# Handbook of Solid Waste Management and Waste Minimization Technologies

Nicholas P. Cheremisinoff, Ph.D.

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# PREFACE

This volume covers the practices and technologies that are and can be applied to the management and prevention of solid waste. It is the third volume in a series that focuses on approaches to improving environmental performance in a cost-effective manner. Earlier volumes in this Butterworth-Heinemann series are the *Handbook of Water and Wastewater Treatment Technologies* and *Handbook of Air Pollution Prevention and Control.* In addition, the book *Green Profits: The Manager's Handbook for ISO 14001 and Pollution Prevention* establishes much of the foundation for and philosophy behind these volumes.

The current volume is intended to provide engineers, environmental managers, and students with a survey of the technologies and strategies for reducing solid waste generation, and in applying resource recovery, and waste-to-energy techniques. Discussions focus on both municipal and industrial solid wastes. The interdependency of pollution and waste media cannot be readily distinguished, so in many instances relationships between waste management and pollution control and prevention strategies for air and water are included in topical discussions.

There are eight chapters to this volume. Chapter 1 provides a general overview of the principles behind source reduction and waste minimization. Although differences between the strategies behind pollution prevention (P2) and waste minimization are pointed out, they are so closely linked that both subjects are treated interchangeably at times throughout the book. Chapter 2 provides a broad overview of the U.S. environmental statutes and liabilities associated with environmental management. Although the focus is on solid waste, it would be foolish to consider only those regulations that deal with this pollution medium. All regulations dealing with the environment and public safety have a bearing on solid waste management, particularly regulated hazardous chemicals.

Chapter 3 focuses on the problem of municipal solid waste. This is a worldwide problem that impacts on the very sustainability of mankind and on the preservation of Mother Earth's natural resources. Scientific studies imply that the rate at which natural resources are being consumed exceeds the growth in renewable resources by nearly 20%. This means that our lifestyles and those of emerging nations and countries in transition which are improving their quality of life rapidly are unsustainable over the next several generations. A major philosophical change is needed in how we design and use products in our everyday lives, as well as how we view and manage wastes. We may look at solid waste as an enormous management issue that requires huge financial resources to address, or we can view the horrendous volumes of wastes as a source of renewable energy and materials recovery.

Chapter 4 discusses landfill operations and focuses on gas energy recovery. Landfilling operations are the final disposal of solid wastes. The practice should be viewed plain and simply as a practice that is uneconomical. It requires enormous effort, it has many hidden costs, it limits land redevelopment opportunities, and it poses indefinite health threats. Despite these shortcomings, it is the most widely practiced strategy for solid waste disposal worldwide. As a strategy for both industry and municipalities, it should be discouraged and phased out.

Chapter 5 provides an overview of solid waste volume reduction technologies. To reduce the costs for waste disposal, investments in these technologies are needed. These reduce waste transport and disposal fees and facilitate waste handling operations. They supplement landfilling operations, and hence, they are uneconomical from a broad sense of waste management strategies. These represent treatment technologies or in some cases they are control or end-of-pipe treatment technologies. They have high capital investments and long-term operation and maintenance costs, plus they are energy consumers. Until landfilling and incineration practices are phased out, these technologies are essential. Their one advantage is that they can be applied in P2 and waste minimization solutions, especially in developing refuse-derived fuels or in resource recovery and recycling applications.

Chapter 6 provides and overview of biosolids applications. This is a strategy that converts municipal sludges into soil conditioners and fertilizers. Although touted as a green technology by EPA, in many ways it still represents a treatment strategy. The volume of municipal sludge generated by POTWs makes this an essential post-treatment technology. More than 11% of the biosolids generated presently in the United States still winds up in landfills, and further there is significant resistance on the part of many communities using this strategy. Biosolids applications do make sense; however, it is wrong to imply that this is a green technology. There are disadvantages, and further, the economics must make sense in order for this to be applied as an effective waste management strategy.

Chapter 7 provides a summary of industry sources of waste and pollution, along with general practices and strategies for environmental management. It is intended to provide the reader with a general reference on industry strategies and an appreciation of the broad range of problems that industry deals with. Where appropriate, specific solid waste handling strategies are discussed.

Chapter 8 covers the topic of establishing pollution prevention and waste minimization programs. In order for these to be effective, they must be implemented as formalized, dedicated programs. This is best accomplished through an environmental management system or EMS. For discussions on how an EMS and P2 work hand in hand, the reader should refer to *Green Profits*. Chapter 8 expands on the principles of environmental cost accounting methods presented in Green Profits by discussing the use of life-cycle costing methods. These calculation methods are standard tools used to assess the merits of any type of investment. They are most appropriate for devising waste management strategies because they enable one to select the least costly technologies. Waste management represents a long-term investment, and as such, cost considerations are a critical consideration.

A key feature of this volume is the glossary provided at the end. The glossary contains more than 1000 terms and can serve as a handy reference for the reader in addressing waste management issues.

*Nicholas P. Cheremisinoff*

# ABOUT THE AUTHOR

Nicholas P. Cheremisinoff is an industry consultant specializing in pollution prevention and environmentally responsible care issues. He has more than 20 years of experience in applied research, manufacturing, and international project management, and has worked extensively throughout Russia, parts of Central and Eastern Europe, Korea, Latin America, and the United States. He has assisted and implemented projects for the World Bank Organization, the U.S. Department of Energy, the U.S. Trade and Development Agency, the U.S. Export and Import Bank, the U.S. Agency for International Development, the European Union, Chemonics International, Booz-Allen & Hamilton, and many others. Dr. Cheremisinoff has contributed extensively to the industrial press, having authored, coauthored, or edited more than 100 technical reference books, and several hundred articles. He received his B.S., M.S., and Ph.D. degrees in chemical engineering from Clarkson College of Technology. He can be reached by e-mail at ncheremisi@aol.com. Interested readers may also visit his Web site at www.ecoexpert.net.

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# Chapter 1

# SOURCE REDUCTION AND WASTE MINIMIZATION

## INTRODUCTION

From an overall material consumption standpoint, excessive quantities of waste in society result from inefficient production processes on the industrial side, and low durability of goods and unsustainable consumption patterns on the consumer side. While total waste quantities are a reflection of the loss of resources, the hazardous components contained in product wastes and their release into the environment determine the priorities and challenges for effective waste management strategies, so that extensive environmental hazards can be avoided.

The specific challenges for waste management for municipal and industrial wastes are both similar, and yet uniquely different. Compositions of wastes within each category vary enormously, but as a general rule, industrial waste streams contain a wider variety and more concentrated forms of hazardous materials and therefore require special technologies and handling procedures.

In both categories of wastes there are major opportunities for both prevention and resource recovery. Furthermore, waste-to-energy options exist among those solid waste streams that have high organic contents, which generally is the case for many municipal wastes.

As discussed in *Green Profits: The Manager's Handbook for ISO 14001 and Pollution Prevention* (Butterworth-Heinemann Publishers, 2001), those waste management strategies that focus on source reduction and resource recovery and reuse have proven to be more cost effective over the long run, and they are less damaging to the environment simply because they prevent or minimize waste generation at the source. It is this general theme that the book focuses on. Since there is a wealth of information that exists in printed matter and on the World Wide Web concerning regulatory requirements and control and treatment technologies, discussions concerning what has become a mature industry, namely waste management in the conventional sense, are not dwelled upon. This book focuses on those strategies and technologies that prevent and minimize solid waste and various forms of pollution rather than on end-of-pipe treatment techniques and disposal practices. For example, although landfilling is the most widely adopted practice worldwide for municipal waste disposal, the reader will not find detailed discussions dealing with this subject. Aside from the fact that there is an enormous amount of published information on landfill design and operation available, landfilling along with the various treatment technologies which stabilize hazardous materials are simply not cost-effective, even though they enable companies and municipalities to meet environmental compliance. Disposal and treatment technologies require major long-term investments in capital equipment and have ongoing costs. But in addition, the waste and pollution that are treated and disposed of still persist, posing continuous and future threats to the public and environment.

This chapter lays the foundation for those approaches that are not based upon the so-called end-of-pipe treatment and disposal-based technologies. These alternatives are loosely coined *waste minimization*, *waste-to-energy*, and *resource recovery and reuse* or *recycling*. In previous publications we have referred to all of these simply as *pollution prevention* or P2. Although there may be a better general term or phrase that best describes all of these alternative strategies, we will be consistent with the earlier publications and apply the term P2 again, recognizing that it is not always used in the strictest sense of source reduction. Furthermore, little distinction, if any, is made between the terms waste and pollution. Pollution is waste. In an ideal world, processes would operate at 100% efficiency and consumers would not have any unusable or worn-out products to discard. But the reality is that all manufacturing operations generate by-products that have no value and consumer products have throw-away packaging and limited life spans. These forms of solid waste simply represent lost money stemming from the inefficiencies of industry and the lifestyles of society. This book focuses on recapturing and minimizing the financial losses, which will improve the environmental performances of both industry and the public.

## FUTURE AND LONG-TERM LIABILITIES

For industry, when wastes and pollution are created during manufacturing, the generator maintains liability forever. In other words, the ownership of waste can never really be passed on. For example, when we landfill there is always the risk that wastes can breach the landfill liner and contaminate the groundwater. While the owner/operator of the landfill carries responsibilities for remediation in this scenario, the generator of the waste or portion of waste stream contributing to groundwater contamination also has a legal responsibility to share in the costs of remediation. This is what is meant by the terms *joint and several liabilities*. In the United States the federal environmental legislation, that defines this, is CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act).

Following this scenario further, if the contaminated groundwater impacts on off-site property values or perhaps creates a public risk due to chemical or infectious exposures, then the generator faces liabilities from civil actions, which may include direct damages from further remediation, devaluation of property values, pain and suffering and medical bills for injured parties, and/or toxic torts.

Even if the waste entering the groundwater is a nonregulated material, there may be legal exposure. This is especially true when we consider the fact that many chemicals were not recognized as being hazardous or toxic only a few years ago. A good example is ammonium perchlorate (used as an ingredient in some fertilizer and in rocket propellant formulations). For decades this chemical was considered a nontoxic material; however, in the late 1990s studies showed that it has adverse impacts on the human thyroid gland. Companies that inadvertently contaminated groundwater from the use of this chemical during a time period where it was considered safe and not regulated face huge cleanup costs plus toxic torts many years after their operations ceased. Such litigations can cost many millions of dollars in legal fees to address.

Another important concept of our environmental laws is that they are *retroactive*. A company cannot obviate their responsibility for cleanup actions needed because waste disposal or chemical handling practices were considered legal at the time of the operations. And as history has shown us, environmental laws and enforcement become more stringent over time.

These point to the concern that waste handling practices and wastes/pollution forms that are considered within legal and safe limits today may not be in the future. We can view these as future and long-term liabilities resulting from poor environmental performance and also derived from ignoring life-cycle principles.

End-of-pipe treatment technologies and disposal practices not only carry high operating and capital costs, but they invite future and long-term liabilities. These technologies and practices only help to control emissions and wastes to within legal limits of the day, and although the limits protect the public and environment based on current understanding of risks, they incrementally add to the stockpile of waste materials. Since these wastes continue to persist long after disposal, the generator always has a smoking gun sitting around. The only true way to eliminate these liabilities is to eliminate the waste and pollution in the first place, at the source.

## THE HIERARCHY OF WASTE MANAGEMENT

Waste and pollution management approaches can be described as strategies. At the municipal level these strategies traditionally have relied on disposal practices (predominantly landfilling and incineration), whereas industry has employed intermediate steps of treatment and stabilization of the more hazardous wastes. Industry strategies are based on *end-of-pipe treatment technologies*, which are more appropriately referred to as *control strategies*, meaning their aim is really to control emissions and wastes to within legally allowable limits of discharge. Both strategies have two disadvantages:

1. They require ongoing costs that are associated with operations and maintenance and with use of energy, and they carry many hidden and indirect costs and liabilities.
2. Releases of infectious, toxic, and hazardous components to the environment continue for many years, posing long-term health risks to the public and endangerment to the environment simply because waste forms are only transformed and not entirely eliminated or completely immobilized.

Waste/pollution management strategies based on prevention strive to eradicate both of the above disadvantages because they eliminate the pollution or waste at the source. They tend to be only partially successful in reducing the first disadvantage because in a number of cases, P2 strategies rely on technology investments which have OM&R (operation, maintenance, and repair costs) as well as other ongoing costs (e.g., labor, energy). But in general, when properly implemented, they are more cost effective than disposal and treatment technologies. Minimization strategies tend to reduce the risks associated with the second disadvantage, but may also offset some of the costs and liabilities noted with the first disadvantage.

When we view the gambit of strategies that are available, a generalized hierarchy based on long-term liabilities or risks associated with waste/pollution management and the costs associated with each becomes apparent. This hierarchy is as follows:

- *Prevention* - This strategy prevents wastes from ever being formed in the first place.

- *Recycling/Resource Recovery/Waste-to-Energy* ($R^3$WE) - Recycling and reuse of materials, the recovery of certain wastes for reuse (known as *resource recovery*), and the conversion of certain types of waste into useful energy such as heat, electricity, and hot water are strategies which recover and offset costs for overall waste management.

- *Treatment* - When wastes cannot be prevented or minimized through reuse or recycling, then we need to pursue strategies aimed at reducing volumes and/or toxicity. Treatment technologies are processes that focus on stabilization of wastes, reducing toxicity, reducing volume before ultimate disposal, or in some cases creating limited-use by-products.

- *Disposal* - The only other strategy available is disposal. Waste disposal practices are integrated into the environmental management strategies of all municipalities, are integral to most manufacturing operations, and quite often are among the highest direct cost components. From a business standpoint, it is the least desirable strategy and one that can be directly addressed by waste minimization and P2 practices.

Figure 1 illustrates the hierarchy in a graphical format by comparing the relative risks and costs associated with each strategy. Strategies that reduce or eliminate wastes before they are even created are preferable to those that incur ongoing expenses for treating and disposing of wastes that are generated continuously because long-term risks and costs are lower.

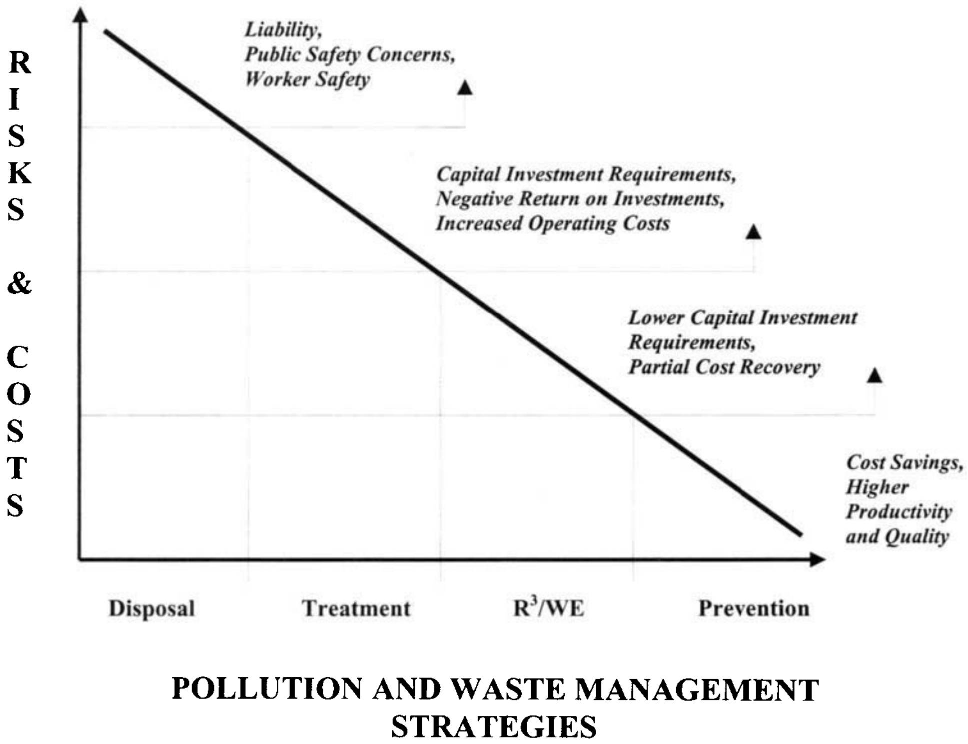


Figure 1. Hierarchy of pollution and waste management strategies.

Prevention has been more successfully applied and understood at the manufacturing level than at the municipal, because companies can readily achieve direct cost savings. P2 strategies have proven to be advantageous since the practices are more cost effective than control-based technologies; hence, companies save money in meeting their environmental obligations.

More recently, some companies have begun applying principles of *designing for the environment*, whereby new products entering the marketplace are more environmentally friendly and generate less solid waste, are biodegradable, or can be readily recycled. This approach is based on life-cycle principles, which we will get to shortly.

At the municipal level, pollution prevention requires major changes in consumer patterns and lifestyles. The general public, while genuinely concerned and knowledgeable about the environment, has not received widespread education on preventive techniques, nor are there many choices in selecting more environmentally friendly forms of consumer products from among the items that support our lifestyles. This leaves municipalities with the option of $R^3$WE. We may look at the hundreds of millions of tons of solid waste generated each year worldwide as an enormous and costly waste disposal effort that continues to deplete our natural resources and requires enormous ongoing expenditures, or we may view these wastes as a virtual gold mine of resources from which useful by-products and energy can be recovered. By the same token, resource recovery, WTE (waste-to-energy), and recycling strategies do not entirely eliminate solid waste disposal problems, and further, they only make sense when such strategies are economically viable.

Figure 1 in some ways is an oversimplification. In terms of capital and direct operating costs, pollution control, treatment, and disposal options generally appear more cost effective than some high-level investments into so-called *green technologies*. A green technology is one which is considered environmentally friendly, but may carry a high investment. As an example, the investment in converting from a coal-fired electricity generating plant to natural gas is seemingly hard to justify from an economic standpoint, and indeed some case-specific studies show the investment to be unattractive. However, many investment studies often overlook the likelihood of long-term and future liabilities. These are rarely given sufficient attention in investment strategies that focus on pollution and waste management.

## THE PRINCIPLES OF LIFE CYCLE

The term life cycle refers to *cradle to grave*. If we view any product as a living entity, that product has a birth, a period of life in society, and then death.

Historically, science and technology have focused on new ideas, concepts, products, and their applications, with the objective of giving a useful life to products that serve our needs. But in the past we have given little thought to the demise of these entities. By ignoring the end cycle, we lose sight of the fact that the natural resources that have gone into making products are not infinite, and that on a worldwide basis the rate at which we consume products with a throw-away mentality is unsustainable. Furthermore, we do long-term and even irreparable damage to our environment by introducing more and more waste and pollution into the environment. By the same token, when we rely on inefficient technologies to mass-produce products, we continually waste more resources and generate more pollution.

Life-cycle principles give equal consideration to all three phases of existence of a product, including how the product is made. These principles are not new, and indeed have been around for decades, but we are only now getting around to learning how to apply them effectively in designing new products and more efficient technologies. This is known as *design for the environment.*

We must recognize that since we do not live in a utopian society, economics overshadows many decisions. For industry, sustainability and growth are tied to profitability. To sustain businesses and to maintain or grow profit margins, among other things companies must meet their environmental obligations in a cost-effective manner. Few companies, if any, will spend more to protect the environment than is necessary beyond their legal requirements. Some industry readers may disagree with this statement and point out that there are companies that indeed "go beyond compliance." But even these businesses are in fact relying on economic forces that enhance their profitability. Companies that allocate more funds toward exceeding environmental performance reap financial benefits from such areas as public opinion and investor confidence that provide them competitive advantages. These impacts ultimately result in positive effects on profit margins.

With this logic then, life-cycle principles are most effectively applied today as an economic instrument, which is called *life-cycle costing* or LCC. LCC is applied to life cycle costing analyses (LCCA) as a basis for comparing the economic attractiveness of different environmental management strategies or technology investments. In other words, instead of changing the product design (which ultimately is what needs to be done to really improve the environmental performance of society on the whole), LCC tools are being applied more effectively today in making decisions on whether simply meeting compliance with controls is less or more costly than preventive or minimization technologies.

As an example, consider a steelmaking plant. The two technology routes for steel making are the basic oxygen converter and the electric arc furnace (EAF). The basic oxygen furnace (BOF) may be described as a "dirty" technology, producing significant amounts of air pollution, and therefore requiring many sophisticated and costly air pollution controls. Although the EAF steelmaking process is more environmentally friendly, it requires a very high capital investment. An LCC analysis will enable a comparison of the costs for each of these technologies over the life of the plant. By comparing all the costs components such as capital equipment, OM&R, energy requirements, productivities between the technologies, and the costs for controls or the savings from eliminating certain controls, as well as the final scrap value of the equipment, we can determine which is the least life cost or most attractive investment option. With both technologies we may meet legal requirements of safe air emissions, but only one of these is likely to be attractive from a financial standpoint based on local economies and the long-range business plans of the company, as well as the reduction of long-term risks associated with environmental management. LCC tools and their application to developing pollution and waste management strategies are discussed later in this book.

