistry, solution that contains 1 mole of a substance per liter of solvent.

Molecular weight: The weight of 1 molecule of a substance relative to carbon-12, expressed in grams.

Mole (mol): SI unit for the amount of a substance; the amount of a substance that contains as many elementary entities as there are atoms in 12 g of the isotope carbon-12.

Molecule: The fundamental particle that characterizes a compound. It consists of a group of atoms held together by chemical bonds.

Monitor wells: Wells installed specifically to provide a means to monitor a contaminant plume in soil or groundwater.

Monitoring: Process whereby a contaminant is tracked.

Montreal Protocol: Required signatory countries to reduce their consumption of chlorofluorocarbons by 20% by 1993 and by 50% by 1998.

Morphogenesis: Evolutionary development of the structure of an organism or part.

Motility: An organism's ability to move.

Municipal services sources of MSW: Restaurants, hotels, stores, motels, service stations, repair shops, markets, office building, and print shops produce such municipal solid waste.

Municipal solid waste (MSW): Municipally derived wastes, including paper, yard wastes, glass, metals, and plastics.

Mycelium: An interwoven mass of threadlike filaments or hyphae comprising the main body of most fungi; they produce the reproductive structures, or "fruiting bodies" (e.g., mushrooms).

Mycology: The branch of botany that deals with fungi.

National Ambient Air-Quality Standards (NAAQs): Standards established by USEPA at two levels**:** primary and secondary. Primary standards must be set at levels that will protect public health and include an "adequate margin of safety," regardless of whether the standards are economically or technologically achievable. Primary standards must protect even the most sensitive individuals, including the elderly and those with respiratory ailments. Secondary air quality standards are meant to be even more stringent than primary standards. Secondary standards are established to protect public welfare (e.g., structures, crops, animal, fabrics).

National Priorities List (NPL): Identifies the worst waste sites in the nation based on such factors as the quantities and toxicity of wastes involved, the exposure pathways, the number of people potentially exposed, and the importance and vulnerability of the underlying groundwater.

Nekton: In a water environment, the free-swimming organisms.

Neustons: In a water environment, the organisms living on the surface.

Neutrally stable atmosphere: An intermediate class between stable and unstable conditions; will cause a smoke-stack plume to take on the appearance of a cone as the edges of the plume spread out in a V shape.

Neutron: Elementary particles that have approximately the same mass as protons but have no charge. They are one constituent of the atomic nucleus.

Niche: The functional role of an organism within its community; the complete ecological description of an individual species (including habitat, feeding requirements, etc.).

Nitrates: In freshwater pollution, a nutrient, usually from fertilizer, that enters the water system and can be toxic to animals and humans in high enough concentrations.

Nitrification: The process that takes place in soil when bacteria oxidize ammonia, turning it into nitrates.

Nitrogen cycle: The natural circulation of nitrogen through the environment.

Nitrogen dioxide (NO_2): A reddish-brown, highly toxic gas with a pungent odor. One of the seven known nitrogen oxides that contribute to photochemical smog and primarily affect the respiratory system.

Nitrogen fixation: Nature accomplishes nitrogen fixation by means of nitrogen-fixing bacteria.

Nitrogen oxide (NO): A colorless gas used as an anesthetic; soil bacteria form NO from decomposing nitrogenous material.

Non-*in situ* technology: Remediation/recycling technology that takes place away from the contamination site.

Noncarbonate hardness: A property of water such that the hardness cannot be removed by boiling and is classified as permanent.

Nonmetals: An element that tends to gain electrons to complete its outer shell.

Nonpoint source: Source of pollution in which wastes are not released at one specific, identifiable point but from a number of points that are spread out and difficult to identify and control.

Nonpoint-source pollution: Pollution that cannot be traced to a specific source but rather comes from multiple generalized sources.

Nonrenewable resources: Resources that exist in finite supply or are consumed at a rate faster than the rate at which they can be renewed.

Nonspecific source wastes: Generic wastes commonly produced by manufacturing and industrial processes (e.g., spent solvents).

Nonvolatile: A substance that does not evaporate at normal temperatures when exposed to the air.

Normal lapse rate: The normal rate of temperature change with height; on average, temperature decreases 65°C/100 meters.

Nucleoid: The primitive nuclear region of the procaryotic cell.

Nutrient cycles: See *Biogeochemical cycles.*

Nutrients: Elements or compounds needed for the survival, growth, and reproduction of a plant or animal.

Nutrition: The process of nourishing or being nourished.