## COSTS OF ENVIRONMENTAL MANAGEMENT

The costs for environmental management fall into four groups, which we have referred to as tiers in previous publications on P2, namely:

- Tier 1. Usual and normal costs
- Tier 2. Hidden and indirect costs
- Tier 3. Future and long-term liability costs
- Tier 4. Less tangible costs

These categories are referred to as tiers because they represent layers of costs that we need to unveil in order to truly understand the life cycle costs associated with the level of environmental performance they target to achieve.

*Usual and normal costs* are direct costs for compliance. These are easy to define for control-based technologies and most companies have a clear understanding of them up front. They generally are well tracked, or at least should be. Examples include capital equipment costs (e.g., costs for electrostatic precipitators, scrubbers, wastewater treatment equipment), the costs for operating those controls (e.g., manpower, utilities, such as water and electricity), OM&R costs for controls, operator training, waste transportation and disposal costs such as landfill tipping fees, and a number of other items that are recognizable in any capital intensive engineering project. Examples are provided in Fig. 2. Such cost components are easy to define in a LCC analysis and are the group of data most often relied upon in comparing life-cycle investment options between competing alternatives. However, they do not provide a complete or even a majority accounting for the true costs associated with environmental management.

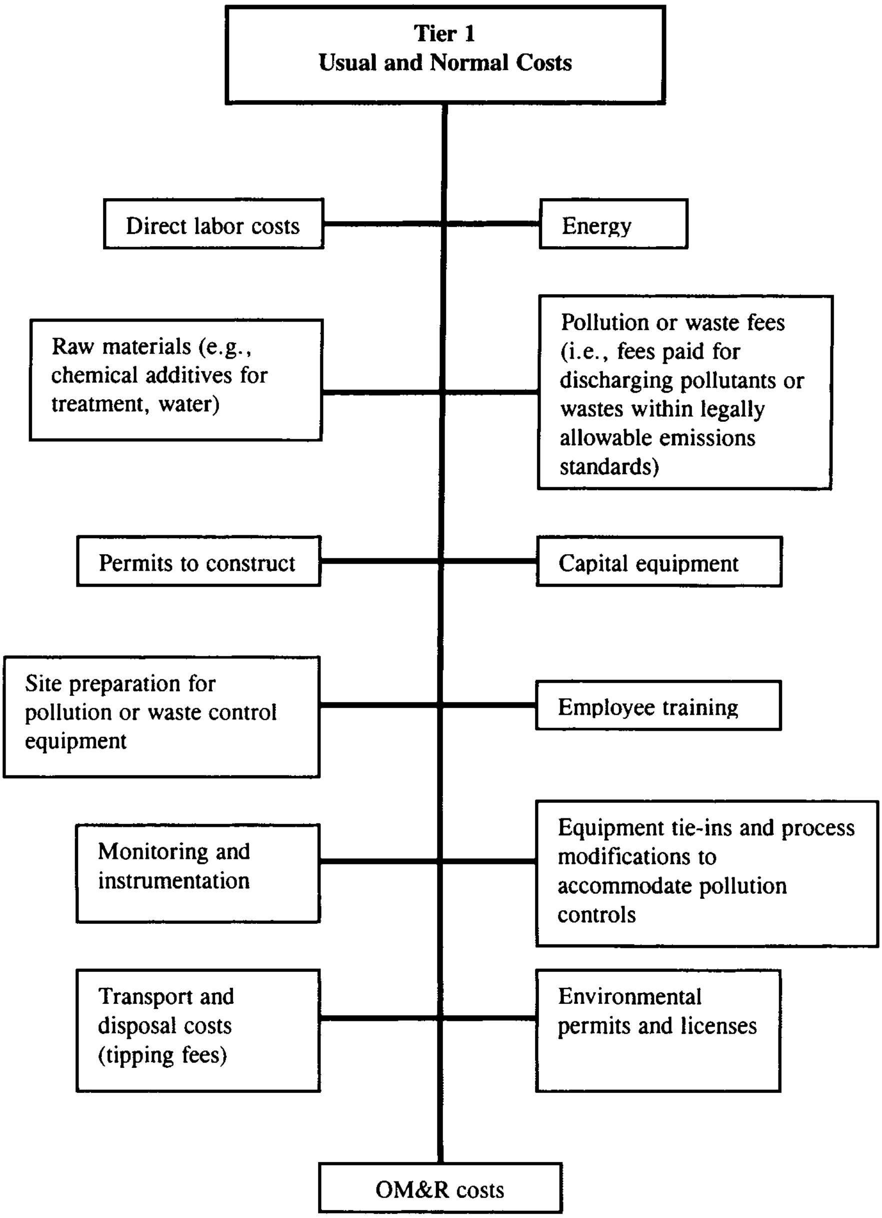


Figure 2. Examples of easily tracked usual and normal costs.

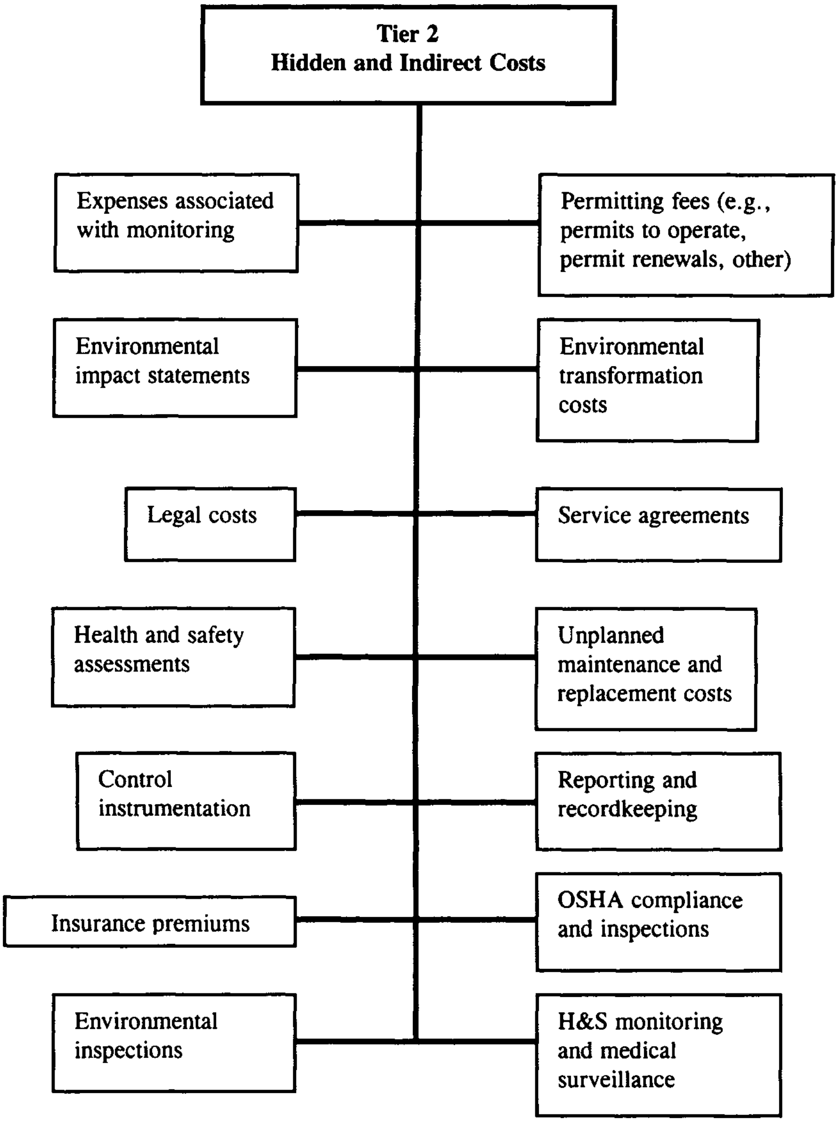


Figure 3. Examples of hidden and indirect costs not always tracked.

*Hidden and indirect costs* include those of monitoring (e.g., manpower, controls, lab support), permits to operate controls and for point source discharges, permits and licenses for waste storage and treatment, environmental impact statements, service agreements for transport, disposal, and instrumentation/equipment maintenance, manpower costs for recordkeeping and reporting, and insurance premiums to cover fire, explosion, and environmental damages that might occur from the operations.

Among the hidden components are environmental transformation costs. These are the costs associated with transforming a pollution or waste problem from one form to another. For example, controlling an air pollution problem simply transforms the form of the pollution to a water and/or solid waste problem. There are both tier 1 and tier 2 costs associated with the transformation technologies. Some companies are sensitive to the tier 2 components, but many are not. They certainly are not examined closely enough when selecting many environmental management strategies, yet they can play a major role in an investment decision when LCC tools are applied. Examples of tier 2 costs are given in Fig. 3. A useful exercise for the reader is to add on to this list as it certainly is not all-inclusive.

Some skeptical readers may argue that some of the components listed in Fig. 3 are small and may be ignored. However, that depends on the magnitude of operations and whether or not they are recurring throughout the life of an operation.

*Future and long-term liability costs* (tier 3) are among the hardest for many companies to account for because they are based upon future events. Cost components in this group depend upon both the level of environmental performance a company achieves, and the effectiveness of the environmental strategies employed. Examples are listed in Fig. 4. Among these examples, only inflation is a component that we might be able to predict with some degree of confidence and can factor into a LCC analysis when comparing options in terms of investment costs. But other costs in this tier depend on the likelihood of certain events occurring.

Certainly, if a company consistently shows poor environmental performance, the probability of some of these costs materializing and developing into long-term liabilities and ongoing remediation costs is high. But even when companies are consistently within compliance requirements using control-based technologies there is the potential for future exposures to some of the items listed in Fig. 4 since waste forms are never truly eliminated. Tier 3 costs can arise from the risks of relying upon certain technologies and strategies that, although enable companies to achieve consistent environmental performance from a regulatory standpoint, pose a future financial exposure from a scenario that is more likely than not to occur. As example; if landfilling is relied upon to dispose of hazardous wastes, the potential exists for the liner to be breached and contaminate the groundwater, resulting in offsite and third-party damages. Or if a manufacturing operation relies on a chemical component that is toxic, workers could sue a company for chromic exposures resulting from their handling of the material over their years of service. This in turn could result in an insurance company raising premiums for medical coverage. If these types of scenarios are more likely to occur than not, or simply stated, have a reasonably high probability of occurrence, then there is a strong basis for choosing pollution prevention and waste minimization strategies.

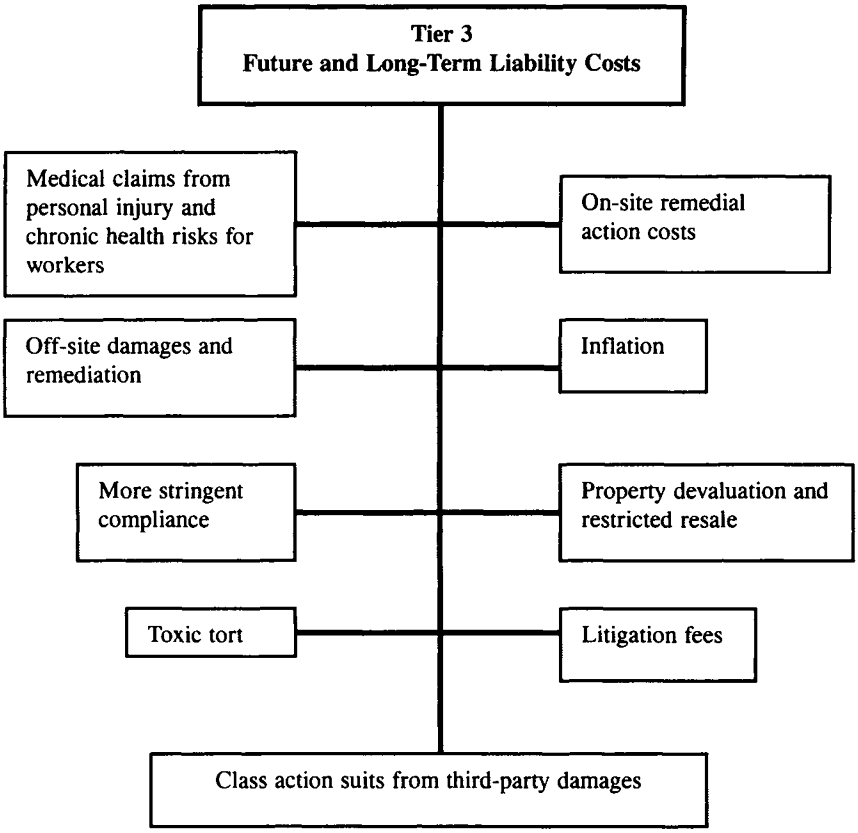


Figure 4. Examples of costs related to future events (i.e., long-term and future liabilities).

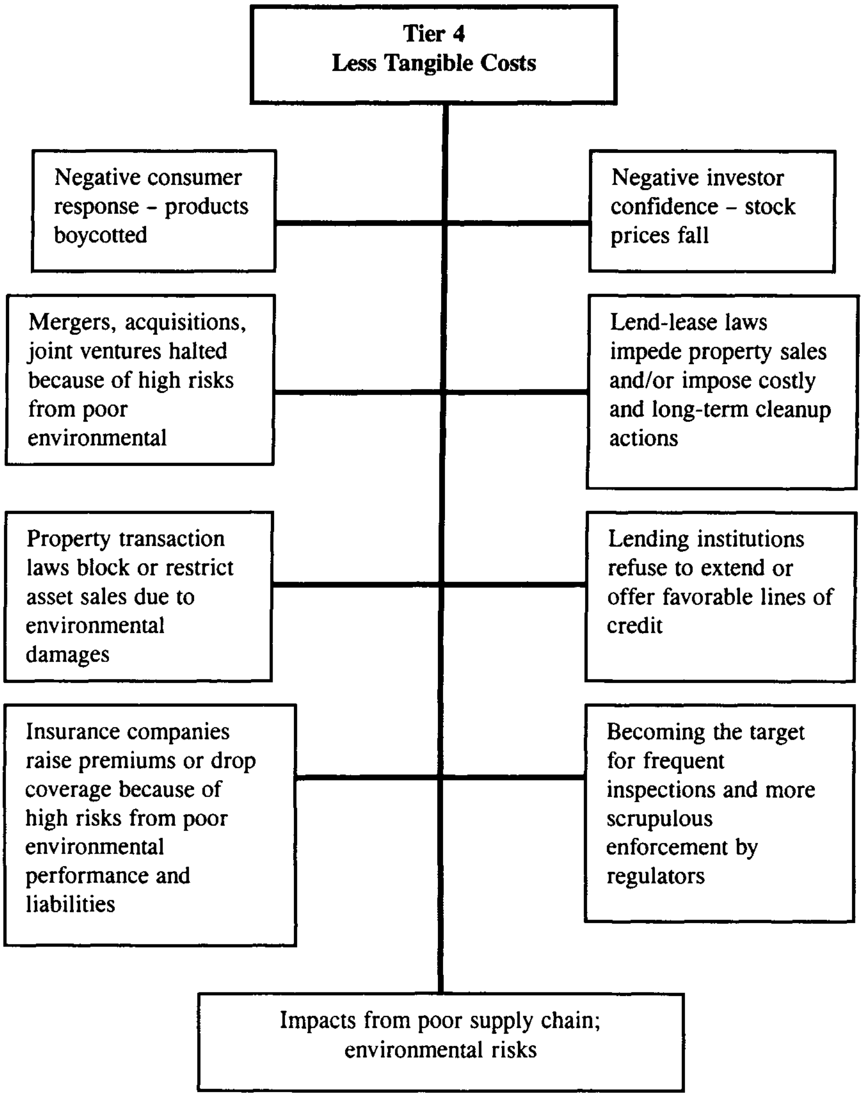


Figure 5. Less tangible costs from poor environmental management practices that are hard to predict.

*Less tangible costs* (tier 4) are even more difficult to grasp, but they do play a critical role in developing the proper investments for environmental management strategies. Fig. 5 provides some examples. These again are cost impacts that can arise from poor environmental performance. But again, the poor performance may come from control-based strategies that consistently meet compliance schedules, such as site cleanup costs at the time operations are shut down or are sold. The main point is that if operations never generated waste or pollution, then the possibility of ever having to deal with the financial impacts arising from their generation and existence would never have to be addressed.

Further to tier 4 considerations, there is an ancient Chinese proverb that says that 10,000 years of an impeccable reputation can be destroyed by a single event. A single major environmental mishap can shake investor confidence, cause consumers to boycott products and seek out alternatives, and prevent joint ventures, mergers; and acquisitions from moving forward because of the concern for inheriting some of the financial liabilities associated with an environmental exposure issue. Lending institutions since the 1980s have consistently turned down loans and limited lines of credit to companies that have the perception of poor environmental performance. Many states have property transaction laws that require environmental audits as a prerequisite to property sales. When wastes and pollution persist, even though they have been controlled to within legal limits of discharge, residual levels or stockpiled wastes can become issues under these laws and impose restrictions or terms for cleanup before a transaction can proceed. An even more complex consideration is a company's relationship with subcontractors and suppliers. For large multinational corporations, public image and investor confidence are major concerns. When suppliers show poor environmental performance or are implicated in a serious environmental mishap, the perception is simply guilt by association. This is an area known as supply chain environmental risk management (SCERM). This is however, a subject area that goes beyond the focus of this volume.

## P2 AND WASTE MINIMIZATION AT WORK

The following case study, summarized from EPA-625-7-91-017, illustrates how P2/waste minimization is applied in practice to identifying alternative strategies for solid waste management.

A small pharmaceutical plant manufactures erythromycin base and erythromycin derivatives (erythromycin thiocyanate, erythromycin stearate, erythromycin estolate). These products are used as growth promoters and as a disease preventative in animal feed. The products are manufactured as bulk chemicals for further processing.

To identify alternative strategies based upon prevention and waste minimization, an assessment by a team of company personnel was applied. At the time of the assessment the plant was operating at 50% of its design capacity. The manufacturing technology is based on batch fermentation.

Note that an assessment or audit has several stages to it. In a later chapter we will summarize the various steps to conducting waste minimization and pollution prevention audits. Audits are both qualitative and quantitative in nature. It is the application of material and energy balances that plays a major role in identifying cost savings opportunities and assisting in the stimulation of ideas for replacing end-of-pipe treatment technologies with preventive practices.

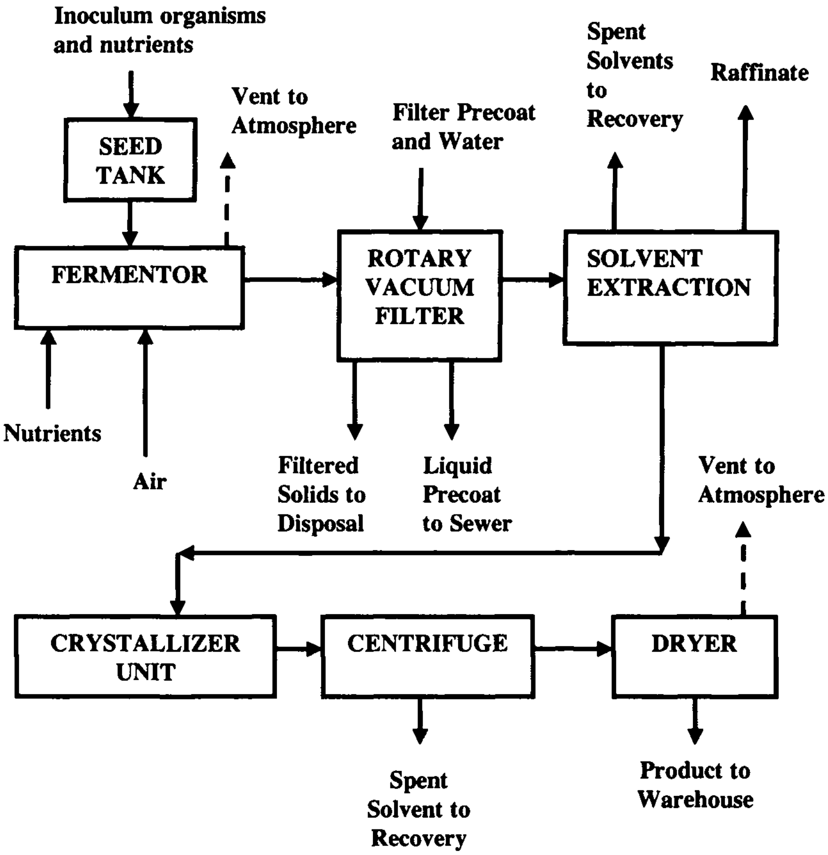


Figure 6. Process flow scheme for pharmaceutical plant example.

In reading over the following case study, bear in mind that the operations of any plant are dynamic, and audits provide only a brief snapshot of the events occurring. For this reason, effective waste minimization and pollution prevention audits need to incorporate follow-up sessions, with a focus on monitoring the improvements over time.

The raw materials used in the manufacture of products are:

- Inoculum organisms
- Nutrients for fermentation (e.g., sugar, flour, fillers)
- Solvents for product recovery (acetone is used for product recovery during erythromycin base campaigns, and amyl acetate is used for base derivative manufacturing campaigns)
- Ammonium thiocyanate (for the manufacture of erythromycin thiocyanate)
- Acetic acid for processing
- Diatomaceous earth filter aid for fermentation broth processing
- Sodium carbonate, sulfuric acid, and sodium hydroxide for pH control

### *The Process*

Fig. 6 illustrates a simplified process flow sheet of the operation. Following the process flow scheme, the steps to manufacturing are as follows:

1. A lab culture of inoculum is delivered to a sterile 2000-gallon seed tank containing nutrients suspended in an aqueous medium.
2. After the initial fermentation period the seed tank contents are transferred to a 67000-gallon fermentation vessel. The entire fermentation cycle is 7 days, with nutrients added over the course of the fermentation. During this process step, the contents of the vessel are aerated and mildly agitated. The contents are carefully monitored for sterility. Fermentation off-gas is released to the atmosphere.
3. Upon maturation the harvest solution containing erythromycin base is transferred to a holding tank for further processing. Approximately 5 batches per week are harvested. Once the plant goes to full capacity, harvesting will increase to 10 batches per week.
4. The erythromycin base is next separated from the fermentation broth by means of rotary vacuum filtration. The filtration units are first precoated with an aqueous slurry of filter aid. The aqueous filtrate from the filter aid application step is discharged to the sewer. Solid cake is scraped from the filter surface using a doctor blade. The cake drops onto a conveyor belt, and from there it is transferred to a disposal bin for off-site disposal. Filtrate containing the erythromycin base is sent to the solvent extraction stage of the process.
5. The product-recovery phase is based on solvent extraction. The erythromycin is recovered using multistage liquid-liquid extraction. Rich organic solvent layer and the raffinate (the water layer that contains some solvent) are recycled.
6. The erythromycin-rich extract is sent to a crystallizer for product recovery.

7. In the next step, crystallized erythromycin base is separated by centrifugation. The centrifuge cake is sent to a fluid bed dryer, and the centrate (spent solvents) are recovered and recycled.
8. The dried, recovered product is drummed in the last stage of the process and is ready for shipment to customers.
9. For the production of erythromycin thiocyanate, erythromycin base is reacted with ammonium thiocyanate prior to crystallization. It is then crystallized, centrifuged, dried, and drummed.

## The Waste Streams

The following are the waste streams generated during manufacturing.

### *Filtration Process Wastes*

The harvests are filtered using rotary vacuum filters coated with diatomaceous earth filter aid. The wastes are the aqueous precoat filter plus the wet filter cake.

During the operation, the precoat is applied continuously at a rate of 1100 kg/hr. The filtrate is discharged to the sewer without any pretreatment. Solid filter cake waste (mycelia and filter aid) are generated at a rate of 1243 kg/hr. This waste is removed to an off-site landfill in 5- to 10-ton load shipments. All of the waste is considered to be nonhazardous. The solid filter cake waste is the largest waste stream generated by the process on a volume basis. The unit costs for disposal are as follows. A waste hauler has been contracted at a rate of $160 for the first 6 tons, and then $16 per ton thereafter. The plant disposes between 7 and 10 loads per week.

### *Solvents*

Spent solvents are recycled from the product recovery and purification stages of the process. Between 2000 and 3000 gallons of solvent is used for a single fermentation harvest. The solvent recovery stage of the operation generates about two 55-gallon drums of still bottoms per week, which is a regulated hazardous waste.

### *Equipment Cleaning Wastes*

The process equipment must be thoroughly cleaned and sterilized between manufacturing campaigns in order to ensure product purity and to maintain operating efficiency. These washwaters are generated intermittently. A caustic solution is used to clean out the fermentation vessels, and the washwaters are sent to the sewer. The amount of washwaters generated in this operation is not measured.

### *Spills*

Spills result from inadvertent material discharges. Two types of spills were noted during a walkthrough of this facility. These are spillage of dry filter aid material and wet filter cake. Spills are an obvious housekeeping issue at any plant operation. Most often they are not tracked and so the cumulative losses, including financial, are rarely realized. A spill prevention program is a well worthwhile activity and one that is a low-cost P2 investment. Monitoring the savings can provide the incentives for implementing more P2 and waste minimization activities.

### *Air Emissions*

Air emissions from the process predominantly occur from the solvent recovery and the product-drying stages of the operation; however, there are fugitive air emissions occurring at various points in the downstream product finishing stages. Air emissions problems from a process like this can represent a formidable challenge in terms of control and permitting. In this example we only focus on the solid wastes.

## Waste Minimization Practices

The following are recommended actions for reducing the wastes generated.

### *Filtration Process Wastes*

The liquid waste generated by the vacuum filters is nonhazardous, and there are no real costs associated with sending this material for final disposal to the sewer. Hence, no corrective actions on the part of the company are needed, and there are no cost advantages to considering other strategies.

The filter cake is a nonhazardous and nonregulated waste, but it does cost the company to manage and dispose of this material. There are 10 loads per week of this material that are transported to an offsite landfill. This translates into 364 to 520 loads per year (or about 3,276 to 4,680 tons per year) of filter cake waste to the landfill. Furthermore, this waste quantity will increase significantly once the plant reaches full capacity.

At a cost of $208 per 9-ton load, the current yearly costs for filter cake waste disposal is between $76,000 and $108,000. At the plant's full operating capacity the disposal costs will increase to $250,000 per year. Clearly there are very attractive savings from eliminating or reducing this waste. In fact, there are from $400,000 to possibly more than $1 million over a 5-year period associated with the disposal of this waste stream. This is money that could be used for modernizing the plant, increasing capacity and addressing debottlenecking issues, enhancing product quality, or even investing in short-term certificates of deposit.

Instead of paying this money to a waste disposal contractor, the following alternatives might offset some or all of these costs:

Alternative 1: Sell the spent filter cake material as a fertilizer. In order for this material to be marketable as a fertilizer the nitrogen, phosphorus, and potassium (N + P + K) levels must be above 5%.

Alternative 2: The waste has the potential to be sold into a market that has a need for soil fillers and conditioners. These markets are often regional, and so some effort is needed in identifying a potential customer. In addition, the waste has an odor problem, which would make it unacceptable in some applications. To eliminate the odor problem, the waste would likely require some posttreatment step. This would be an offset cost that needs to be carefully assessed in evaluating this proposed option.

Alternative 3: The third alternative is to replace the rotary vacuum filters with an alternative technology that does not create as much solid waste. A possibility is to use ultrafiltration, which would eliminate the need for a precoat filter. This approach would achieve the desired volume reduction needed to bring down the costs for disposal. It does require a proof-of-principle demonstration through pilot and perhaps plant trials, but with up to $1 million over a 5-year period at stake, the strategy is well worth defining.

### *Solvents*

The current solvent-recovery process includes a stripping column, an evaporator, and a rectifying column. In the solvent-recovery stage about 99% of the solvents are recovered and recycled through the process.

The solvent requirement per harvest is between 2000 and 3000 gallons, and the cost of raw solvent is $1.78 per gallon. Hence, recycling saves between $3530 and $5290 per harvest. These savings are offset by:

- the operating costs for the recovery units
- still bottoms disposal (two 55-gallon drums per week still bottoms are generated. These wastes must be incinerated and cost the company between $250 and $300 per drum)
- solvent make-up for the nonrecovered solvent

Although there are some small credits associated with the inefficiency of recovery, at 99% recycling this represents a low priority for the plant. If feedstock prices for solvents increase in the future, a level of effort would be justified in improving the recovery efficiency.

### *Equipment Cleaning Wastes*

Since the washwaters are nonhazardous and do not require any pretreatment prior to being disposed of to the sewer, there are no credits to try and capture by eliminating or minimizing this practice.

### *Spills*

The only spills observed are those involving the filter cake handling. There are small savings associated with losses of diatomaceous earth and hence some improved P2 housekeeping practices should be applied to minimize these losses. For the spent filter cake spills, there can be financial losses associated with these losses should we find this waste to be applicable as a byproduct stream (i.e., as a fertilizer or soil additive). Again, low-cost measures such as improved P2 housekeeping should be practiced to minimize such incidents to avoid possible safety hazards among workers, if for nothing else.

## Synopsis

This is an example of the kinds of thought processes that go into a P2 and waste minimization assessment. The assessment consists of an *audit* of the operations the focus of the audit is to do the following:
1. Identify the environmental aspects associated with each unit operation within the process.
2. Assess the impact from the environmental aspect on the business operations, in terms of both compliance and costs.
3. Devise more cost-effective options that achieve compliance.

In this case study, there are no serious hazardous wastes handled in the operation, except for the still bottoms, and occasional caustic wash waters, which could not be quantified in the analysis. The potential costs savings associated with managing the solid waste are direct, and there are sizable and well-defined credits to try and capture by minimizing or eliminating the waste stream altogether. An alternative technology investment (the microscreens) can reduce the volume of solid wastes. This clearly is attractive from the standpoint of improved environmental performance. Whether the investment is attractive enough or can be justified by a reasonable payback period would have to be determined from a LCC analysis.

## A SHORT REVIEW

There is an overwhelming number of success stories that illustrate the benefits of pollution prevention strategies. Many examples for a variety of industry categories are summarized in earlier publications devoted to this subject (Cheremisinoff, N. P., *Handbook of Pollution Prevention Practices*, 2001, and Cheremisinoff, N. P. and A. Bendavid-Val, *Green Profits: The Manager's Handbook for ISO 14001 and Pollution Prevention*, 2001). These case studies show distinct financial advantages to companies by identifying reductions not only in pollution and the costs associated with pollution/waste management, but through reduced raw material consumption, energy savings, reductions in treatment and disposal of wastes, and reductions in labor associated with environmental management. Many P2 and waste minimization strategies, such as substituting toxic materials with safer alternatives, do not require process changes, and as such are simple and cost very little to implement. The areas in which P2 have proven effective include the elimination and reduction of impacts from:

- Treatment, disposal, and associated labor costs
- Wildlife and habitat damage
- Property devaluation
- Remediation costs
- Civil and criminal fines
- Permitting fees
- Insurance costs
- Process outages and disruptions

There are case studies that testify to the fact that P2 benefits result in:

- Enhanced public image - consumers more favorably view businesses that adopt and practice P2 strategies, and the marketing of these practices can assist in increasing a company's profits.
- Increased productivity and efficiency - P2 assessments have proven helpful in identifying opportunities that decrease raw materials use, eliminate unnecessary operations, increase throughput, reduce off-spec product

generation, and improve yields.

- Reduced regulatory burden - improving environmental performance and achieving performance goals that exceed compliance have been demonstrated in many P2 programs, which in turn reduce the costs of compliance,
- Decreased liability - handling hazardous and toxic materials brings along with it high liabilities should an accident such as a fire or explosion, or a major spill occur.
- Improved environmental health and safety - P2 practices can be applied to all forms of pollution media. Reduction in pollution minimizes worker exposure and conserves resources and landfill space.

The costs for environmental management are multilayered or tiered, and in some categories depends on the likelihood of future events that are difficult to predict with confidence. However, clearly the risks of encountering future and intangible costs can be minimized and possibly eliminated by choosing preventive strategies over control-based ones. The application of LCC tools, described later, provide the means of selecting cost-effective waste management strategies.

# Chapter 2

# ENVIRONMENTAL LAWS AND REGULATORY DRIVERS

## INTRODUCTION

The United States, like many other technologically advanced nations, has extensive and complex environmental laws that are designed to protect the public and the environment. Although there are differences between the environmental regulations between countries, the single most important factor that ensures minimal risks to health and the environment from exposures to wastes and pollution is the degree of enforcement. In the United States there are both aggressive enforcement and major penalties for willful violations of environmental statutes. Such penalties range from heavy fines to the termination of business operations, and even imprisonment of responsible parties. Even innocent violations or accidental releases of hazardous materials can result in very significant and costly fines, especially for situations that place the public at risk from exposure to chemicals. From a purely economic standpoint, private enterprises and governments cannot afford to be lax about the management of environmental issues surrounding their operations.

Pollution is a multimedia problem. Because pollution forms undergo transformations between states of matter, either naturally or during treatment and control, any one form of regulated waste may fall under the regulatory guidance of several environmental statutes. And as noted in the previous chapter, environmental laws are retroactive and they carry joint and several liabilities. Compliance to the laws requires ongoing costs, and there are also future financial risks from regulations even though compliance was achieved over the life of a business operation.

In this chapter a general overview of the most important environmental statutes is given. Readers that are unfamiliar with the regulations should visit the U.S. EPA Web site to assess which ones are most applicable to their operations and the wastes that they are generating.

**MAJOR U.S. ENVIRONMENTAL LAWS**

**Clean Air Act (CAA)**

**Clean Water Act (CWA)**

**Emergency Planning & Community Right-To-Know (EPCRA)**

**Federal Insecticide, Fungicide and Rodenticide Act (FIFRA)**

**National Environmental Policy Act (NEPA)**

**Occupational Safety and Health Act (OSHA)**

**Oil Pollution Control Act of 1990 (OPA)**

**Pollution Prevention Act (PPA)**

**Resource Conservation and Recovery Act (RCRA)**

**Safe Drinking Water Act (SDWA)**

**Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA or Superfund)**

**Superfund Amendments and Reauthorization Act**

**Toxic Substances Control Act (TSCA)**

## NEPA

The National Environmental Policy Act (NEPA) was passed in 1970 along with the Environmental Quality Improvement Act, the Environmental Education Act, and the Environmental Protection Agency (EPA). The main objective of these federal enactments was to ensure that the environment be protected against both public and private actions that failed to take account of costs or harms inflicted on the eco-system. The EPA was supposed to monitor and analyze the environment, conduct research, and work closely with state and local governments to devise pollution control policies. NEPA (really enacted in 1969) has been described as some of the most far-reaching environmental legislation ever passed by Congress. The basic purpose of NEPA is to force governmental agencies to consider the effects on the environment of their decisions. State laws also reflect the same concerns; and common-law actions in nuisance allow adversely affected property owners to seek a judicial remedy for environmental harms.

## RCRA

RCRA is the Resource Conservation and Recovery Act, which was enacted by Congress in 1976. RCRA's primary goals are to protect human health and the environment from the potential hazards of waste disposal, to conserve energy and natural resources, to reduce the amount of waste generated, and to ensure that wastes are managed in an environmentally sound manner. RCRA regulates the management of solid waste (e.g., garbage), hazardous waste, and underground storage tanks holding petroleum products or certain chemicals.

RCRA provides legal definitions of hazardous wastes. A waste may be considered hazardous if it is ignitable (i.e., burns readily), corrosive, or reactive (e.g., explosive). A waste may also be considered hazardous if it contains certain amounts of toxic chemicals. In addition to these characteristic wastes, EPA has also developed a list of more than 500 specific hazardous wastes. Hazardous waste takes many physical forms and may be solid, semisolid, or even liquid. In 1999, more than 20,000 hazardous waste generators produced over 40 million tons of hazardous waste regulated by RCRA.

In any given state, EPA or a state hazardous waste agency enforces the hazardous waste laws. EPA encourages states to assume primary responsibility for implementing the hazardous waste program through state adoption, authorization, and implementation of the regulations. Many types of businesses generate hazardous waste. For example, the following types of businesses typically generate hazardous waste: dry cleaners, auto repair shops, hospitals, exterminators, and photo processing centers. Some hazardous waste generators are larger companies, such as chemical manufacturers, electroplating companies, and petroleum refineries. The RCRA hazardous waste program regulates commercial businesses as well as federal, state, and local government facilities that generate, transport, treat, store, or dispose of hazardous waste. Each of these entities is regulated to ensure proper management of hazardous waste from the moment it is generated until its ultimate disposal or destruction. Hazardous wastes that are generated in the home, such as mineral spirits and old paint, are not regulated by the federal RCRA program. Many communities provide collection centers or pick-up services for the management of household hazardous waste. Local recycling centers or fire departments may be able to provide more information about locations and details.

According to the EPA regulations, solid waste means any garbage, or refuse, sludge from a wastewater treatment plant, water supply treatment plant, or air pollution control facility and other discarded material, including solid, liquid, semisolid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities. In 1998, approximately 220 million tons of municipal solid waste or garbage was generated in the United States. This means each person generated an average of 4.46 pounds of solid waste per day. Landfills that collect household garbage are predominately regulated by state and local governments. EPA has, however, established minimum criteria that these landfills must meet in order to stay open. The only hazardous waste that municipal landfills can accept is household hazardous waste and waste that is exempt from hazardous waste regulation.

## CLEAN AIR ACT

The Clean Air Act (42 U.S.C. s/s 7401 et seq. (1970)) is the comprehensive federal law that regulates air emissions from area, stationary, and mobile sources. This law authorizes the U.S. EPA to establish National Ambient Air Quality Standards (NAAQS) to protect public health and the environment. The goal of the act was to set and achieve NAAQS in every state by 1975. The setting of maximum pollutant standards was coupled with directing the states to develop state implementation plans (SIPs) applicable to appropriate industrial sources in the state. The act was amended in 1977 primarily to set new goals (dates) for achieving attainment of NAAQS since many areas of the country had failed to meet the deadlines. The 1990 amendments to the Clean Air Act in large part were intended to meet unaddressed or insufficiently addressed problems such as acid rain, ground-level ozone, stratospheric ozone depletion, and air toxics.

## CLEAN WATER ACT

Growing public awareness and concern for controlling water pollution led to enactment of the Federal Water Pollution Control Act Amendments of 1972. As amended in 1977, this law became commonly known as the Clean Water Act. The act established the basic structure for regulating discharges of pollutants into the waters of the United States. It gave EPA the authority to implement pollution control programs such as setting wastewater standards for industry. The Clean Water Act also continued requirements to set water quality standards for all contaminants in surface waters. The Act made it unlawful for any person to discharge any pollutant from a point source into navigable waters, unless a permit was obtained under its provisions. It also funded the construction of sewage treatment plants under the construction grants program and recognized the need for planning to address the critical problems posed by non-point-source pollution. Subsequent enactments modified some of the earlier Clean Water Act provisions. Revisions in 1981 streamlined the municipal construction grants process, improving the capabilities of treatment plants built under the program. Changes in 1987 phased out the construction grants program, replacing it with the State Water Pollution Control Revolving Fund, more commonly known as the Clean Water State Revolving Fund. This new funding strategy addressed water quality needs by building on EPA-state partnerships.

## CERCLA

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), commonly known as Superfund, was enacted by Congress on December 11, 1980. This law created a tax on the chemical and petroleum industries and provided broad federal authority to respond directly to releases or threatened releases of hazardous substances that may endanger public health or the environment. Over 5 years, $1.6 billion was collected and the tax went to a trust fund for cleaning up abandoned or uncontrolled hazardous waste sites. CERCLA:

- Established prohibitions and requirements concerning closed and abandoned hazardous waste sites
- Provided for liability of persons responsible for releases of hazardous waste at these sites
- Established a trust fund to provide for cleanup when no responsible party could be identified.

The law authorizes two kinds of response actions:

- Short-term removals, where actions may be taken to address releases or threatened releases requiring prompt response.
- Long-term remedial response actions that permanently and significantly reduce the dangers associated with releases or threats of releases of hazardous substances that are serious, but not immediately life threatening. These actions can be conducted only at sites listed on EPA's National Priorities List (NPL).

CERCLA also enabled the revision of the National Contingency Plan (NCP). The NCP provided the guidelines and procedures needed to respond to releases and threatened releases of hazardous substances, pollutants, or contaminants. The NCP also established the NPL. CERCLA was amended by the Superfund Amendments and Reauthorization Act (SARA) on October 17, 1986.

## EMERGENCY PLANNING AND COMMUNITY RIGHT TO KNOW ACT

42 U.S.C. 11001 et seq. (1986), also known as Title III of SARA, EPCRA was enacted by Congress as the national legislation on community safety. This law was designated to help local communities protect public health, safety, and the environment from chemical hazards. To implement EPCRA, Congress required each state to appoint a State Emergency Response Commission (SERC). The

SERCs were required to divide their states into Emergency Planning Districts and to name a Local Emergency Planning Committee (LEPC) for each district. Broad representation by fire fighters, health officials, government and media representatives, community groups, industrial facilities, and emergency managers ensures that all necessary elements of the planning process are represented.

## SUPERFUND AMENDMENTS AND REAUTHORIZATION ACT

The Superfund Amendments and Reauthorization Act (42 U.S.C.9601 et seq. (1986)) reauthorized CERCLA to continue cleanup activities around the country. Several site-specific amendments, definitions clarifications, and technical requirements were added to the legislation, including additional enforcement authorities. Title III of SARA also authorized the Emergency Planning and Community Right-to-Know Act (EPCRA). SARA reflected EPA's experience in administering the complex Superfund program during its first 6 years and made several important changes and additions to the program. SARA:

- stressed the importance of permanent remedies and innovative treatment technologies in cleaning up hazardous waste sites
- required Superfund actions to consider the standards and requirements found in other state and federal environmental laws and regulations
- provided new enforcement authorities and settlement tools
- increased state involvement in every phase of the Superfund program
- increased the focus on human health problems posed by hazardous waste sites
- encouraged greater citizen participation in making decisions on how sites should be cleaned up
- increased the size of the trust fund to $8.5 billion

SARA also required EPA to revise the Hazard Ranking System (HRS) to ensure that it accurately assessed the relative degree of risk to human health and the environment posed by uncontrolled hazardous waste sites that may be placed on the National Priorities List (NPL).