Oligotrophic lake: A lake with a low supply of plant nutrients.

Organelle: A specialized part of a cell that resembles and functions as an organ.

Organic chemistry: Branch of chemistry concerned with compounds of carbon.

Organic matter: Includes both natural and synthetic molecules containing carbon and usually hydrogen. All living matter is made up of organic molecules.

Organic substance: Any substance containing carbon.

Overgrazing: Consumption of vegetation on rangeland by grazing animals to the point that the vegetation cannot be renewed or is renewed at a rate slower than consumption.

Oxidation: The process by which electrons are lost.

Oxidation–reduction: The (redox) process where electrons are lost and gained.

Oxidize: To combine with oxygen.

Oxygen: An element that readily unites with materials.

Oxygen sag curve: The oxygen content in a stream or river system after organic pollution is introduced into the water body; organic pollution causes a profusion in growth of organisms that tends to decrease the amount (sag) of oxygen available.

Ozone holes: Holes created in the ozone layer because of chemicals, especially CFCs.

Ozone (O_3): Found naturally in the atmosphere in the ozonosphere; a constituent of photochemical smog.

Packed tower: A remediation method (scrubber) employed to clean a contaminated gaseous waste stream by exposing the waste stream to biological media or chemical scrubbing agents.

Parasite: Primary, secondary, or higher consumer that feeds on a plant or animal, known as a host, over an extended period of time.

Parent material: The unconsolidated and more or less chemically weathered mineral or organic matter from which pedogonic processes develop the solum of soils.

Particulate matter: Normally refers to dust and fumes; travels easily through air.

Pascal (Pa): A unit of pressure equal to 1 newton per square meter.

Pathogen: Any disease-producing organism.

Pedologist: A person who studies soils.

Peds: A unit of soil structure such as an aggregate, crumb, prism, block, or granule formed by natural processes.

Pellicle: A *euglena* structure that allows for turning and flexing of the cell.

Period: An interval of geologic time that is a subdivision of an era and made up of epochs; a horizontal row of the periodic table that contains elements with approximately the same energy.

Periodic law: The properties of elements are periodic functions of the atomic number.

Periodic table: An arrangement of all elements in order of increasing atomic numbers and grouped by similar physical and chemical characteristics into periods; based on the chemical law that physical or chemical properties of the elements are periodic functions of their atomic weights.

Permanent pond: Actually a misnomer, as no pond is permanent. Generally, a pond shallow enough to permit aquatic plants to penetrate the surface anywhere over its entire mass; its mass is not so great as to allow formation of large waves that could erode the shoreline. Such ponds have no temperature layering, rather a gradient of temperatures extending from the surface to bottom.

Permitting system: A key element of RCRA, this system works to ensure the safe operation of facilities that treat, store, or dispose of hazardous wastes.

Perpetual resource: A resource such as solar energy that comes from an essentially inexhaustible source and thus will always be available on a human time scale regardless of whether or how it is used.

Persistent substance: A chemical product with a tendency to persist in the environment for quite some time (e.g., plastics).

Pesticide: Any chemical designed to kill weeds, insects, fungi, rodents, and other organisms that humans consider to be undesirable.

pH: A numerical designation of relative acidity and alkalinity. A pH of 7 indicates precise neutrality; higher values indicate increasing alkalinity, and lower values indicate increasing acidity.

Phosphates: A nutrient substance obtained from fertilizers.

Phosphorus cycle: A biogeochemical cycle in which phosphorus is converted into various chemical forms and transported through the biosphere.

Photochemical reaction: A reaction induced by the presence of light.

Photochemical smog: Complex mixture of air pollutants in the atmosphere due to hydrocarbon and nitrogen oxide reactions under the influence of sunlight.

Photosynthesis: A complex process that occurs in the cells of green plants whereby radiant energy from the sun is used to combine carbon dioxide (CO_2) and water (H_2O) to produce oxygen (O_2) and simple sugar or food molecules, such as glucose.

Physical change: The process that alters one or more physical properties of an element or compound without altering its chemical composition. Examples include changing the size and shape of a sample of matter and changing a sample of matter from one physical state to another.

Physical weathering: The physical changes produced in rocks by atmospheric agents (e.g., wind, precipitation, heat, cold).

Pioneer community: The first successfully integrated set of plants, animals, and decomposers found in an area undergoing primary ecological succession.

Piping failure: A common equipment component failure in many different systems; it is the most common cause of underground storage tank spills.