## NATIONAL CONTINGENCY PLAN

The National Oil and Hazardous Substances Pollution Contingency Plan, more commonly called the National Contingency Plan or NCP, is the federal government's blueprint for responding to both oil spills and hazardous substance releases.

The National Contingency Plan is the result of our country's efforts to develop a national response capability and promote overall coordination among the hierarchy of responders and contingency plans. The first National Contingency Plan was developed and published in 1968 in response to a massive oil spill from the oil tanker *Torrey Canyon* off the coast of England the year before. More than 37 million gallons of crude oil spilled into the water, causing massive environmental damage. To avoid the problems faced by response officials involved in this incident, U.S. officials developed a coordinated approach to cope with potential spills in U.S. waters.

The 1968 plan provided the first comprehensive system of accident reporting, spill containment, and cleanup and established a response headquarters, a national reaction team, and regional reaction teams (precursors to the current National Response Team and Regional Response Teams).

Congress has broadened the scope of the National Contingency Plan over the years. As required by the Clean Water Act of 1972, the NCP was revised the following year to include a framework for responding to hazardous substance spills as well as oil discharges. Following the passage of Superfund legislation in 1980, the NCP was broadened to cover releases at hazardous waste sites requiring emergency removal actions.

Over the years, additional revisions have been made to the NCP to keep pace with the enactment of legislation. The latest revisions to the NCP were finalized in 1994 to reflect the oil spill provisions of the Oil Pollution Act of 1990.

Refer to Table 1 for a summary of the regulations that implement the Emergency Response Plan. Note as an example that "40 CFR 300" means that the regulation is in Volume 40, Part 300, of the CFR.

Table 1. Regulations Implementing the Emergency Response Plan

| **Overview** | **Reference** | **Summary of key provisions** |
|---|---|---|
| National Contingency Plan | 40 CFR 300 | Oil and hazardous Substances |
| Oil Pollution Prevention | 40 CFR 112 *(1.3M, 436 pages)* **Abstract** | Oil |
| Discharge of Oil | 40 CFR 110 | Oil |
| Extremely Hazardous Substances | 40 CFR 355 | Hazardous substances |
| Local Governments Reimbursement | 40 CFR 310 | Hazardous substances |
| Reportable Quantities Requirement | 40 CFR 302 | Hazardous substances |

## OIL POLLUTION ACT

The Oil Pollution Act (OPA) was signed into law in August 1990, largely in response to rising public concern following the *Exxon Valdez* incident. The OPA improved the nation's ability to prevent and respond to oil spills by establishing provisions that expand the federal government's ability, and provide the money and resources necessary, to respond to oil spills. The OPA also created the national Oil Spill Liability Trust Fund, which is available to provide up to $1 billion per spill incident. In addition, the OPA provided new requirements for contingency planning both by government and industry. The National Oil and Hazardous Substances Pollution Contingency Plan (NCP) has been expanded in a three-tiered approach: the Federal government is required to direct all public and private response efforts for certain types of spill events; Area Committees, composed of federal, state, and local government officials, must develop detailed, location-specific Area Contingency Plans; and owners or operators of vessels and certain facilities that pose a serious threat to the environment must prepare their own facility response plans. Finally, the OPA increased penalties for regulatory noncompliance, broadened the response and enforcement authorities of the federal government, and preserved state authority to establish law governing oil spill prevention and response.

## FEDERAL INSECTICIDE, FUNGICIDE AND RODENTICIDE ACT

The primary focus of FIFRA (7 U.S.C. s/s 136 et seq. (1972)) was to provide federal control of pesticide distribution, sale, and use. EPA was given authority under FIFRA not only to study the consequences of pesticide usage but also to require users (farmers, utility companies, and others) to register when purchasing pesticides. Through later amendments to the law, users also must take exams for certification as applicators of pesticides. All pesticides used in the United States must be registered (licensed) by EPA. Registration ensures that pesticides will be properly labeled and that if used in accordance with specifications, they will not cause unreasonable harm to the environment.

## OCCUPATIONAL SAFETY AND HEALTH ACT

Congress passed the Occupational and Safety Health Act (29 U.S.C. 651 et seq. (1970)) to ensure worker and workplace safety. Their goal was to make sure employers provide their workers a place of employment free from recognized hazards to safety and health, such as exposure to toxic chemicals, excessive noise levels, mechanical dangers, heat or cold stress, or unsanitary conditions. In order to establish standards for workplace health and safety, the act also created the National Institute for Occupational Safety and Health (NIOSH) as the research institution for the Occupational Safety and Health Administration (OSHA). OSHA is a division of the U.S. Department of Labor that oversees the administration of the act and enforces standards in all 50 states.

## POLLUTION PREVENTION ACT

The Pollution Prevention Act (42 U.S.C. 13101 and 13102, s/s et seq. (1990)) focused industry, government, and public attention on reducing the amount of pollution through cost-effective changes in production, operation, and raw materials use. Opportunities for source reduction are often not realized because of existing regulations, and the industrial resources required for compliance, focus on treatment and disposal. Source reduction is fundamentally different and more desirable than waste management or pollution control. Pollution prevention also includes other practices that increase efficiency in the use of energy, water, or other natural resources and protect our resource base through conservation. Practices include recycling, source reduction, and sustainable agriculture.

## SAFE DRINKING WATER ACT

The Safe Drinking Water Act (42 U.S.C. s/s 300f et seq. (1974)) was established to protect the quality of drinking water in the United States. This law focuses on all waters actually or potentially designed for drinking use, whether from aboveground or underground sources. The act authorized EPA to establish safe standards of purity and required all owners or operators of public water systems to comply with primary (health-related) standards. State governments, which assume this power from EPA, also encourage attainment of secondary standards (nuisance-related).

## TOXIC SUBSTANCES CONTROL ACT

The Toxic Substances Control Act (TSCA, 15 U.S.C. s/s 2601 et seq. (1976)) of 1976 was enacted by Congress to give EPA the ability to track the 75,000 industrial chemicals currently produced or imported into the United States. EPA repeatedly screens these chemicals and can require reporting or testing of those that may pose an environmental or human-health hazard. EPA can ban the manufacture and import of those chemicals that pose an unreasonable risk. Also, EPA has mechanisms in place to track the thousands of new chemicals that industry develops each year with either unknown or dangerous characteristics. EPA then can control these chemicals as necessary to protect human health and the environment. TSCA supplements other federal statutes, including the Clean Air Act and the Toxic Release Inventory under EPCRA.

## A SHORT REVIEW

When dealing with solid wastes and pollution, there is no one single law that applies. Environmental compliance requires a keen understanding of all the environmental laws that may impact on an operation. The way companies address this most effectively is through the application of an *initial environmental review* or IER.

An IER examines the environmental aspects associated with an operation and determines which regulations require compliance. Compliance is best handled by means of an *environmental management system* or EMS, of which the most well-known one is ISO14001.

# Chapter 3

# MUNICIPAL SOLID WASTE

## INTRODUCTION

The disposal of municipal solid waste (MSW) is one of the more serious and controversial urban issues facing local governments in the United States, and indeed most technologically developed nations. Despite innovative technologies, production decisions and marketing strategies that have helped in better managing solid waste, per capita generation of garbage continues to surge. Local governments dispose of solid waste through three main strategies: composting, incineration and landfilling. Composting, a process involving bacteria as an agent to decompose waste materials into soil additives, removes leaves and yard waste from the waste stream, thereby lessening volume. Incineration involves the burning of solid waste and not only effects significant volume reduction but also produces energy in the form of steam or electricity. Because other disposal alternatives leave some portion of the waste untreated or produce some type of residue, landfills serve as the terminal approach to waste management.

Although using the same methodologies, solid waste management practices still differ widely throughout the world. As examples, Japan burns more than 70% of its solid waste, while more than 84% of American waste goes into landfills. Unfortunately, both methods contribute to increased pollution. With its heavy reliance on incineration, Japan must deal with dangerous air emissions and ash disposal. Incinerator smoke contains such toxic substances as dioxins, sulfur dioxide, and oxides of nitrogen. The concentration of dioxins in Japan's atmosphere is three times that of the United States.

But landfills are also environmentally challenging. They contain significant contaminants that can pollute underground aquifers and surface water. Further, they harbor large amounts of carbon dioxide, methane, and other toxic gases that contribute to the greenhouse effect. Eventually, landfills reach capacity and many are being capped at great expense.

Although technology exists to remove toxic chemicals from incinerator smoke, and to prevent landfills from leaking, it is generally expensive and subject to strict federal and state regulation. U.S. laws authorize local governments to participate in preparing and implementing local plans that embody sound principles of solid waste management, natural resource conservation, and energy production. When LCC tools are applied, more cost-effective management practices that serve communities for many decades can be chosen. These investments must be supplemented and focus heavily on reducing waste at the source and recycling. Reducing garbage output is becoming a major environmental priority in the United States. Many local governments now require recycling and waste reduction by residents and businesses as the cornerstone of an effective solid waste program. In this chapter we examine the problem of MSW along with the alternative strategies and technologies that are displacing landfilling and incineration.

## THE COMPOSITION OF MUNICIPAL WASTE

Municipal solid waste (MSW) is commonly known as trash or garbage. It comprises everyday items, such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, batteries, and other consumer-related product forms. The composition of MSW depends on a number of factors such as the lifestyles of the population, their relative standards of living, general consumer patterns, and the level of technological advancement of a particular country. In the United States the average composition (before recycling) is widely reported to be as shown in Table 1:

Table 1. Typical Composition of MSW Reported in the United States.

| **Waste component** | **Weight %** |
|---|---|
| Paper | 38.1 |
| Yard waste | 12.1 |
| Food waste | 10.9 |
| Plastics | 10.5 |
| Metals | 7.8 |
| Rubber, leather, textiles | 6.6 |
| Glass | 5.5 |
| Wood | 5.3 |
| Miscellaneous inorganic waste | 3.2 |

A portion of household wastes are hazardous. Households often discard common items such as paint, solvent-based cleaners, oils, batteries, and pesticides. These items contain hazardous chemicals. Such discarded items are referred to as *household hazardous waste* (HHW).

Municipal waste management systems that rely exclusively on landfills have little need to characterize the types and quantities of material disposed, unless the waste streams comprise significant quantities of hazardous wastes. As communities rely more on source reduction, recycling, composting, and waste-to-energy (WTE) technologies, the need for reliable data about what is in the waste stream becomes paramount to the waste management program's success. Each of these technologies addresses discrete segments of the waste stream. These data assist municipalities in:

- Determining the best management methods for different materials
- Planning recycling and composting programs by identifying the amounts of recyclables and organic materials generated by residential, commercial, and possibly industrial sectors
- Sizing of WTE facilities based on the amount of wastes remaining in the waste stream after recycling and composting
- Estimating waste transportation and separation costs using local estimates of total municipal waste volume and weight

Waste characterization studies provide baseline data for municipalities to measure their progress toward specific waste management goals. In addition, projections of the size and composition of the future MSW stream helps communities plan MSW management facilities that often have operating lifetimes of several decades.

The use of literature reported data for local planning is likely to lead to inaccurate estimates of local MSW quantities and composition and could result in costly mistakes in purchasing equipment and sizing facilities. Local waste characterizations, on the other hand, are based on actual waste stream studies conducted at landfills, WTE facilities, materials recovery facilities (MRFs), or transfer stations. Properly conducted studies can provide information about the amount of specific products and materials generated by each sector (i.e., residential, commercial, or industrial), the amount of waste recycled, seasonal variations in the waste stream, and differences between urban, suburban, and rural areas. Waste characterization studies often include the following elements:

- An approach to sample collection that ensures representative sampling
- Four-season sorts of at least one week each
- Multiple waste categories (e.g., about 25), with added detail on recyclables
- Waste quantities by generation source
- An estimation of the heat value of waste if WTE is being considered
- A survey of businesses, haulers, and brokers to quantify commercial recycling activities and disposal practices

A waste characterization can also include sample sorts of restaurant, hotel, office, and manufacturer waste to determine waste generation and characterization by sector, and curbside sorts to establish baseline data for tracking source reduction programs, household hazardous wastes, and program effectiveness.

Identifying generation rates and management methods for commercial waste is particularly important. On average, commercial waste accounts for 40% of the municipal waste stream in North America, but percentages vary by community. As an example, there are some rural areas that generate almost no commercial waste. Construction and demolition debris is sometimes a major portion of the waste stream and a good source of recyclable materials. Construction and demolition debris can be included in commercial waste estimates or broken out separately. The composition of commercial and industrial waste is significantly different from that of residential waste. Residential waste includes high volumes of paper, glass, food, and yard waste, whereas commercial and industrial waste includes high volumes of paper, metals, and wood. The primary waste generators in the commercial sector tend to be hotels, restaurants, shopping centers, and hospitals.

Waste characterization studies need to be updated periodically to account for changes in population density, industrial concentration, and community affluence. To anticipate changes in the size and composition of the MSW stream and to make decisions concerning its management, local officials generally make projections of the future MSW stream based on the impact of at least two factors: (a) demographics; and (b) recycling, composting, and source reduction programs. Although consumer behavior and product composition also are important factors affecting MSW generation and composition, the impact of these factors is difficult to predict and can have an ambiguous overall affect. Some general trends are, however, evident. The percentage of paper and plastics in the waste stream is expected to continue increasing. Also, glass and steel containers are likely to continue to be replaced by lighter materials, such as aluminum and plastic. Changes in local industry and commerce will also affect the size and composition of the commercial and industrial waste streams.

## WASTE VOLUME GROWTH TRENDS

The volumes generated per capita also depend on similar if not the same factors that influence composition. In the United States the combined MSW from residents, businesses, and institutions exceeded 230 million tons (1999 data reported by the EPA Web site: www.epa.gov). This figure represents about 4.6 lbs (2.09 kg) of waste per person per day. In contrast, in 1960, the U.S. estimated MSW generation figure per capita was 2.7 lbs (1.22 kg). Trends in MSW generation for the United States are shown in Fig. 1.

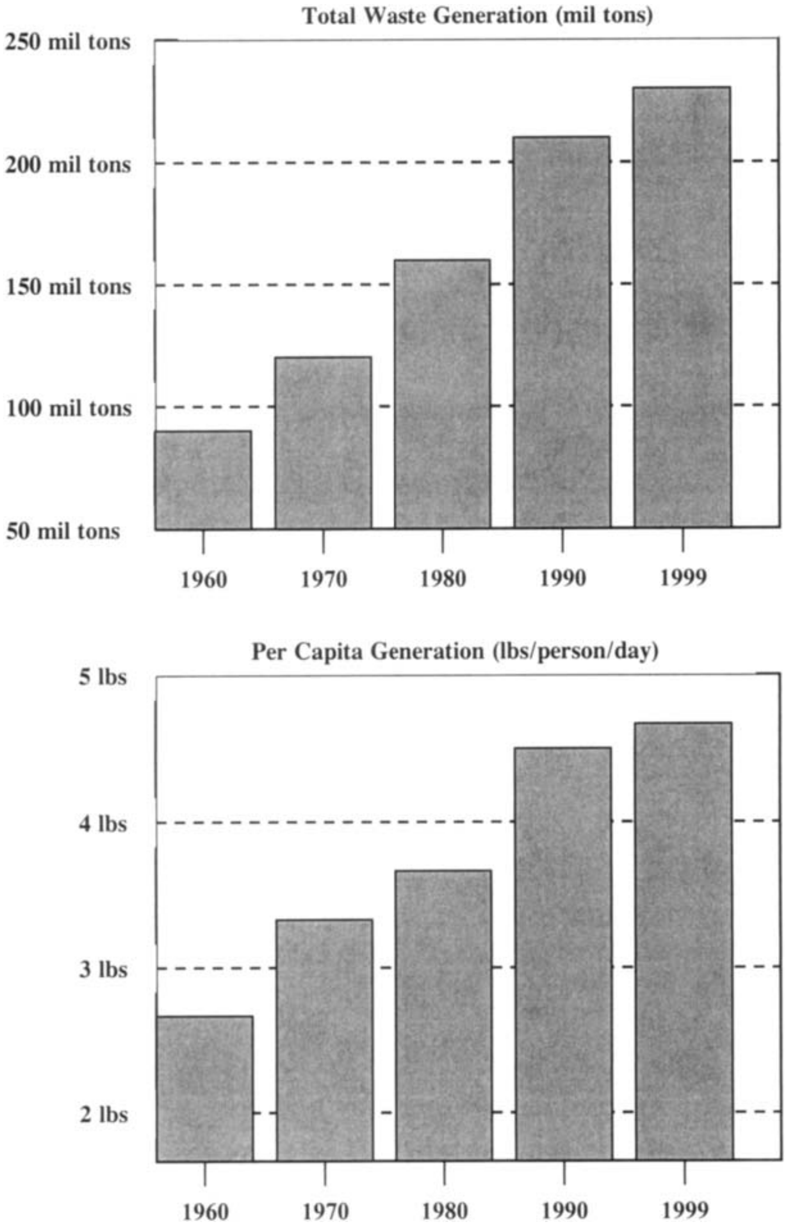


Figure 1. Trends in municipal waste generation growth in the United States.

The trends shown in Fig. 1 indicate an alarming rate of increase in less than a generation. This raises concerns for the overconsumption of nonrenewable resources, and the ability to effectively manage these waste volumes.

Changes in MSW generation can be attributed to demographics and can be broken down into two basic factors:

- Changes in population
- Changes in per-capita generation

Population growth or decline due to changes in the birth rate, death rate, or migration significantly affect the generation of residential, commercial, and industrial MSW. Although national average populations in technologically advanced countries are expected to continue to increase, regions and localities can expect to see much more dynamic changes due to migration and other factors. Note also that industrial solid waste patterns are also dynamic and change as demographic shifts in society take place. This also leads to the need for more complex and well-thought-out waste management strategies.

Per-capita generation depends on at least three major factors: socioeconomic status, the degree of urbanization, and household size. The effect of socioeconomic status on MSW generation is uncertain. As societies become more affluent on average, they have purchased more of all goods, which has increased waste generation. Rural areas often have lower per-capita generation rates than urban areas for at least some components of the waste stream (e.g., fewer newspapers because they are printed weekly rather than daily and are more often burned as fuel).

In the chapters to follow we will examine alternative strategies for waste management at both the municipal and industrial levels. Bear in mind that consumer patterns also need to change as resources become more scarce. Recycling, composting, and source reduction initiatives have altered the MSW stream that is sent to WTE facilities and landfills. Since these programs reduce the portion of certain materials in the waste stream, the proportion of the remaining, untargeted components must necessarily increase.

## WASTE TO ENERGY

Incineration is the combustion of waste in a controlled manner in order to destroy it or transform it into less hazardous, less bulky, or more controllable constituents. Incineration may be used to dispose of a wide range of waste streams including MSW, commercial, clinical, and certain types of industrial waste. Incineration is generally the second most frequently selected method of waste management after landfill for MSW.

MSW comprises residential and commercial refuse and makes up the largest source of waste in industrialized countries. Disposal is a major concern in many parts of the world simply because landfill space is becoming scarce. Although there are significant environmental trade-offs, incineration of MSW with energy recovery can be viewed as an attractive alternative to landfilling in many situations.

The construction of energy from waste facilities is very controversial and has evoked a great deal of public criticism and objections, largely because of air pollution. Since there is a greater prevalence for toxic and hazardous materials in industrial waste streams, the successful application to managing industry solid waste problems has been at a lower level, but still substantial.

There are three basic methods relied upon to convert solid waste into useful energy such as electricity and heat. In the case of MSW, all three methods produce energy from the organic portion of the waste. The organic matter would eventually be converted to methane and carbon dioxide by natural processes. Methane is the main constituent of natural gas, and hence these technology options simply capitalize on what would happen naturally. Since methane formation from the decomposition of the organic waste components of MSW occurs naturally, energy from waste can be viewed in part as not contributing to greenhouse gases. Determining the specific technology that is most appropriate for a given region depends on a number of factors, including the local methods of collecting, processing, and disposing of MSW, and local environmental regulations.

## LIFE-CYCLE CONSIDERATIONS

The benefits associated with incineration technologies include:

- A reduction in the volume and weight of waste, especially of bulky solids with a high combustible content. The reduction can be up to 90% of the volume and 75% of the weight of materials that would otherwise go to landfill.
- Destruction of some wastes and detoxification of others to render them more suitable for final disposal, e.g. combustible carcinogens, pathologically contaminated materials, toxic organic compounds, or biologically active materials that could affect sewage treatment works.
- Destruction of the organic component of biodegradable waste that, when landfilled, directly generates landfill gas (LFG).
- Recovery of energy from organic wastes with sufficient organic value.

- Replacement of fossil fuel for energy generation with beneficial consequences in the greenhouse effect.