Plankton: Microscopic floating plant and animal organisms in lakes, rivers, and oceans.

Planktonic: See *Plankton.*

Plasma membrane: See *Cytoplasmic membrane.*

Plate tower: Used for absorption scrubbing; plate towers contain perforated horizontal plates or trays designed to provide a large liquid–gas interfacial area. The polluted air stream rises up through the perforations in each plate, and the rising gas prevents liquid from draining through the openings rather than through a downpipe. During continuous operation, contact is maintained between air and the liquid, allowing gaseous contaminants to be removed and clean air to emerge from the top of the tower.

Plume: (1) The column of noncombustible products emitted from a fire or smokestack. (2) A vapor cloud formation having shape and buoyancy. (3) A contaminant formation dispersing through the subsurface.

Point source: Discernible conduits, including pipes, ditches, channels, sewers, tunnels, or vessels, from which pollutants are discharged.

Point-source pollution: Pollution that can be traced to an identifiable source.

Pollute: To impair the quality of some portion of the environment by the addition of harmful impurities.

Pond: A still body of water, smaller than a lake and often of artificial construction.

Pond succession: Pond transformation process whereby a young pond is formed and develops over time to a mature pond and then to a senescent (old) pond.

Pool zone: In a body of moving water (river or stream), the quiet or still water portion.

Positive crankcase ventilation (PCV): Technology used to control crankcase emissions.

Preliminary treatment: (1) In wastewater, treatment occurring prior to primary treatment. (2) In industrial applications, pretreatment of waste streams before they become plant effluent and then influent into wastewater treatment plants for further treatment.

Pressure: Force per unit area.

Pressure gradient force: A variation of pressure with position.

Primary consumers: In the food chain, organisms that consume producers (autotrophs).

Primary exposure pathways: In site remediation, the exposure pathways that directly affect site operations and personnel or directly affect the cleanup levels that must be achieved by the remedial technology.

Primary pollutants: Pollutants emitted directly into the atmosphere, where they exert an adverse influence on human health or the environment. The six primary pollutants are carbon dioxide, carbon monoxide, sulfur oxides, nitrogen oxides, hydrocarbons, and particulates. All but carbon dioxide are regulated in the United States.

Primary standards: The Clean Air Act (NAAQS) air quality standard covering criteria pollutants.

Primary treatment: Wastewater treatment process in which mechanical treatment is employed to screen out large solids and settle out suspended solids.

Procaryotic: A type of primitive cell lacking a membrane-delimited nucleus.

Producers: Organisms that use solar energy (green plant) or chemical energy (some bacteria) to manufacture their own organic substances (food) from inorganic nutrients.

Profundal: Deepwater zone of a lake not penetrated by sunlight.

Proton: Component of a nucleus, 2000 times more massive than an electron; differs from a neutron by its positive (+1) electrical charge. The atomic number of an atom is equal to the number of protons in its nucleus.

Protozoa: Single-celled microorganisms; includes the most primitive forms of animal life.

Pumping well system: In control technology for leaking USTs, the preferred method used to recover free product from the water table when the spill is deep.

Radiation: The emitting of energy from an atom in the form of particles of electromagnetic waves; energy waves that travel with the speed of light and, upon arrival at a surface, are absorbed, reflected, or transmitted.

Radiative inversions: A nocturnal phenomenon caused by cooling of the Earth's surface. Inversions prompt the formation of fog and simultaneously trap gases and particulates, creating a concentration of pollutants.

Radioactive material: Any material that spontaneously emits ionizing radiation.

Rapids zone: The turbulent zone of a stream or river in which water is agitated by subsurface obstructions causing turbulence and aeration of water.

Reactive: The tendency of a material to react chemically with other substances.

Recharge area: The area in which precipitation percolates through to recharge groundwater.

Recovery zone: The zone in a stream or river where contamination is reduced by the self-purification process.

Recycle: The process of recovery and reuse of materials from waste streams.

Recycling technology: The technology available to recycle or reuse waste products; processes such as composting and hot- and cold-mix asphalt incorporation.

Reduction: Removal of oxygen from a compound; lowering of oxidation number resulting from a gain of electrons.

Refuse: Rubbish and garbage from residential sources.

Relative humidity: The percentage of moisture in given volume of air at a given temperature in relation to the amount of moisture the same volume of air would contain at the saturation point.

Renewable resources: Resources that can be depleted in the short run if used or contaminated too rapidly but that normally are replaced through natural processes.