The disadvantages of incineration technologies largely lie with environmental trade-offs from transforming solid waste to air pollution. There is genuine concern over the environmental and public health implications of incineration, particularly due to heavy metals and dioxins in incinerator emissions to the atmosphere. This concern led to the adoption of legislation controlling the incineration process in most industrialized countries. The ongoing costs for controls increase the life cycle costs significantly. Although modern incinerators comply with existing air emissions legislation, there is still public concern that the levels emitted pose long-term health risks. The emissions of most environmental concern from mass burn incinerators for MSW are:

- Particulate matter
- Heavy metals such as mercury, cadmium, lead, arsenic, zinc, chromium, copper, nickel, etc.
- Acidic and corrosive gases such as hydrogen chloride, hydrogen fluoride, sulfur dioxide, and nitrogen oxides
- Products of incomplete combustion such as carbon monoxide, dioxins, furans, and polycyclic aromatic hydrocarbons
- Contaminated wastewater
- Contaminated ash

Strong advocates of this technology argue that air emission standards are strict and that these technologies are inherently safe. However, we must always bear in mind that there are still many unknowns about the long-term health risks of numerous air emissions.

Other issues and concerns regarding the use of incineration as a waste treatment method are as follows:

- Because of the high capital investment requirements, incineration generally entails much higher costs and longer payback periods than final disposal to landfill.

- There is a lack of flexibility in the choice of waste disposal options once incineration is chosen. Because of the high capital cost, the incinerator must be tied to long-term waste disposal contracts.
- The incinerator is designed on the basis of a certain calorific value for the waste. Removal of materials such as paper and plastics for recycling and resource recovery reduce the overall calorific value of the waste and consequently affect incinerator performance.
- The incineration process still produces a solid waste residue that requires management and final disposal.

## MASS INCINERATION TECHNOLOGIES FOR MSW

MSW has a broad compositional and size distribution. It is comprised of both organic matter (combustible materials) and non-organic (non-combustible) matter. Particle sizes range from dust to large, bulky materials like discarded furniture and appliances. The specific composition in any one location is a major factor in choosing from among reduction, reuse, and recycling strategies.

The average energy content of typical MSW is about 10,000 kilojoules per kilogram (kJ/kg). Table 2 provides a breakdown of the heating value of MSW by approximate composition of materials.

A typical mass incineration electricity generating plant would require about 45 tons of MSW to generate 1 megawatt (MW) of electricity of power for 24 hours. For many large cities in North America, MSW can supply as much as 10% of the electrical demand. Since the landfill tipping fees for many large municipalities tend to be high, mass burning may be an economically attractive alternative. To evaluate the merits of such an option, a full life cycle costing analysis (LCCA) is needed, using information pertinent to the local economy and cost factors of the region.

Table 2. Average Composition and Heating Values for MSW.

| **Waste Component** | **Weight %** | **Heating Value (MJ/kg)** |
|---|---|---|
| Paper and paper products | 37.8 | 17.7 |
| Plastic | 4.6 | 33.5 |
| Rubber and leather | 2.2 | 23.5 |
| Textiles | 3.3 | 32.5 |
| Wood | 3.0 | 20.0 |
| Food wastes | 14.2 | 15.1 |
| Yard wastes | 14.6 | 17.0 |
| Glass and ceramics | 9.0 | 0 |
| Metals | 8.2 | 0 |
| Miscellaneous inorganic | 3.1 | 0 |

Mass burning is the oldest, simplest, and most widely used method of recovering energy from MSW. Mass burn incineration typically involves waste throughputs of between 10 and 50 tons per hour, with other types of incineration dealing with throughputs of around 1 to 2 tons per hour.

Successful combustion of waste material relies on time, temperature and the degree of turbulence. The specific incinerator design requirements with regards to these parameters are as follows:

- Residence time in furnace - 2 seconds minimum for effective combustion of any organic material
- Temperature - 850°C average (measured via a time-temperature profile throughout the furnace) for municipal and less offensive wastes
- Turbulence - High turbulence required in the combustion zone to avoid dead spots or short circuiting in the furnace

The suitability of incineration as a waste management option depends upon the properties and composition of the waste type, in particular its fuel properties. In this respect, the proximate analysis (ash, moisture, and volatile contents) and the ultimate analysis (of constituent elements) can be used to assess how a particular waste stream will burn in an incinerator and the calculation of any potential emissions. Typically, municipal solid waste can sustain combustion without the requirement for auxiliary fuel where the moisture content falls below 60%, the ash content is less than 25%, and the volatile fraction does not exceed 50%.

A schematic diagram of a typical mass burn incinerator with energy recovery is illustrated in Fig. 2. The various operations and steps involved in a mass incineration plant for MSW with energy recovery are as follows:

- Waste is deposited into a pit where an overhead crane removes oversized items and mixes the waste to evenly distribute materials and moisture.
- The crane feeds the waste into a charging hopper from which it is fed on to a grate, usually by means of a hydraulic ram.
- The grate agitates and transports the waste across the combustion chamber, promoting combustion efficiency.
- Combustion air is introduced from under the grate (underfire air) and from nozzles located in the furnace above the grate (overfire air). Underfire air initiates combustion and cools the grate. Overfire air helps to mix the combustion gases, ensures more complete combustion, and reduces oxides of nitrogen ($NO_x$).
- Non-combustible (i.e., inert) material and ash are discharged from the end of the grate into a water quench tank. From there they are removed for further treatment, and, ultimately, either recovered for use in construction or other applications, or disposed of to landfill.
- Energy is transferred from the hot flue gases to water in the tubes of a waterwall boiler, generating hot water and steam. The steam is used either to turn a turbine to generate electricity or for local heating and/or power combinations.
- The cooled flue gases pass through pollution control equipment including scrubbers (for acid gas removal), electrostatic precipitators (for dust removal) and/or fabric filters (for fine particulate removal) and sometimes activated carbon (for additional mercury and dioxin control) before exhaustion to the atmosphere via a stack.

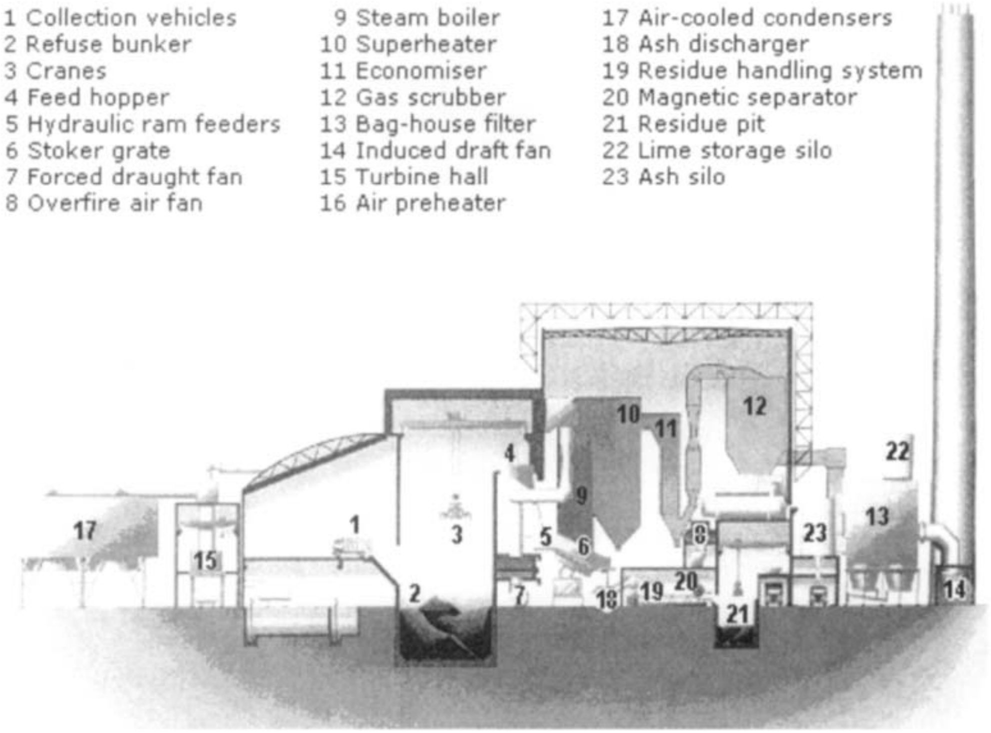


Figure 2. Schematic of mass incineration system for energy recovery.

## WATERWALL INCINERATION TECHNOLOGY

In this technology the raw MSW is incinerated directly in the furnace, usually without any preprocessing of the waste. The primary product is steam, which can be used directly or converted to electricity, hot water, or chilled water. A schematic for a typical waterwall furnace for unprocessed MSW is illustrated in Fig. 3 and further details are shown in Fig. 4.

This technology has been around for many years and is relied upon in various industry applications. Coal-burning operations in the utility sector are prime examples of the efficient use of this technology. The schematics shown in Fig. 3 and 4 provide a summary of the basic steps involved in the burning operation. As with all combustion technologies, a solid waste residue or ash is left that ultimately must be disposed of. The vast majority of this residue winds up in landfills.

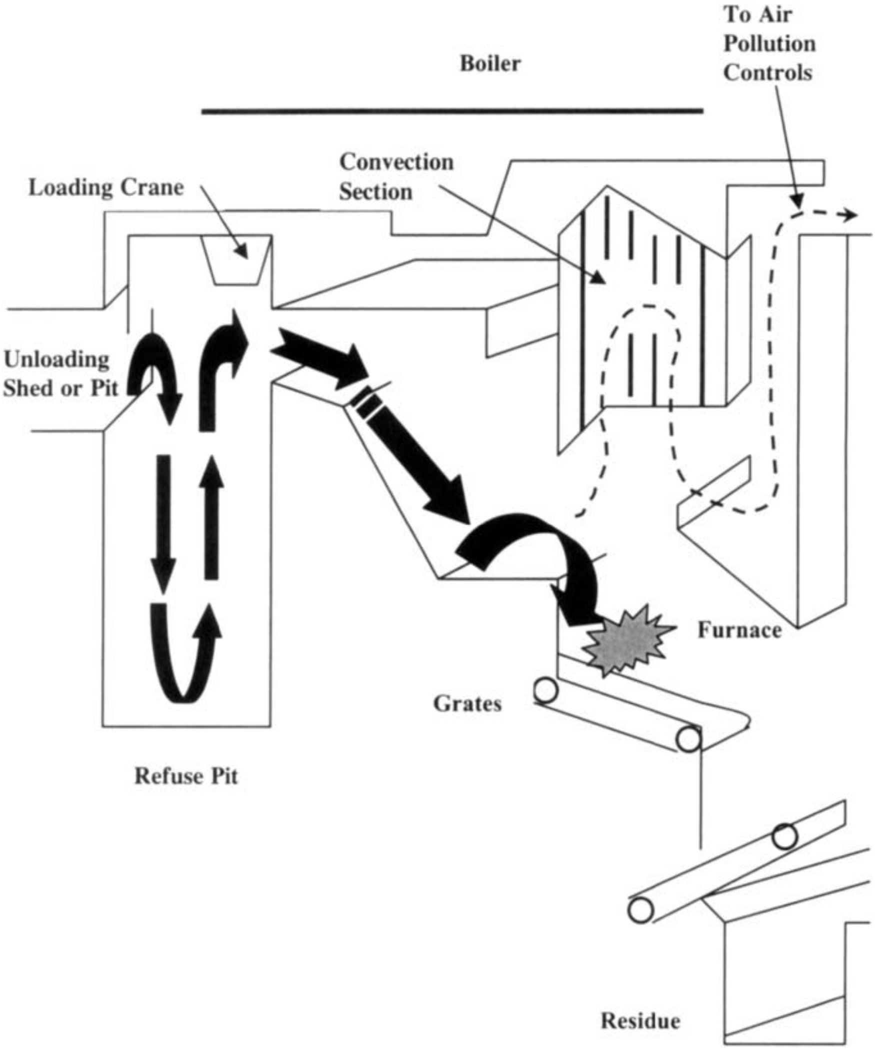


Figure 3. Waterwall furnace for unprocessed MSW.

Some installations perform shredding prior to burning to reduce the waste size. This practice also facilitates material recovery. This adds equipment and operating costs to the investment, so resource recovery is favored to offset some of the OM&R costs and achieve an earlier payback for the investment. Sorting practices for the raw MSW can reduce or eliminate the need for shredding, but again these represent trade-off costs. Some of the responsibility for sorting can be passed on to the generator by restricting the waste forms that are considered acceptable for the mass incineration system.

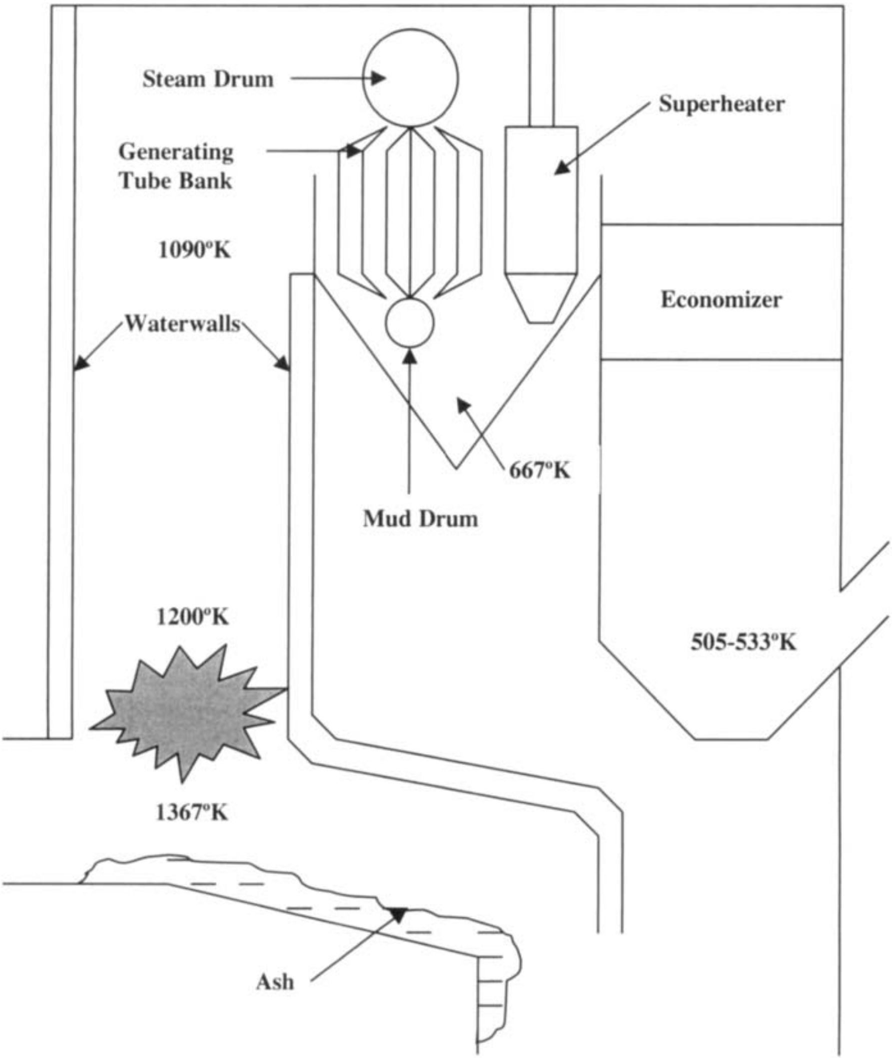


Figure 4. Details of waterwall furnace system.

Additional resource recovery can be performed on the ash. Ferrous metal can be separated out by magnetic separation after incineration is performed. Again, the economics should be examined in a LCCA to determine if this is cost effective.

Waterwall incineration is not a new technology. The origins of this technology go back to post World War II in Europe. Today's European designs favor several small modular furnaces operated in parallel. In the United States, the practice is to use larger units that do not favor modular units.

## SMALL-SCALE INCINERATION UNITS

Small-scale modular incinerators are capable of achieving heat recovery as steam or hot water. They generally do not require materials recovery stages. Many applications have focused on wastes from hospitals, schools, various institutions, and industries where the wastes are more homogeneous than MSW.

For MSW the system designs generally involve small individual furnaces. Large-scale incineration is accomplished by operating several identical units or modules. MSW is usually incinerated in two stages. In the first stage, raw MSW is combusted in a starved air environment (i.e., insufficient air is supplied so that incomplete combustion occurs). This results in the formation of a combustible gas and a by-product residue. The gas from the first or primary combustion stage is then burned with an auxiliary fuel such as oil or natural gas in a secondary combustion chamber with excess air. The hot gases from this chamber are passed through a waste-heat recovery boiler (or a heat exchanger) in order to generate steam, hot water, or hot air for space heating. Two-stage systems tend to be more economical and have the advantage of reducing particulate air emissions.

## FLUIDIZED BED INCINERATORS

Fluidized-bed incinerators consist of a bed of sand or similar inert material contained in a chamber. The bed is fluidized by an upward flow of primary combustion air. The waste is introduced to the preheated bed, where it is efficiently dispersed and heated to the mixture's ignition temperature. There are three main types of fluidized-bed furnaces, which can be identified according to the flow dynamics of the two-phase system: bubbling, turbulent, or circulating beds. A wide variety of wastes have been treated in fluidized bed incinerators, including MSW, sewage sludge, hazardous waste, liquid and gaseous wastes, and wastes with difficult combustion properties. Incineration of MSW based on this technology is best achieved with prescreening and shredding or the production of RDF (refuse-derived fuel) pellets.

The advantages of the fluidized bed techniques include the following:

- There is a high combustion efficiency at a relatively low temperature, with the waste feed normally being ignited spontaneously once the bed has been preheated to around 500°C.
- The operating temperature (circa 850°C) is ideal for in situ removal of $SO_2/SO_3$ by dry means (limestone or dolomite addition).

- The bed cools very slowly, and a rapid startup is therefore possible after 8 to 16 hours of shutdown.
- It possesses good waste feed flexibility.
- It is capable of high conversion efficiency for power generation, especially where the combustion is pressurized.
- It can achieve high heat transfer rates from the bed to the wall and bed internals, leading to a strictly homogenous bed temperature.

The technology's disadvantages include the following:

- A waste feed particle size of less than 300 mm is required.
- A relatively high pressure drop is needed to fluidize a bed of granular particles.
- The incinerator flue gas carries a high dust load.
- The regulation and control of fluidized beds is complicated.
- The possible silica incrustation of bed material limits the operating temperature to around 850 to 950°C.
- The wear on submerged surfaces, the occurrence of attrition upon bed particles, the evolution of the particle size distribution, and the composition of the bed material cannot yet be predicted because of inadequate operating experience with fluidized bed combustors.

A fluidized-bed incineration system can effectively incinerate wet refuse, which is usually difficult to burn without adding fuel, as well as sewage sludge and night soil sludge. It can therefore eliminate problems such as the generation of noxious odors from the putrefaction of refuse and sludge at landfill sites, which attract flies and birds to cause nearby residents to complain. The sand in the fluidized-bed incinerator (FBI) diffuses the intense heat which results when plastics, which have extremely high calorific values, are burned. As a result, there is no generation of clinkers that can be formed by irregular high temperatures at various locations within the incinerator. Therefore, plastics can be stably burned using an FBI. This means that refuse, including such plastics, can be collected and easily incinerated. Since sand has great heat capacity, the temperature in the incinerator does not greatly vary even after the incinerator has been shut down. When the incinerator is restarted on the following day, its internal temperature reaches the rated treatment capacity range almost immediately, without the need to operate any auxiliary fuel firing equipment. Also, no unburnt combustibles remain after the operation is shut down, and as a result there is no discharge of foul odors or smoke due to continuing combustion, as is found with stoker-type incinerators. Fig. 5 illustrates the major components of an FBI. The design illustrated is based on a classical fluid-bed system configuration which has been around for many years.

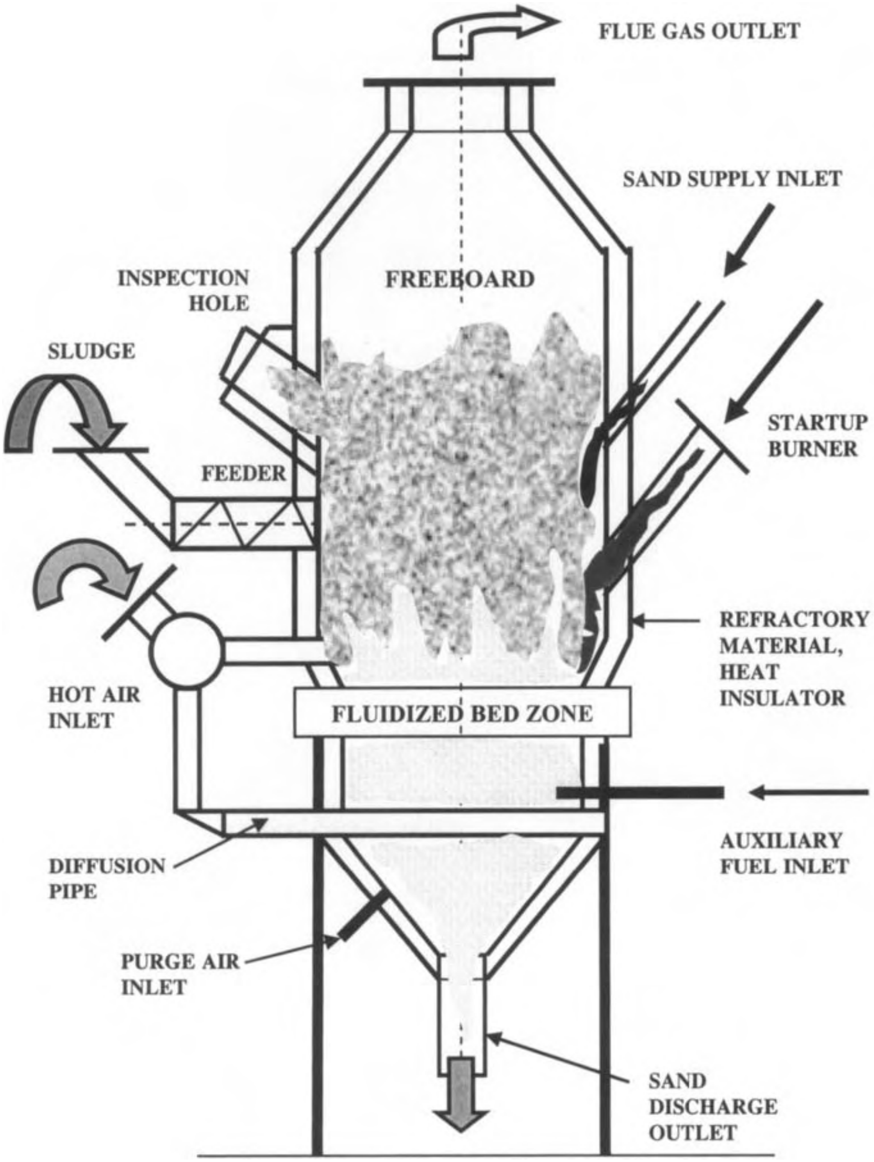


Figure 5. Details of fluid-bed incinerator.

Infilco Degremont, Inc. (see www.Equip.com and Infilco Degremont, Inc., P.O. Box 71390, Richmond, VA 23255-1390, telephone: 804-756-7600) markets a smokeless, odorless process to incinerate wastewater and other sludges. This nonhazardous technology, which meets or exceeds air quality emission regulations, is currently in use in the municipal and industrial markets. Gas temperatures leaving the reactor are 1500°F, thus providing complete destruction of odor-causing organics and eliminating the need for expensive, fuel-hungry afterburners. Figure 6 shows a teardrop shape design which reduces freeboard gas velocity and increases residence time for more enhanced combustion. There are many industry sectors that utilize FBI or operate systems such as dryers and various types of chemical reactors that rely on the principles of gas--solids fluidization. It is a well-established technology with equipment scale-up principles that are generally well understood. The most challenging issues associated with FBI designs are the proper selection of the operating flow regime (bubbling, churning, slugging). This is largely tied to the nature of the waste being incinerated. Such characteristics as waste particle size, density, moisture content, and whether or not agglomerates or so-called *clinkers* are formed can greatly influence the fludization regime and the combustion efficiency.

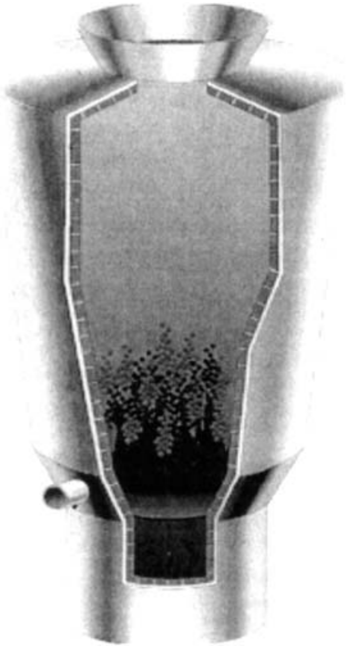


Figure 6. Teardrop FBI configuration manufactured by Infilco Degremont, Inc., P.O. Box 71390, Richmond, VA 23255-1390.

## REFUSE-DERIVED FUEL SYSTEMS

Refuse-derived fuel (RDF) is a result of processing solid waste to separate the combustible fraction from the noncombustibles, such as metals, glass, and cinders in MSW. RDF is predominantly composed of paper, plastic, wood and kitchen or yard wastes and has a higher energy content than untreated MSW, typically in the range of 12,000 to 13,000 kJ/kg. This heating value will vary, depending upon local paper and plastic recycling programs. Like MSW, RDF can be burned to produce electricity and/or heat. RDF processing is often combined with the recovery of metals, glass, and other recyclable materials in a resource recovery facility, thereby improving on paybacks for investments and offsetting OM&R costs. At the present time, RDF combustion is less common than mass burning for MSW, but this may change in the future as recovery of recyclable materials and environmental concerns over incinerator emissions become more important.

Two major benefits of RDF are:

- It can be shredded into uniformly sized particles or densified into briquets. Both of these characteristics facilitate handling, transportation, and combustion. Easily handled, RDF can often be burned or co-fired with another fuel such as wood or coal in an existing facility. RDF is thus valuable as a low-cost additive, which can reduce the costs of generating heat or electricity in a variety of applications. Mass burning of MSW requires specially designed boilers to handle the uneven composition of MSW.
- Fewer noncombustibles such as heavy metals are incinerated. Although metals are inert and give off no energy when they are incinerated, the high temperatures of a MSW furnace cause metals to partially volatize, resulting in release of toxic fumes and fly ash. The composition of RDF is more uniform than that of MSW; therefore fewer combustion controls are required for RDF combustion facilities than for facilities burning untreated MSW.

The majority of RDF combustion facilities generate electricity. On average, capital costs per ton of capacity are higher for RDF combustion units than for mass-burn and modular WTE units. RDFs dehydrate and the municipal solid waste forms into small pellets or fluffy material which allows easy transportation, storage, and combustible stability. Furthermore, efficient use of RDF as an energy resource contributes to recycling strategies. Noncombustible materials such as ferrous materials, glass, grit, and other materials that are not combustible are first removed. The remaining material is then sold as RDF and used in dedicated RDF boilers or coincinerated with coal or oil in a multifuel boiler.

RDF is often used to replace traditional fuels in industrial processes or power stations.

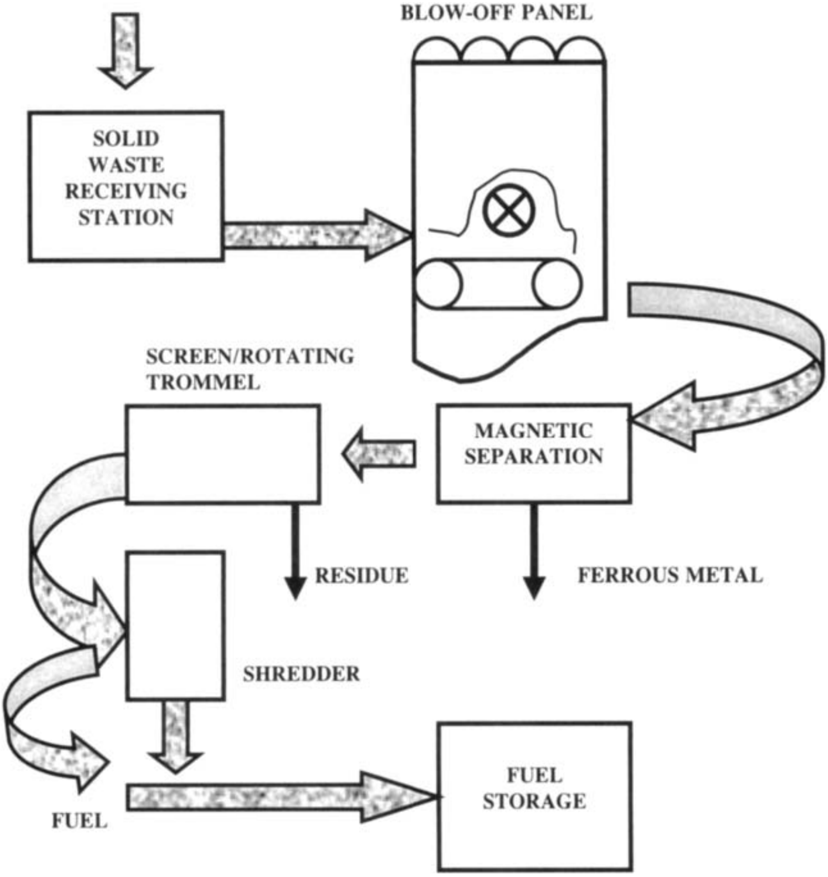


Figure 7. RDF manufacturing process scheme.

There are two main types of RDF: coarse-RDF (c-RDF) and densified pellet or briquette (d-RDF). RDF is produced by processing waste into coarse or densified RDF after first mechanically removing the noncombustible materials, such as metal and glass. A RFD plant with a capacity of approximately 100,000 tons of waste per year may occupy up to 0.6 hectares or an area equivalent to a soccer field for the fuel production facility. An extra hectare is required for the combustion facility. The vent height would be between 10 and 15 m high. Land requirements are approximately circa 5000 to 6000 m$^2$ for the RDF production facility and 1000 m$^2$ for the combustion facility of a plant 90,000 to 100,000 tons per annum (approximate size). Plants require a revolving screen (trommel), a shredder, and a boiler or power plant. Figure 7 illustrates a process scheme for a RDF manufacturing facility. There are a number of variations for these processes. In addition to the process scheme illustrated in Fig. 6, other dry processing schemes first shred the waste and then send the material to an air classifier that separates out the light organic material from metals and other heavy organic and inorganic materials. The light material is then sent through a rotating screen (or trommel) that removes abrasive fine sand, glass, and grit. Heavy materials from the classifier and trommel then move to a magnetic separator that recovers ferrous material. Some facilities also attempt to recover aluminum, glass, and mixed nonferrous metals. Refer to Figure 8.

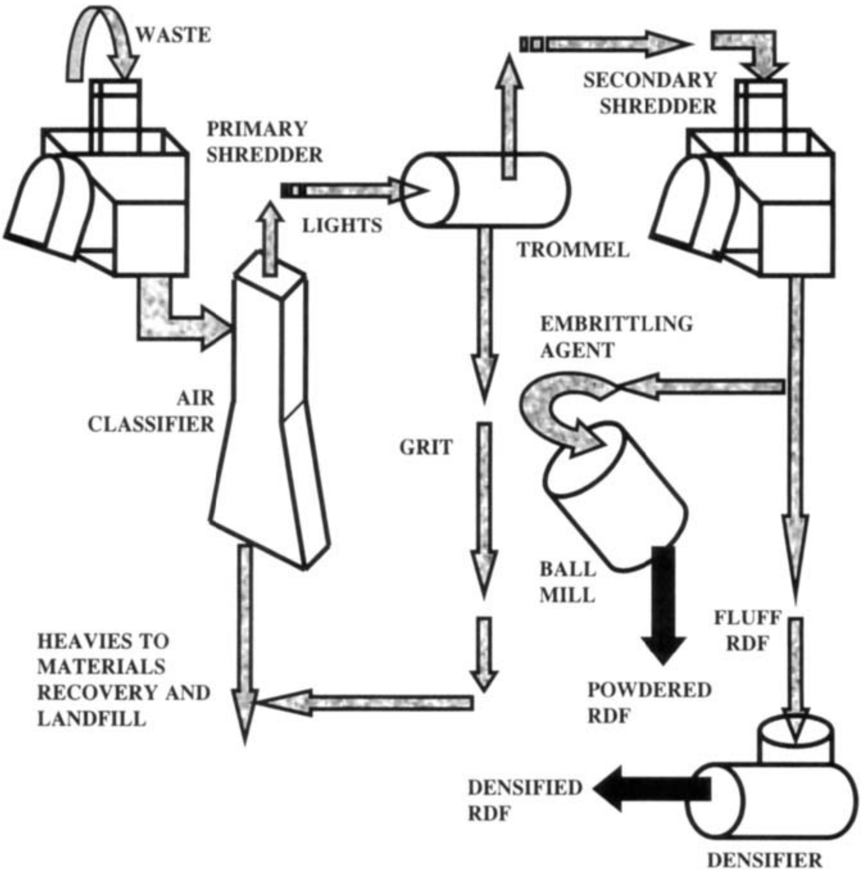


Figure 8. Dry processing scheme for making RDF.

The process illustrated in Fig. 8 shows the light organic material from the trammel being sent to a secondary shredder that further reduces the size of the particulates. The intermediate product that is formed at this stage is referred to as *fluff RDF*. The fluff RDF can be passed through as palletizing or briquetting machine to produce densified RDF. Densification of the product improves storage, handling, and stoker-furnace characteristics. As an alternative, the light output from the trommel can be treated with a chemical embrittling agent and then ground into a fine powder in a ball mill. This results in a material that is a dust or powdered RDF. Typical particle sizes are around 0.15 mm.

Another process known as the wet RDF method makes use of a machine called a *hydropulper*. A hydropulper is essentially a large blender. In this method raw refuse is fed to the hydropulper where high-speed rotating cutters chop the waste in a water slurry. Large items are removed while the remaining suspension is pumped into a liquid cyclone separator which removes the smaller, heavier materials. The water is drained off leaving a wet RDF which has between 20 and 50% moisture content. This material can be burned alone or be employed as a supplemental fuel with coal depending upon the water content.

The wet method has several advantages over the dry method of RDF production. First, sewage sludge can be mixed with the wet pulp prior to dewatering and the resultant mixture can be burned as a method of codisposal. Second, this method reduces the risk of explosion due to spontaneous combustion. In the dry process, shredding is a stage of the operation that is prone to conditions for spontaneous combustion depending on the fineness of the material being processed. Since this step is eliminated in the wet method, the potential hazard is mitigated.

A third advantage is that some organic fiber can be recovered from the wet process, and although the quality of the fiber is too poor to be used in the manufacture of recycled paper products, it has found application as a reinforcing material in roofing profiles.

A major disadvantage of the wet method is that it requires significantly higher operating costs than the dry technology. This comes from the fact that the wet product or pulp must be dried to an acceptable level for combustion. Usually thermal methods are required beyond simple drainage.

## BIOMASS-DERIVED RDF

Biomass-derived fuels have been highly successful in Europe. Finland as an example has hundreds of plants which produce heat and power from various types of biomass fuels. Because of the wide variety of fuels, the fuel handling systems are designed to be versatile. The raw feedstock for these systems is typically bark, peat, wood chips, sludge, industrial wood, and various types of combustible waste, including MSW.

A typical biomass handling system is illustrated in Fig. 9. The simplified scheme provides an overall identification of the major operations involved.

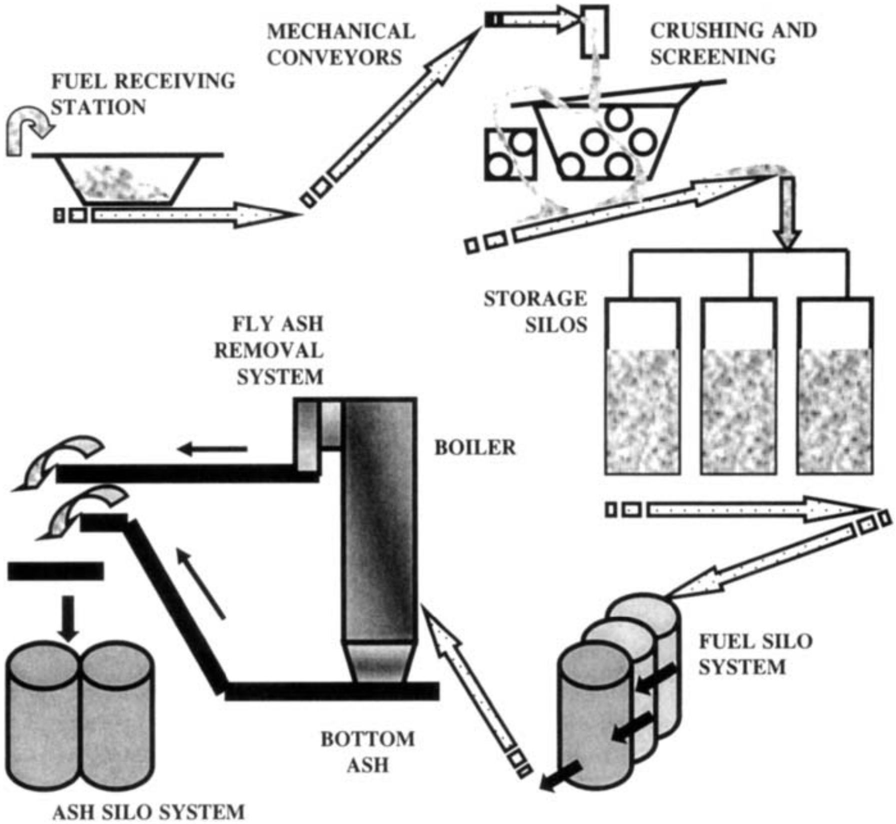


Figure. 9. Schematic for biomass handling operation.

The objective of developing cost-effective and efficient fuel drying technology is to increase the thermal efficiency of the RDF. Plants that generate heat from the burning of biomass-derived RDF are referred to as *biomass-fired energy plants*.

A conceptualized schematic for a process is illustrated in Fig. 10. These systems are highly efficient and can be operated both in small-scale modular units and as large-scale single units depending upon the application. There are both municipal and industrial applications for these designs, although MSW has been the most prevalent area of use.

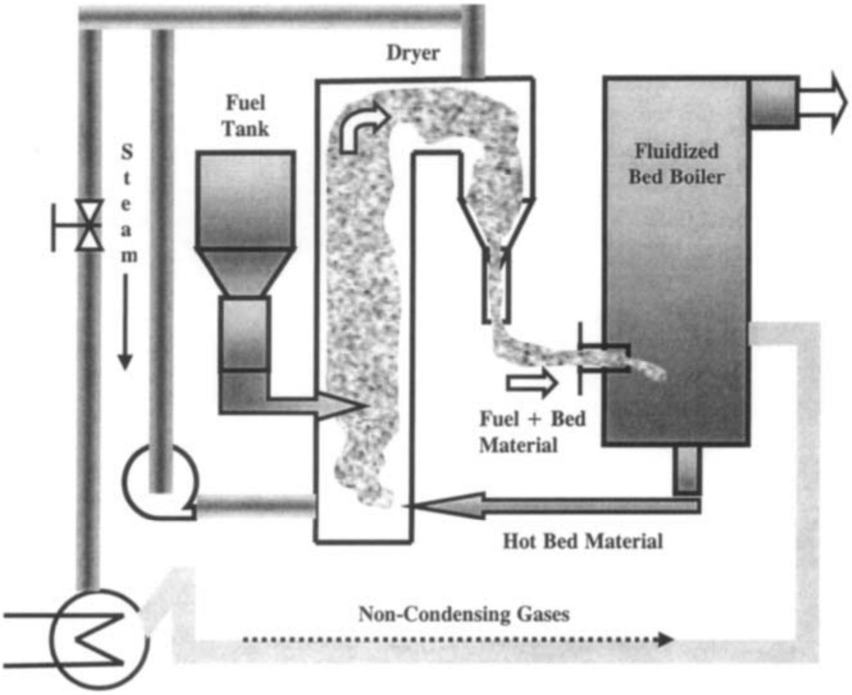


Figure 10. Schematic of bed mixing dryer.

In order to burn biomass a wide range of combustion methods can be chosen on the power-plant scale. In Europe the most commonly used methods are grate firing and fluidized-bed combustion. From an economic and applicability point of view, the combustion of biomass often takes place in multifuel boilers, which additionally use natural gas, oil, or coal. Biomass combustion is based on several combustion methods, including pulverized fuel combustion, grate combustion, fluidized-bed combustion, and gasification/gas combustion. Comments on each of these technologies are given below.

*Pulverized combustion* is a rarely used alternative for wood residues. The plants are almost always too small for feasible pulverized combustion. Pulverized combustion is used in large peat and coal fired plants.

*Grate combustion* has been the most usual form of combustion in past, but is seldom used any more in new large-scale boiler investments, because of higher investment costs, greater emissions, and limited availability for multi-fuel use. However, in smaller-capacity boilers, below 20 $MW_e$, and for wet fuel, such as bark residue in sawmills, grate firing methods offer competitive solutions with minor fuel prehandling investments and low emissions. Improved grate-firing makes it possible to use very moist fuels, such as sawdust. Sawmills and other mechanical wood-processing plants produce wood fuel, which can be used to generate heat for drying sawn timber. The approach is cost-effective if excess heat can be sold to a district heating network or utilized for drying or as process steam. Fuel conversion of old oil-fired heating boilers (of up to 1 $MW_{th}$) represents a considerable niche potential for biomass. Such a conversion can be implemented by retrofitting the boiler with a fixed-bed gasifier or with a special burner. Both technologies are commercial.

An alternative still in the laboratory stage is replacement of fuel oil by biomass-derived pyrolysis oil. Production and utilization of pyrolysis oil is investigated and technologies developed in many countries.