Representative sample: A sample of a universe or whole, such as a waste pile, lagoon, or groundwater that can be expected to exhibit the average properties of the whole.

Reservoir: A large and deep human-created standing body of freshwater.

Residential sources of MSW: Household waste consisting primarily of paper, glass, vegetable waste, paperboard, ash, tin cans, etc.

Resource: Something that serves a need, is useful, and is available at a particular cost.

Resource Conservation and Recovery Act (RCRA) of 1976: Act passed by U.S. Congress to control dumping of waste materials (also known as the Cradle-to-Grave Act).

Reuse: To use a product again and again in the same form, as when returnable glass bottles are cleaned and refilled.

Ribosomes: In bacterial cytoplasm, minute, rounded bodies made of RNA that are loosely attached to the plasma membrane; they are the site of protein synthesis and are part of the translation process.

Risk assessment: Evaluation of the threat to public health and the environment posed by a hazardous waste facility; considering the probability of an incident and its effects.

Risk characterization: Final step in risk assessment process estimating potential adverse health effects under the conditions of exposure found and described in the exposure assessment.

Rivers and Harbors Act (1899): The first legislative authority given to a federal agency (U.S. Army Corps of Engineers) to prevent dumping wastes into rivers and harbors.

Rotifers: A minute multicellular aquatic organism with a wheel-like ring of cilia at the anterior end.

Rubbish: Combustible waste, paper, cartons, rags, wood scraps, and combustible floor sweepings, for example, from domestic, commercial, and industrial sources.

Running losses: Evaporative emissions from internal combustion engine as a result of driving; losses also occur when the fuel is heated by the road surface and when fuel is forced from the fuel tank while the vehicle is being operated and the fuel tank becomes hot.

Runoff: Surface water entering rivers, freshwater lakes, or reservoirs from land surfaces.

Safe Drinking Water Act (SDWA): Mandated USEPA to establish drinking water standards for all public water systems serving 25 or more people or having 15 or more connections.

Saline water: Water with excessive salt content.

Salt spreading: Applying salt to roadways in the winter to help reduce ice and snow accumulations; road salts contaminate soil during runoff.

Sanitary landfill: A method of solid waste disposal designed to minimize water pollution from runoff and leaching; waste is covered with a layer of soil within a day after being deposited at the landfill site.

Sanitary wastewater: Separate sewer system designed to remove domestic wastes from residential areas.

Saprophyte: An organism that uses enzymes to feed on waste products of living organisms or tissues of dead organisms.

SARA (Superfund Amendments and Reauthorization Act of 1986): See *CERCLA*.

Saturated zone: Subsurface soil saturated with water; the water table.

Scaling: When carbonate hardwater is heated, calcium carbonate and magnesium hydroxide are precipitated out of solution, forming a rock-hard scale that clogs hotwater pipes and reduces the efficiency of boilers, water heaters, and heat exchangers.

Science: The observation, identification, description, experimental investigation, and theoretical explanation of natural phenomena.

Scientific method: A systematic form of inquiry that involves observation, speculation, and reasoning.

Sea-level rise: The natural rise of sea level that occurs in cyclical patterns throughout history; may be the result of human impacts on global warming.

Second law of thermodynamics: Natural law that dictates that in any conversion of heat energy to useful work some of the initial energy input is always degraded to a lower quality, more dispersed, less useful form of energy, usually low-temperature heat that flows into the environment; law cannot be broken even in terms of energy quality.

Secondary drinking water standards: The unenforceable guidelines based on both aesthetics, including taste, odor, and color of drinking water, as well as non-aesthetic characteristics such as corrosivity and hardness.

Secondary exposure pathways: In onsite remediation, these occur during site operations and exhibit significant decreases with time as treatment progresses (e.g., wind-blown dust).

Secondary standards: Refers to NAAQS requirement to protect public welfare.

Secondary treatment of sewage: The removal of impurities from water by the digestive action of various small organisms in the presence of air or oxygen.

Secure landfill: A land site used for the storage of hazardous solid and liquid wastes, which are normally placed in containers and buried in a restricted-access area that is continually monitored. Such landfills are located above geologic strata that are supposed to prevent the leaching of wastes into groundwater.

Sedimentary: Refers to a rock formed from materials deposited from suspension or precipitated from solution and usually being more or less consolidated. The principal sedimentary rocks are sandstones, shales, limestones, and conglomerates.

Sediments: Soil particles dislodged by rain drops that travel via runoff into streams, rivers, lakes, or oceans and are deposited there.

Self-purification: The natural phenomenon occurring in running water systems (streams and rivers) whereby physical, chemical, and biological processes work to self-purify the water.

Senescent pond: A pond that has reached old age.

Separation: A hazardous waste treatment technology (filtration and separation) whereby filtration is used to separate solid particles from a liquid stream through the use of semiporous media; driven by a pressure difference across the media and caused by gravity, centrifugal force, vacuum, or elevated pressure.

Septic zone: In the self-purification process that takes place in running water bodies (streams or rivers), the zone characterized by heavy organic pollution and low dissolved oxygen levels.

Sheet piling: In *in situ* isolation/containment technology, the physical driving of rigid sheets, pilings of wood, steel, or concrete into the ground to form a barrier for containment.

Silage liquor: The liquid drained or leached from fodder prepared by storing and fermenting green forage plants in a silo.

Sinks: Areas, whether natural or artificial, where the products or effluents from production and consumption in one place are physically exported to another for storage or dispersal.

Slope: A soil property in which the steepness of the soil layer is directly related to the degree of erosion that may occur.

Slope winds: Winds that move through a typical river valley; they flow downhill into the valley floor.

Slurry walls: In *in situ* isolation/containment, fixed underground physical barriers formed in an excavated trench by pumping slurry, usually a bentonite or cement and water mixture.

Smog: Term used to describe visible air pollution; a dense, discolored haze containing large quantities or soot, ash, and gaseous pollutants such as sulfur dioxide and carbon dioxide.

Soft water: Water with a hardness of less than 50 ppm.

Soil: A dynamic natural body in which plants grow; it is composed of mineral and organic materials and living forms.

Soil boring: Using a boring tool (such as an auger) to take soil samples for analysis.

Soil factors: In *in situ* soil remediation, soil factors include water content, porosity/permeability, clay content, and adsorption site density.

Soil fertility: The quality of a soil that enables it to provide essential chemical elements in quantities and proportions for the growth of specified plants.

Soil forming process: The mode of origin of the soil, with special reference to the processes or soil-forming factors responsible for the development of the solum, or true soil, from the unconsolidated parent material.

Soil horizon: A layer of soil, approximately parallel to the soil surface, differing in properties and characteristics from adjacent layers below or above it.

Soil pollution: Contamination of the soil and subsurface by the addition of contaminants or pollutants.

Soil profile: A vertical section of the soil from the surface through all its horizons, including C horizons.

Soil remediation: The use of various techniques or technologies to decontaminate or dispose of contaminated soil.

Soil sampling: Conducted to analyze the type, texture, and structure of a soil; samples of contaminated soil are collected to determine the degree and extent of contamination and for other analysis.

Soil structure: The combination or arrangement of primary soil particles into secondary particles, units, or peds. These secondary units may be, but usually are not, arranged in the profile in such a manner as to give a distinctive characteristic pattern. The secondary units are characterized and classified on the basis of size, shape, and degree of distinctness into classes, types, and grades, respectively.

Soil texture: The relative proportions of the various soil separates in a soil.

Soil washing and extraction: In pollution control technology used for USTs, used to leach contaminants from the soil into a leaching medium, after which the extracted contaminants are removed by conventional methods.

Solid: Matter that has a definite volume and a definite shape.

Solid waste: Any normally solid material that is useless or unwanted that results from human or animal activities.

Solid Waste Disposal Act (1965): The first major step taken by U.S. legislators to promote (among other things) the demonstration, construction, and application of solid waste management and resource recovery systems to preserve and enhance the quality of air, water, and land resources.

Solid waste stream: A stream of solid waste materials as a whole.

Solidification: A stabilization technique used to convert hazardous waste from its original form to a physically and chemically more stable material; accomplished by reducing the mobility of hazardous compounds in the waste prior to its land disposal.

Solubility: The ability of a substance to mix with water.

Solute: The dissolved substance in a solution.

Solvent: The substance in excess in a solution.

Sorption: Process of adsorption or absorption of a substance on or in another substance.

Species: A group of individuals or populations potentially able to interbreed and unable to produce fertile offspring when bred with other sorts of animals and plants.

Specific gravity: Ratio of the weight of the volume of liquid or solid to the weight of an equal volume of water.

Specific heat: The amount of heat energy in calories necessary to raise the temperature of 1 gram of the substance 1°C.

Specific source wastes: Wastes from specifically identified industries, including wood preserving, petroleum refining, and organic chemical manufacturing. Typically includes sludges, still bottoms, wastewaters, spent catalysts, and residues.