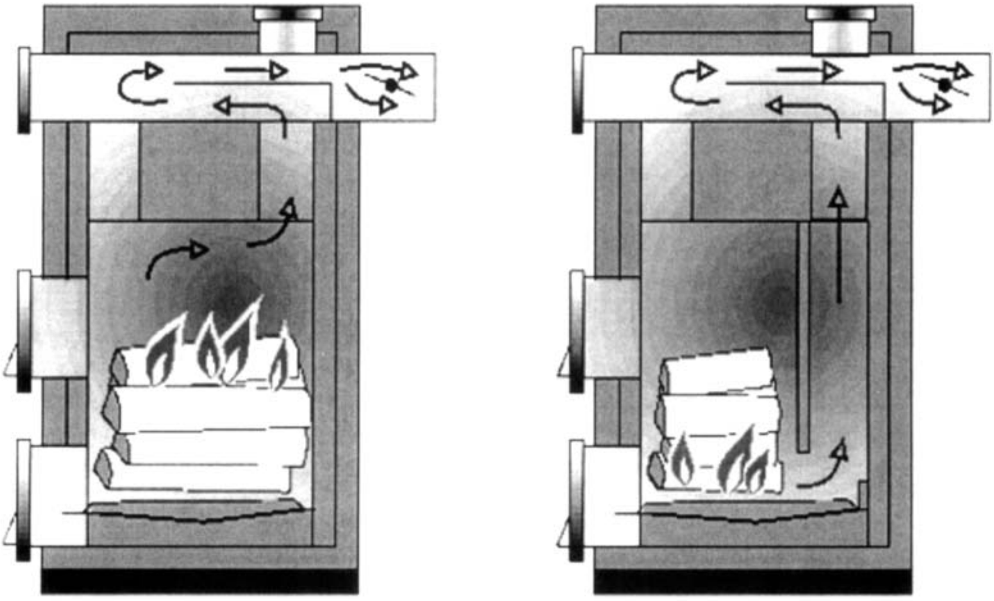
*Small-scale grate boilers* ($<500$ $kW_{th}$) are usually over-fire or under-fire boilers as illustrated by the diagrams in Fig. 11. In an over-fire boiler, fuel combustion takes place in the whole fuel batch at the same time. It is normally equipped with a primary air inlet, the grate and secondary air inlet over the fuel batch, in the gas combustion zone. They are hand-fired using natural draft. *Over-fire boilers* are usually connected to heat accumulators having volume 1 to 5 $m^3$. The most common fuel is chopped firewood. In *under-fire boilers* gasification and partial combustion take place in only a small amount of fuel and final combustion in a separate combustion chamber. Usual fuels in under-fire boilers are wood chips, chopped wood, and sod peat.

Among latest innovations are *down-draft boilers*. Flue gases are forced to flow down through holes in a ceramic grate. Secondary combustion air is introduced at this point. After this fuel gases flow along ceramic tunnels where final combustion takes place in a high-temperature environment. Traditional *under-feed stokers* are used for combustion of sawdust, wood chips, and wood residues from sawmills.

A special kind of *horizontal stoker burner,* illustrated in Fig. 12, is suitable for the combustion of wood biomass has been on the market for about 20 years in

Europe. Most of the devices have been designed for output range 20 to 40 $kW_{th}$, and they are used for heating of detached houses and farms.

Note that there are many varieties of these systems marketed throughout the world. They generally tend to be more popular and economical in Western Europe, quite often because of their small scale. They have not penetrated the Eastern European market which seems to be an ideal candidate for wide-scale applications, but in general solid waste management and WTE technologies have not been given serious attention in that part of the world. For the most part, the small-scale technologies have never been popular in the United States.



Over-fire boiler

Under-fire boiler

Figure 11. Illustrates an over-fire and under-fire boiler for wood fuels.

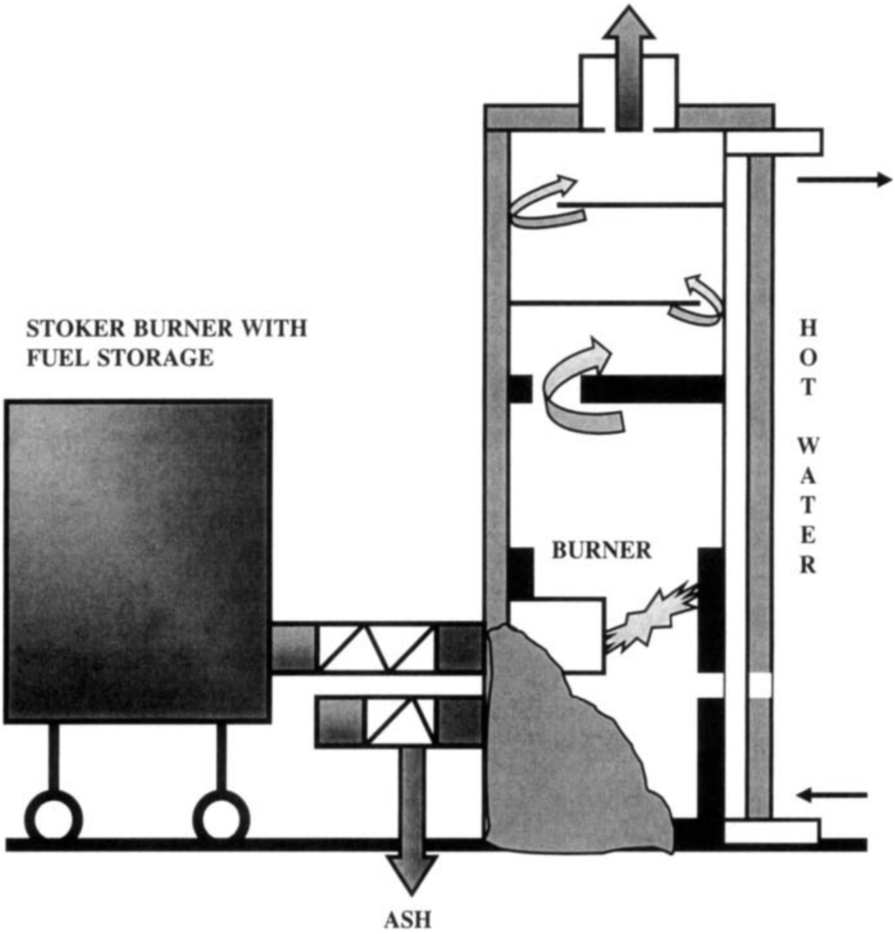


Figure 12. Stoker burner with preheating of combustion air for wood-chip and biomass RDF burning.

*Fluidized-bed combustion* (FBC) technology has made it possible to significantly increase the utilization of various biomasses and wastes in power and heat generation. The pulp and paper industry served as a forerunner because of the adequate biomass and waste fuel supply and energy demand on site. The range of available biomasses and wastes includes wood-based fuels and residues, such as bark, wood chips, and sawdust, sludge from paper mills and de-inking plants, and other wastes, such as municipal sludges, paper waste, packaging waste, and RDF. New environmental regulations and taxation of fossil fuels have recently further increased interest in the use of biomasses and wastes in energy generation. In many cases disposal by burning is the only available method of waste treatment. A promising way to fulfill these targets and to utilize energy is to apply co-combustion or gasification of different fuels and wastes. Fluidized-bed combustion has mainly been used in new plants and many grate-fired boilers have been converted to fluidized-bed boilers. Early concepts were based on *bubbling fluidized beds* (BFB). Since the beginning of the 1970s the development of *circulating fluidized-bed technology* (CFB) has been very intensive and successful.

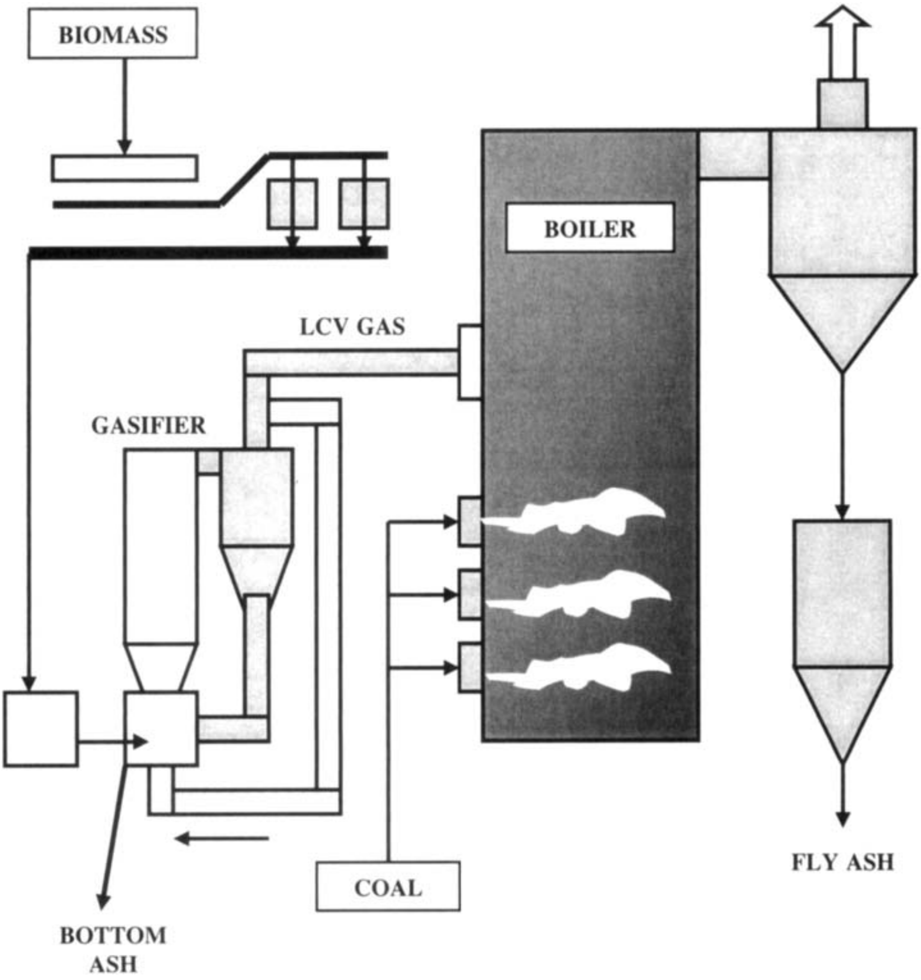


Figure 13. Coutilization of gasified biomass, RDF, and coal.

Fluidized-bed technology has a commercially proven track record in its superiority in the efficient, economic and environmentally sound combustion of a large variety of fuels starting from very high-ash fuels, such as oil shale, and very moist fuels, such as bark and sludges up to high-grade fuels, such as low-sulfur bituminous coals. BFB units are offered up to 100 $MW_e$ and CFB units up to 400 to 600 $MW_{th}$.

CFB boilers have proven feasibility to burn about 70 different fuels alone or in cocombustion mode. BFB boilers have proven their feasibility for biomass and waste fuels with similar characteristics especially in lower capacities, starting from 5 $MW_{th}$ with well-preprocessed fuel. *CFB gasification technology* has been developed for various biomasses since the 1970s. In gasification air and steam are used to gasify the fuel. The product gas is burned in a boiler equipped with a gas burner. Steam can be used to control the consistency of the ash. The moisture content of the fuel may be up to 50%. The process is not suitable for pulverized fuels. Refer to Fig. 13 for an example of a process scheme utilizing an updraft gasifier. Commercial applications ranging from 15 to 35 $MW_{th}$ were delivered before the mid-1980s and applied in sulfate pulp mills for firing low-grade product gas produced from various biomasses in lime-reburning kilns. Despite this reliable operation, the economy of atmospheric gasification became poor in the mid-1980s with the lowering price of oil. More advanced fuel drying and gasification technologies combined with environmental regulations have recently improved the feasibility of gasification.

## PYROLYSIS

The technology of pyrolysis is a form of incineration that chemically decomposes organic materials by heat in the absence of oxygen. Pyrolysis typically occurs under pressure and at operating temperatures above 430°C (800°F). In practice, it is not possible to achieve a completely oxygen-free atmosphere. Because some oxygen is present in any pyrolysis system, a small amount of oxidation occurs. If volatile or semivolatile materials are present in the waste, thermal desorption takes place.

During pyrolysis organic matter is transformed into gases, small quantities of liquid, and a solid residue containing carbon and ash. Off-gases are generally treated in a secondary thermal oxidation unit. Particulate removal equipment such as electrostatic precipitators is also employed.

There are several variations of pyrolysis systems, including the rotary kiln, rotary hearth furnace, and fluidized-bed furnace. Unit designs are similar to incinerators except that they operate at lower temperatures and with less air supply.

The *rotary kiln* is a refractory-lined, slightly inclined, rotating cylinder that serves as a heating chamber. Rotary kilns are usually equipped with an afterburner, a quench, and an air pollution control system. The rotary kiln is a refractory-lined, slightly inclined, rotating cylinder that serves as a combustion chamber and operates at temperatures up to 980°F (1800°F). Incinerator off-gas requires treatment by an air pollution control system to remove particulates and neutralize and remove acid gases (HCl, $NO_x$, and $SO_x$). Baghouses, venturi scrubbers, and wet electrostatic precipitators remove particulates; packed-bed scrubbers and spray driers remove acid gases.

The *circulating fluidized bed* (CFB) uses high-velocity air to circulate and suspend the waste particles in a heating loop and operates at temperatures up to 430°C (800°F). A CFB uses high-velocity air to circulate and suspend the waste particles in a combustion loop and operates at temperatures up to 870°F (1600°F). An experimental unit, the *infrared unit* uses electrical resistance heating elements or indirect-fired radiant U-tubes to heat material passing through the chamber on a conveyor belt and operates at temperatures up to 870°F (1600°F). The infrared combustion technology is a mobile thermal processing system that uses electrically powered silicon carbide rods to heat organic wastes to combustion temperatures. Waste is fed into the primary chamber and exposed to infrared radiant heat (up to 1850°F) provided by silicon carbide rods above the conveyor belt. A blower delivers air to selected locations along the belt to control the oxidation rate of the waste feed. Any remaining combustibles are incinerated in an afterburner.

Major applications of pyrolysis are in the treating and destruction of semivolatile organic compounds (SVOCs), fuels, and pesticides in soil. The process is applicable for the treatment of organics from refinery wastes, coal tar wastes, creosote-contaminated soils, hydrocarbons, and volatile organic compounds (VOCs). Limited performance data are available for pyrolytic systems treating hazardous wastes containing PCBs, dioxins, and other organics. The quality of this information has not been determined.

Soil treatment costs at off-site incinerators range from $220 to $1100 per metric ton ($200 to $1000 per ton) of soil, including all project costs. Mobile units that can be operated on-site will reduce soil transportation costs. Soils contaminated with PCBs or dioxins cost $1650 to $6600 per metric ton ($1500 to $6000 per ton) to incinerate.

High temperatures, 870 to 1200°C (1400 to 2200°F), are used to volatilize and combust (in the presence of oxygen) halogenated and other refractory organics in hazardous wastes. Often auxiliary fuels are employed to initiate and sustain combustion. The destruction and removal efficiency (DRE) for properly operated incinerators exceeds the 99.99% requirement for hazardous waste and can be operated to meet the 99.9999% requirement for PCBs and dioxins. Off-gases and combustion residuals generally require treatment.

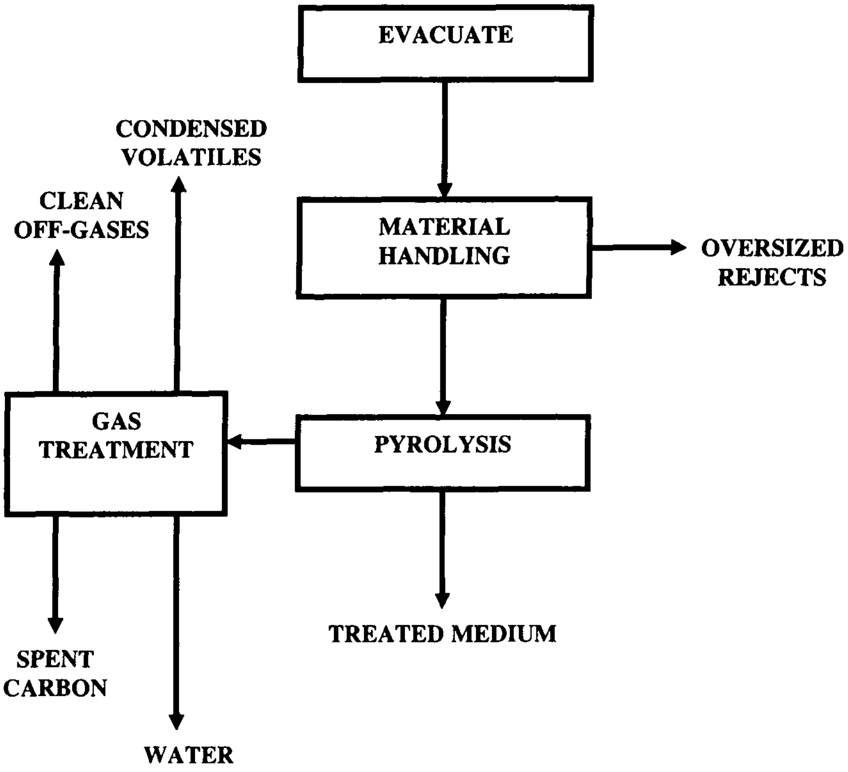


Figure 14. Schematic of a pyrolysis process.

Pyrolysis systems may be applicable to a number or organic materials that *crack* or undergo a chemical decomposition in the presence of heat. Pyrolysis has shown promise in treating organic contaminants in soils and oily sludges. Chemical contaminants for which treatment data exist include PCBs, dioxins, PAHs, and many other organics. Pyrolysis is not effective in either destroying or physically separating inorganic chemicals from the contaminated medium. Volatile metals may be removed as a result of the higher temperatures associated with the process but are similarly not destroyed. The basic process elements of a pyrolysis system are illustrated in Fig. 14. The technology is likely more economical on a small scale, such as in the treatment of certain types of contaminated soils. But for municipal applications, and certainly industrial situations, the technology is cost prohibitive at this point in time.

An emerging application is that of *vacuum pyrolysis* of used tires, which enables the recovery of useful products, such as pyrolytic oil and pyrolytic carbon black (CBp). The light part of the pyrolytic oil contains DL-limonene which has a high price on the market. The naphtha fraction (initial boiling point (IBP) < 160°C) can be used as a high-octane-number component for gasoline. The middle distillate (IBP 204°C) has demonstrated mechanical and lubricating properties similar to those of the commercial aromatic oil. The heavy oil appears promising as a feedstock for the production of needle coke. The surface chemistry of the recovered CBp has been compared with that of commercial carbon black, where the surface morphology of CBp produced by vacuum pyrolysis, as opposed to atmospheric pyrolysis, resembles that of commercial carbon black. The CBp contains a higher concentration of inorganic compounds (especially ZnO and S) than commercial carbon black. The composition of the inorganic part depends on the pyrolysis conditions. An acid base demineralization treatment was shown to significantly reduce the ash concentration of the CBp, thereby improving its quality. The pyrolysis process feasibility looks promising. One old tire can generate, upon vacuum pyrolysis, incomes of at least $2.25, excluding revenues from the tipping fees, with a potential of up to $4.83 per tire upon further development of the market and product improvement. Pyrolysis of rubber is an old concept. Rubber is treated at high temperatures in the absence of air to prevent oxidation. The long polymer chains of the rubber decompose at high temperatures to smaller hydrocarbon molecules. When the pyrolysis is performed under vacuum, the spectrum and quality of products obtained is distinct from the other (usually atmospheric pressure) pyrolysis process. The advantage of a reduced pressure is that secondary decomposition reactions of the gaseous hydrocarbons are limited.

*Molten-salt destruction* is another type of pyrolysis. In molten-salt destruction, a molten-salt incinerator uses a molten, turbulent bed of salt, such as sodium carbonate, as a heat transfer and reaction/scrubbing medium to destroy hazardous materials. Shredded solid waste is injected with air under the surface of the molten salt. Hot gases composed primarily of carbon dioxide, steam, and unreacted air components rise through the molten salt bath, then pass through a secondary reaction zone and an off-gas cleanup system before discharging to the atmosphere.

Other pyrolysis by-products react with the alkaline molten salt to form inorganic products that are retained in the melt. Spent molten salt containing ash is tapped from the reactor, cooled, and placed in a landfill. In molten-salt oxidation (MSO), combustible waste is oxidized in a bath of molten salts at 500 to 950°C, and since there is no direct flame many of the problems associated with incineration are prevented. The salt, being alkaline, scrubs acids from the gases. The heat of the molten salt degrades and melts the waste material. Because the salt bath is liquid, it also removes some particles in the gas. By-products are retained in the melt.

Gases exiting the salt bath are treated by an emission cleanup system before discharge to the atmosphere. MSO offers a clean, effective alternative to incineration for the destruction (by oxidation) of hazardous and mixed wastes, medical wastes, chemical warfare agents, and energetic materials such as explosives, propellants, and pyrotechnics. A very stable and controllable technology, it provides in situ scrubbing of acid gases and particulates. A process scheme is illustrated in Fig. 15.