Spirilla: Bacteria shape characterized as being nonflexible, helical, and curved.

Spoil: Material removed from an excavation.

Sporangiospores: Spores that form within a sac called a *sporangium*. The sporangium is attached to a stalk called a *sporangiophore*.

Spore: Reproductive stage of fungi.

Spring overturn: Lake phenomenon whereby the entire body of water within the lake overturns because of changes in water density.

Stability: Atmospheric turbulence; a function of vertical distribution of atmospheric temperature.

Stability class: Term used to classify the degree of turbulence in the atmosphere.

Stable atmosphere: Marked by air that is cooler at the ground than aloft, by low wind speeds, and consequently by a low degree of turbulence.

Standard temperature and pressure (STP): The density of a gas depends on temperature and pressure, so it is customary to define the pressure and temperature against which the volume of a gas is measured. The normal reference point is standard temperature and pressure: 0°C at a standard atmosphere of 760 mmHg. All gas volumes are referred to these standard conditions.

Stationary sources: Source of air pollution emanating from any fixed or stationary point.

Still bottoms: What remains after a spent solvent is distilled (for recycling); composed of a concentrated, highly toxic mixture, far reduced in volume.

Stockpiles: Certain chemical products (such as road salt) kept in quantity for possible use; runoff from such stockpiles may contribute to soil pollution.

Stormwater: Normal stormwater containing grit and street debris but no domestic or sanitary wastes.

Stratification: Temperature–density relationship of water in temperate lakes (>25 feet in depth) that leads to stratification and subsequent turnover or overturn.

Stratosphere: A region of the atmosphere based on temperature between approximately 10 and 35 miles in altitude.

Stripping: A waste control technology whereby volatile compounds are separated from less volatile ones in a liquid mixture by partitioning the more volatile materials to a gas phase of air or steam.

Subadiabatic: The ambient lapse rate when it is less than the dry adiabatic lapse rate.

Submerged vegetation: In a pond, the submerged plants that grow where light can penetrate the water surface and reach them.

Subsidence inversion: A type of inversion usually associated with a high-pressure system, known as anticyclones, which may significantly affect the dispersion of pollutants over large regions.

Subsoil: That part of the soil below the plow layer.

Substrate: The material or substance upon which an enzyme acts.

Suggested levels: Nonenforceable guidelines for secondary drinking water standards regarding public welfare.

Sulfur cycle: The natural circulation of sulfur through the environment.

Sulfur dioxide: A primary pollutant originating chiefly from the combustion of high-sulfur coals.

Sulfurous smog: The haze that develops in the atmosphere when molecules of sulfuric acid accumulate; the resulting droplets grow in size and become sufficiently large to serve as light scatterers.

Summer stagnation: In lake stratification, a state that occurs in some lakes when the top layer of water is warmer than the bottom layer. It results in layers of different density, with the top being light, the bottom heavy. With increased temperature, the top layer becomes even lighter, and a thermocline forms. From top to bottom, we now have the lightest and warmest on top, medium weight and relatively warm in the middle, and the heaviest and coldest below, with a sharp drop in temperature at the thermocline. The water in these three layers does not mix in circulation. If the thermocline is below the range of effective light penetration, the oxygen supply becomes depleted in the hypolimnion, because both photosynthesis and the surface source of oxygen are eliminated.

Superadiabatic: The lapse rate when a parcel of air starting at 1000 m at 20°C, for example, starts moving downward and becomes cooler and denser than its surroundings. Because the ambient air is unstable, it continues to sink.

Superfund: See *CERCLA* and *SARA*.

Surface condenser: In air pollution control technology, a type of condensation equipment, normally a shell-and-tube heat exchanger. It uses a cooling medium of air or water where the vapor to be condensed is separated from the cooling medium by a metal wall. Coolant flows through the tubes, while the vapor is passed over and condenses on the outside of the tubes and drains off to storage.

Surface impoundment: (1) Another name for a garbage dump. (2) Diked or excavated areas used to store liquid hazardous wastes.

Surface origins: The surface origins of soil contaminants that include gaseous and airborne particulates; infiltration of contaminated surface water; land disposal of solid and liquid waste materials; stockpiles, tailings, and spoil; dumps; salt spreading on roads; animal feedlots; fertilizers and pesticides; accidental spills; and composting of leaves and other wastes.

Surface water: Water on the Earth's surface, exposed to the atmosphere and mostly the product of precipitation.

Surfactant: A surface-active substance (e.g., soap).

Symbiotic: A close relationship between two organisms of different species where both partners benefit from the association.

Synthesis: The formation of a substance or compound from more elementary compounds.

Tailings: The residual fine-grained waste rejected after mining and processing of ore, usually after washing.

Taste and odor: A water quality parameter.

TCLP (Toxicity Characteristics Leaching Procedure): Replaced the EP toxicity test; it is designed to identify wastes likely to leach hazardous concentrations of particular toxic constituents into the surrounding soils or groundwater.

Temperature: A measure of the average kinetic energy of the molecules.

Temperature inversion: A condition characterized by an inverted lapse rate.

Thermal circulation: The result of the relationship based on a law of physics whereby the pressure and volume of a gas are directly related to its temperature.

Thermal incinerator (afterburner): A device used in combustion whereby the contaminant airstream passes around or through a burner and into a refractory-lined residence chamber where oxidation occurs. Flue gas from a thermal incinerator is at high temperature and contains recoverable heat energy.

Thermal inversion: A layer of cool air trapped under a layer of less dense warm air, thus preventing reversing to the normal situation.

Thermal NO_x: Created when nitrogen and oxygen in the combustion air (e.g., within an internal combustion engine) are heated to a high enough temperature (above 1000 K) to cause nitrogen (N_2) and oxygen (O_2) in the air to combine.

Thermal pollution: Increase in water temperature with harmful ecological effects on aquatic ecosystems.

Thermal radiation: Heat energy directly radiated into space from the Earth's surface and atmosphere.

Thermal treatment: In non-*in situ* soil pollution control technology, the complete destruction (by incineration) of petroleum-laden contaminants.

Thermal treatment processes: In waste control technology, incineration of wastes.

Thermocline: The fairly thin transition zone in a lake that separates an upper warmer zone from a lower colder zone.

Thermosphere: A region of the atmosphere based on temperature between approximately 60 miles to several hundred miles in altitude.

Threshold of effect: In the dose–response relationship, the level of "no effect."

Threshold reporting quantity: Level set by USEPA for extremely hazardous substances that if exceeded during spill or release to environment must be reported to appropriate authorities.

Tilth: The physical condition of soil as related to its ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration.

Topsoil: The layer of soil moved in cultivation.

Total dissolved solids: The solids residue after evaporating a sample of water or effluent (expressed in mg/L).

Total Kjeldahl nitrogen (TKN): The total concentration of organic and ammonia nitrogen in wastewater.

Toxic chemicals: Term used by USEPA for chemicals whose total emissions or releases must be reported annually by owners and operators of certain facilities that manufacture, process, or otherwise use a listed toxic chemical. The list of toxic chemicals is identified in Title III of SARA.

Toxic metals: Metals, including arsenic, cadmium, lead, and mercury, that are cumulative toxins and particularly hazardous to human health.

Toxic or hazardous substance: Substances injurious to the health of individual organisms and sometimes fatal.

Toxicity: The degree of poisonousness.

Toxicological evaluation: Part of risk assessment that should answer the question "Does the chemical have an adverse effect?"

Toxin: A poison produced by a plant or animal.

Tracking system: In hazardous waste management, a manifest document that accompanies any waste transported from one location to another.

Transformations: Chemical changes that take place in the atmosphere, such as the conversion of an original pollutant to a secondary pollutant such as ozone.

Trash: Highly combustible waste paper, wood, cardboard cartons, up to 10% treated papers, plastic, or rubber scraps.

Treatment plant site sources of MSW: Water, wastewater, and other industrial treatment processes that produce municipal solids waste (e.g., incineration ash, sludges, biosolids, general plant wastes).

Trench method: In pollution control technology for USTs, a method used to capture the entire leading edge of the contaminant plume.

Trenching: See *Excavation.*

Trophic level: The feeding position occupied by a given organism in a food chain, measured by the number of steps removed from the producers.

Troposphere: A region of the atmosphere based on temperature difference between the Earth's surface and 10 miles in altitude.

Turbidity: Reduced transparency of the atmosphere caused by absorption and scattering of radiation by solid or liquid particles other than clouds and held in suspension.

Turbulence: (1) Uncoordinated movements and a state of continuous change in liquids and gases. (2) One of the three T's of combustion.

Turnover: The mixing of the upper and lower levels of a lake that most often occurs during the spring and fall and is caused by dramatic changes in surface water temperature.

Unconfined aquifer: An aquifer not underlain by an impermeable layer.

Underground storage tanks (USTs): Tanks designed to store chemicals, especially fuels, underground.

United Nations Hazard Class Number System: A system for designating and labeling hazardous materials using a dedicated number system.

Unsaturated zone: Lies just beneath the soil surface and is characterized by crevices that contain both air and water; water contained therein is not available for use.

Unstable atmosphere: Characterized by a high degree of turbulence.

Vacuole: A small cavity in the protoplasm of a cell.

Vadose water: Water in the unsaturated zone that is essentially unavailable for use.

Valence: The net electric charge of an atom or the number of electrons an atom can give up (or acquire) to achieve a completely filled outer shell.

Valley winds: At valley floor level, slope winds transform into valley winds that flow down-valley, often with the flow of a river.

Venting: In pollution control technology, a method of remediating hydrocarbon (gasoline) spills or leaks from USTs.

Venturi: A short tube with a constricted throat used to determine fluid pressures and velocities by measurement of differential pressures generated at the throat as a fluid traverses the tube.

Vernal ponds: Spring ponds, usually of short duration.

Virus: An infectious agent with a simple acellular organization, a protein coat, and a single type of nucleic acid; reproduces only within living host cells.

Volatile: Refers to a substance (usually a liquid) that evaporates at ordinary temperatures if exposed to the air.

Volatile organic compounds (VOCs): Organic compounds that evaporate and contribute to air pollution directly or through chemical or photochemical reactions to produce secondary pollutants, principally ozone.

Volatilization: When a solid or liquid substance passes into the vapor state.

Volume: Surface area (length × width) multiplied by the height.

Warm front: Marks the advance of a warm air mass as it rises up over a cold one.

Waste minimization: An umbrella term that refers to industrial practices that minimize the volume of products, minimize packaging, extend the useful life of products, and minimize the amount of toxic substance in products.

Waste piles: Waste piled at industrial sites and then eventually disposed of in a landfill.

Wastewater: Liquid waste stream primarily produced by five major sources: human and animal wastes, household wastes, industrial wastes, stormwater runoff, and groundwater infiltration.

Water content: In *in situ* volatilization, the influence that water content has on the rate of volatilization by affecting the rates at which chemicals can diffuse through the vadose zone. An increase in solid water content decreases the rate at which volatile compounds are transported to the surface via vapor diffusion.

Water pollutants: Unwanted contaminants that can pollute water.

Water pollution: Any physical or chemical change in surface water or groundwater that can adversely affect living organisms.

Water table: The upper surface of the saturation zone below which all void spaces are filled with water.

Water vapor: The most visible constituent of the atmosphere (H_2O in vapor form).

Waterborne pathogens: The transmission conduit for some pathogenic microorganisms.

Watershed: The region draining into a river, river system, or body of water.

Watershed divide: A ridge of high land dividing two areas drained by different river systems.

Weather: The day-to-day pattern of precipitation, temperature, wind, barometric pressure, and humidity.

Weathering: The chemical and mechanical breakdown of rocks and minerals under the action of atmospheric agencies.

Weight: The force exerted upon any object by gravity.

Wet scrubber: A treatment device (e.g., a stacked tower) in which the contaminant waste stream is passed through microorganism-laden media or through a chemical spray (e.g., a caustic one) to degrade or neutralize the harmful affects of the contaminants.

Wetland: A lowland area, such as a marsh or swamp, saturated with moisture and usually thought of as natural wildlife habitat.

White goods: Large solid waste items such as household appliances (e.g., refrigerators, stoves, dishwashers, washers, dryers).

Wind: Horizontal air motion.

Wind and breezes: Local conditions caused by the circulating movement of warm and cold air (convection) and differences in heating.

Winter kill: A condition that can occur in a lake or pond when the entire water mass is frozen, thereby killing all inhabitants.

Winter stratification: In a lake in winter, the condition that occurs when the epilimnion is ice-bound and is at the lowest temperature and thus lightest, the thermocline is at medium temperature and medium weight, and the hypolimnion is at about 4°C and heaviest.

Worms: In stream ecology, the presence of certain species of worms in bottom sediment indicates stream pollution.

Xenobiotic: Any chemical present in a natural environment that does not normally occur in nature (e.g., pesticides, industrial pollutants).

Young pond: In the cycle of pond evolution, the initial or earliest phase.

Zone of recent pollution: In streams or rivers, the point of pollution discharge.

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