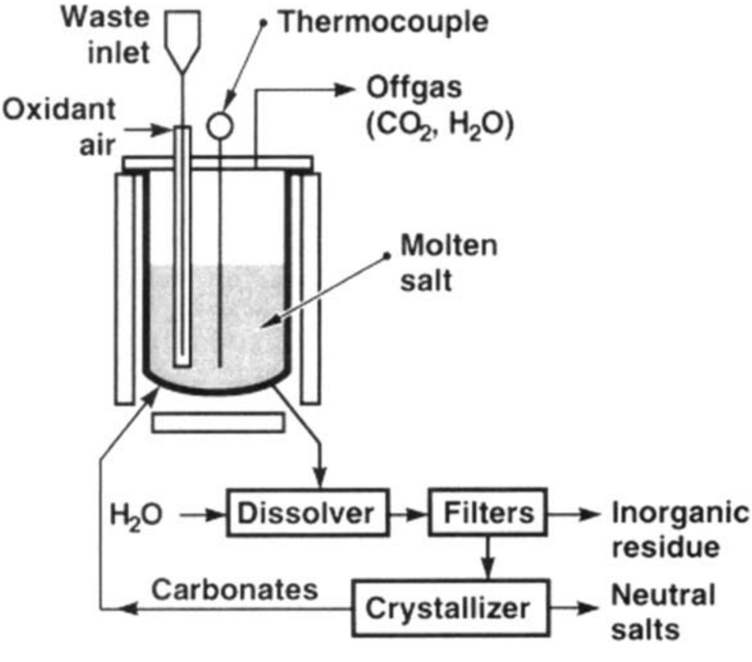


Figure 15. Molten-salt oxidation process.

MSO offers several advantages over incineration. Its lower operating temperatures and liquid-phase media greatly reduce the production of nitrogen oxides and fugitive emissions of radionuclides. The unique chemistry and design of the MSO process achieve negligible dioxin/furan generation.

The *Plasma Energy Pyrolysis System* (PEPS) is an experimental process under development for the destruction of hazardous wastes. The U.S. Army Environmental Center (USAEC), in cooperation with the Tennessee Valley Authority (TVA) and Vanguard Research, Incorporated successfully developed and demonstrated the destruction of hazardous and regulated medical wastes using plasma energy pyrolysis. The PEPS was successfully demonstrated for a 10 ton per day capacity fixed/transportable system in Lorton, Virginia. The Virginia Department of Environmental Quality certified PEPS as an alternative to incineration with a destruction and removal efficiency (DRE) of 99.99999%. With the concern about dioxin formation, this system may have particular interest.

# COMPOSTING

## PRINCIPLES OF COMPOSTING

Composting is receiving increased attention as a means of solid waste (municipal solid waste, biosolids, yard trimmings, food industry wastes etc.) disposal. It is a cost-effective and environmentally friendly component of organic solid waste management. Increased solid waste production and a decrease in available space for landfills have resulted in an increased demand for composting technology.

At any given time, the temperature of a pile of organic waste reflects the balance between microbial heat generation and the loss of heat to the surroundings. The rate of heat generation is a function of factors such as temperature, oxygen, water, nutrients, and the remaining concentration of easily biodegradable organic materials. The rate of heat loss is a function of factors such as ambient temperature, wind velocity, and pile size and shape. Temperature is a powerful determinant of the rate of decomposition. Temperatures of less than 20°C slow decomposition. Temperatures above 60°C are also unfavorable because they kill most of the desirable microorganisms responsible for decomposition. The range of favorable temperatures is approximately 20 to 60°C (or about 70 to 140°F). Precise control over temperature usually is not essential for leaf composting, but gross departure from the desired range should be avoided. Maintenance of the proper temperature, along with oxygenation, is the basic consideration underlying the recommendations for windrow size and turning operations.

Grass clippings are a more *energetic* material (i.e., capable of generating more heat) than leaves and are produced and composted during the warmer part of the year. Overheating is thus more likely and underheating less likely than for leaves. This, along with the need for increased oxygen supply, is why a smaller pile size is recommended when grass clippings are included in a windrow.

Composting is basically an aerobic process (i.e., it requires oxygen), although anaerobic (without oxygen) activity also may occur to a significant extent. Most of the heat produced in composting results from the biodegradation of organic materials with consumption of oxygen and production of carbon dioxide and water. Thus, the waste pile must be sufficiently porous to allow oxygen (from the air) to diffuse in and carbon dioxide to diffuse out. For this reason, materials should be placed loosely in the piles and compaction should be avoided. In the absence of oxygen, anaerobic conditions occur. This can lead to odor production and slowed rates of decomposition.

For leaves, control over process temperature and oxygen content can be exercised to a useful extent (though they are not optimized) through windrow size and turning. A basic problem is to reconcile the needs for oxygenation and heat conservation, which are somewhat in conflict. The need for oxygenation favors small windrows to minimize the distance that air must penetrate within the pile. In contrast, the need for heat conservation, especially in the winter, argues for large windrows for greater insulation. Excessively large windrows, however, might result in excessively high temperatures and anaerobic conditions. These requirements can be reconciled in part by management of windrow size and turning. For almost all composting, windrows should be no more than 6 feet high and 12-14 feet wide.

Water is essential for biological functions in general, and composting is no exception. Adding water (when needed) at the start of composting is very important to ensure adequate moisture throughout the pile at the time of its formation and thereafter. Rainfall, even if heavy, penetrates the pile only slowly and cannot be relied upon to remedy initial dryness. Similarly, once a pile is formed, the interior material is not easily wetted by applying water to the surface. Unless a pile is turned during or shortly after wetting, much of the water will simply evaporate to the air. Initial dryness is a common and serious cause of slow leaf composting rates, and as such should be prevented. An initial moisture content of at least 50% (wet weight basis) is recommended. Leaves also can be excessively wet, slowing oxygen penetration. This condition is self-correcting, as excess water drains from the pile. Depending on weather conditions prior to collection, the leaves might be sufficiently moist upon receipt, but this cannot be relied upon in routine operation. In general, it is better to start with a pile that is too wet than to risk dryness.

Fresh leaves are close to being chemically neutral (neither acidic nor basic, pH near 7), which is desirable for rapid microbial activity. However, with the onset of decomposition even prior to composting, the production of organic acids causes the pH to decline to suboptimal levels, possibly to as low as 4.2 if extensive anaerobic conditions develop. The pH subsequently recovers to a neutral or slightly alkaline level (perhaps pH 7.5) as the acids decompose in the presence of oxygen. A persistently acidic pH is indicative of prolonged anaerobic conditions. Adjustment of the pH with limestone or other additives is not ordinarily necessary. Composting of high nitrogen materials such as grass clippings may lead to pH values as high as 8.5 to 9.5 as ammonia is released. Mixing with leaves will help control this excessive pH rise, as well as reduce ammonia loss.

Microbial activity also requires a variety of other elements, such as nitrogen and phosphorus. Leaves have a high carbon-to-nitrogen ratio (C/N), which can slow microbial action early in the composting period. This nutritional imbalance rights itself as carbon is lost in the form of carbon dioxide, while nitrogen is conserved within the system. Supplementation with nitrogen at the outset would accelerate decomposition, but this measure is not generally necessary. It might be justified, in conjunction with other measures, if the resultant savings in process time were essential for the success of the overall operation. The increased rate of decomposition from nitrogen addition could lead to other problems, such as an increased need for oxygen supply, which would also then have to be addressed. Otherwise, slow decomposition and odors might result. Appreciable deficiency of other nutrients such as phosphorus is not likely. Supplementing the end-product compost with nitrogen, phosphorus, and potassium would increase its quality in terms of plant nutrition. This benefit has to be weighed against the costs of such additions. Grass clippings, on the other hand, contain excess nitrogen and thus have an undesirably low C/N. Unless sufficient available carbon (such as from leaves) is added, ammonia will be lost from the material, producing potential odor problems. The nitrogen also may contaminate ground or surface waters.

Microorganisms found on leaves and yard trimmings are fully capable of starting the composting process and carrying it forward. A variety of commercial "inocula", "starters", and "bioaugmentation" products are offered for sale, and based on testimonials, these are often claimed to be beneficial. However, there is no support for these claims in scientific journals. Properly controlled experimentation indicates that inoculation has no useful effect on the process. Therefore, such products should not be purchased for leaf or yard trimmings composting operations.

Pregrinding or shredding of leaves make them more susceptible to microbial attack, potentially speeding up the composting process. This is not desirable in most cases, unless provision has been made for very frequent turning or blowers to supply the extra oxygen that will be needed, and remove the extra heat that will be generated. It is normally not recommended, and the guidelines given later assume no pregrinding. If any pregrinding is done, smaller piles are recommended. The equipment typically used for the final shredding of finished compost usually is not suitable for shredding of leaves prior to composting.

Site selection is an important decision that should be made only after careful consideration, as each situation is unique. The deliberation over site selection should take into account proximity to residences and streams, prevailing winds, traffic patterns, travel distance and its effect on equipment and labor costs, and other factors, such as local zoning requirements. When selecting a site, the importance of public participation must be stressed. Concerns raised may include odor, traffic, noise, litter, water pollution, and health issues, such as the fungus *Aspergillus fumigatus*. Surrounding property owners and the general public should be educated as to the benefits of composting and assured that their concerns will be addressed. They also need to be informed about the proposed facility, including site capacity, type of material which will be accepted, and the level of technology, including what type of equipment will be utilized.

In New Jersey a state permit or letter of approval is required for all solid waste facilities, including vegetative and leaf composting facilities. The type of permit or approval required depends on the amounts and types of materials accepted. In October 1988, the state adopted an emergency rule which enabled the NJDEPE to expeditiously authorize the operation of leaf and vegetative waste composting facilities. One subsection, N.J.A.C. 7:26-1.11, applies to facilities with a capacity not in excess of 20,000 cubic yards annually which compost leaves only. NJDEPE allows the development of leaf composting demonstration projects for educational purposes on lands owned or operated by recognized academic institutions. Such facilities may accept up to 500 cubic yards of leaves, only. The Soil Conservation District (SCD) may assist in developing and submitting the site plan. SCDs may help develop site plans for the construction, operation, and maintenance of leaf composting facilities (leaves only) located on agricultural or horticultural land, or on lands owned or operated by a recognized academic institution. The SCD must then conduct annual inspections of these facilities to ensure compliance with NJDEPE regulations. Backyard composting activities do not require a permit or approval from the NJDEPE provided that they are limited to the composting of family waste on the premises of one-, or two-family dwellings.

A minimum of an acre per 3000 to 3500 cubic yards of leaves collected is required for the actual composting operation. This assumes the use of the low or intermediate level technology and is in addition to the requirement for a buffer zone.

Use of the intermediate level of technology may require additional space, since smaller windrows are needed to accommodate many turning machines. However, this must be determined individually for the type of equipment chosen. Windrows often can be assumed to have the approximate cross-sectional shape of a semicircle. Necessary aisle space depends again on the type of equipment used. A buffer zone is required between the site activities and neighboring land use to minimize possible odor, noise, dust, and visual impacts. Other than "the larger the better," it is difficult to generalize exact buffer zone requirements for composting. It would seem prudent to provide at least 50 feet between the composting operation and the property line. At least 150 feet must be allowed between composting activities and any sensitive neighboring land uses, such as residential property lines. Additionally, at least a 250-foot buffer is needed between composting activities and a place of human occupancy (house, school, etc.). If grass clippings will be brought to the site, at least 1000-foot buffer zones from the staging and grass clippings handling areas are probably necessary. The buffer zone may include a berm (often of finished compost) to serve as a visual barrier, help control vehicular access, and reduce noise levels off-site. A landscaping plan, including plantings, is strongly recommended to enhance the appearance of the facility.

A centrally located facility is preferable to reduce transportation time and costs, although such sites are not often available or otherwise practical. Access is preferably over noncrowded, nonresidential, hard surface roads. While siting on Green Acres land is not strictly prohibited, it only will be considered as a last resort.

Siting of a leaf composting facility in a flood plain normally is not allowed by many state regulations. During times of high water the windrows might impede water flow, and/or leaves and leachate might wash into the stream. Flooding of the site could pose serious operational difficulties, including problems with equipment access and operation. Flooding of the windrows also may lead to extensive anaerobic conditions and attendant problems of odor and lower decomposition rate. Runoff into nearby streams or other surface waters is another concern because of the water pollution potential of leachate. If grass clippings are composted, nitrogen contamination of groundwater also must be considered.

Steep slopes are unsatisfactory because of problems with erosion, vehicular access, and equipment operation. A gentle slope, however, is desirable to prevent ponding of runoff and leachate. The Soil Conservation Service (SCS) allows a minimum slope of 0.5%, and a maximum of 10%, although 2 to 3% is usually desirable. Initial site preparation usually requires grading, and yearly maintenance should include regrading where necessary. Windrows should run up and down rather than across slopes to allow leachate and runoff to move between piles, rather than through them. Drainage characteristics of a site can be determined from U.S. Geological Survey topographic maps and a plot plan survey.

High soil percolation rates are desirable so that excessive rainwater and leachate will not run off the site. Where percolation is poor, soil modification techniques may be used to improve drainage. With poor percolation, or where an impervious surface is used, particular care must be taken to prevent ponding. While an impervious surface such as pavement may offer advantages in terms of vehicle access and equipment operation, these may be outweighed by the greater difficulties in leachate management.

A high water table is undesirable because it may lead to flooding of the site. Flooding will make operation more difficult and can lead to extensive anaerobic conditions. A high water table also reduces the distance for percolation of leachate. Wetlands and wetland buffer areas especially should be avoided.

The ability to supply water is critical since it usually is necessary to add water to the incoming leaves during much of the collection season. Water can best be supplied by using a hose from a fire hydrant or by pumping from a nearby lake, stream, or well. Use of a water truck usually is not practical because too much water is needed.

Vehicular access to the site must be controlled to prevent illegal dumping. A gate across the entrance road is a minimum precaution. In some cases the entire site may have to be fenced, but usually preexisting features such as streams, trees, and embankments will provide partial security. A berm consisting of earth and finished compost often can serve in place of a fence at other points. Vandalism may be of concern, especially if equipment is to be left on site.

Normally, windrowed leaves burn poorly, since the interior of the pile is wet. While vandals may be able to ignite the dry surface leaves, a major fire is unlikely. Fire safety is further accommodated by having a ready water supply and delivery capacity, initial wetting of the leaves, and providing aisles between windrows as a fire break and for access.

## *ASPERGILLUS FUMIGATUS* AND TOXICS

One relatively new concern with leaf composting is the release of spores of *Aspergillus fumigatus*. This is a common, widespread, naturally occurring fungus found in soil and on vegetative materials. Its airborne spores may produce an allergic response in some people, and in a few cases they are capable of causing infection in individuals with a compromised (weakened) immune system. Because these spores have been found to be of some limited concern in sludge composting, research has been conducted to examine their importance in yard waste composting. *A. fumigatus* appears to pose relatively little risk to neighbors of composting sites with adequate buffer zones. However, workers at a site may receive high exposures, and therefore some precautions seem warranted. Potential workers at the composting site should be screened for conditions that might predispose them to infection or allergic response. Such conditions include asthma, a history of allergic responses, a weakened immune system, the taking of antibiotics or adrenal cortical hormones, and a punctured eardrum. Workers having such conditions should not be assigned to the composting operation (or any other tasks putting them at similar elevated risk) unless a health specialist is consulted. Additionally, wearing an approved dust mask during leaf dropoff, windrow formation and turning, screening, and similar dust-generating operations is recommended. Air conditioner filters in loaders and turning machines should be cleaned frequently. It also is expected that adequate wetting and minimum disturbance of the windrows, as recommended here, will help to reduce potential exposure.

Leaves as collected may contain low levels of some toxic materials. Lead, for example, is present because of its former use in gasoline and paint. Limited testing to date, however, has found only low levels, and these appear to be dropping as use of lead has decreased. Lead levels in leachate typically meet drinking water standards. Some pesticides also may be present, particularly in grass clippings, but again the levels ordinarily are expected to be too low to pose any concern. An unconfirmed 1991 study in Illinois found low levels of 19 pesticides in composting yard wastes. The concentrations were so low that all except one of the 44 samples met the levels allowed in raw agricultural commodities for the 13 detected pesticides for which such levels have been established. (No levels are set for the other 6, which were mostly banned pesticides no longer in use.) In samples from 6 sites in New Jersey only one pesticide, chlordane, was detected. Since chlordane is no longer used, and since it is not taken up by plants, it is believed that this came from the residential soil mixed with the yard waste during raking or bagging. Based on these considerations and findings, yard waste compost is considered safe for residential use without specific testing. The only exception to this would be for composts containing materials from golf courses, where more intensive use of more toxic and persistent compounds is common. Such materials may require testing for specific metals and pesticides before general use.

## ODOR

The major problem encountered even at leaf only composting sites is odor. Starting with relatively innocuous leaves, it is possible to generate odors comparable to those of a barnyard or worse. Grass clippings greatly intensify both the odor strength and its unpleasantness.

In general, odor problems develop in four stages:

- Odorous compounds must be present initially or be produced during processing
- These odors must be released from the pile
- The odors must travel off-site
- They must be detected by sensitive individuals (receptors)

An odor problem can be prevented by eliminating any stage. In most cases, prevention of odor problems can best be achieved by preventing odor formation in the first place (Stage 1). For leaf composting this means avoiding prolonged anaerobic conditions. Under anaerobic conditions, volatile organic acids (which have vinegar, cheesy, goaty, and sour odors), alcohols and esters (fruity, floral, alcohol-like), and amines and sulfur compounds (barnyard, fishy, rotten) can be produced. In contrast, with aerobic conditions only a mild earthy odor is expected. If excessive ammonia or urea-based fertilizer, grass clippings, or other high-nitrogen materials are added, an ammonia odor also may be produced even under aerobic conditions. Prevention of anaerobic conditions is virtually impossible with grass clippings. The major cause of odor production at leaf composting sites is making the windrow too large, especially when first assembled. Because of the initial high concentration of readily degradable material, there is a high demand for oxygen. If the piles are too large, sufficient oxygen cannot penetrate from the outside, and a large anaerobic core develops. Decomposition slows down, switching over to the odor-producing acid fermentation described above.

A second important source of odor production is failure to form windrows quickly enough once the leaves are collected. Leaves cannot be simply dropped at the site for later composting, or collected and stored elsewhere. Although the intention might be to store them, temporary storage of leaves, unless they are very dry, can result in vigorous decomposition within one to two days, leading to anaerobic conditions and the production of offensive odors. Grass clippings, as discussed earlier are almost always odorous already when they are delivered to the composting site.

If odors should be produced at a site, or if odorous materials are dropped off at the site (such as occurs with grass clippings, or previously stored leaves), the second line of defense is to prevent their release (stage 2). This might best be accomplished by leaving the odorous mass undisturbed until oxygen has penetrated sufficiently to destroy the odors. However, this may take several months or even years. Shaving off thin (1- to 2-foot) layers from the edges as they become aerobic may help speed this process.

If a long wait is not practical, another approach may be possible. Since many of the odorous compounds in leaf composting are acidic in nature, raising the pH (neutralizing the acids) will convert them to an ionized (negatively charged, dissociated) form. In this form they cannot be released to the air and will remain in the pile. For example, with the most commonly formed organic acid, acetic acid (vinegar), the reaction is

$$CH_3COOH = CH_3COO^- + H^+$$

Application of pulverized limestone is probably the best way to raise the pH. Sprinkling the limestone in powdered form directly onto surfaces from which odors are escaping may be the simplest approach, although a liquid slurry of limestone in water might be more effective. A layer (1 foot) of finished compost spread over the odorous material also helps to reduce odor release, serving as a "bio-scrubber."

The use of limestone may be ineffective with odors generated from grass clippings or other high nitrogen wastes. Ammonia and amines are weak bases rather than acids, and raising the pH may therefore actually increase odor release:

$$NH_4^+ = NH_3 + H^+$$

If odors are still produced and released despite these precautions, it may still be possible to minimize their off-site impact (Stage 3). This approach relies on timing odor-releasing operations to coincide with favorable wind conditions. A wind sock should be installed at the site to determine wind direction, and odor-releasing operations performed only when the site is downwind of residences and other sensitive neighboring land uses. Also, higher winds are preferable to calm and light wind conditions because the higher the wind speed, the greater the dilution of any released odors.

Some commercially available products claim to mask or eliminate composting odors when sprayed onto windrows. Masking agents try to use another odor (lemon, pine, roses, etc.) to hide the objectionable odors. To our knowledge, they have not been successful at composting sites. Odor elimination agents, with the exception of limestone noted above, are also unsuccessful in our experience.

## LEACHATE

One way in which leachate may pose a problem is by forming small pools or "ponds." Ponding is a concern because it can create an odor problem (since anaerobic conditions are likely to develop both in the pool and in the base of any water saturated piles), serve as a place for mosquito breeding, and interfere with operations on the site (soft, muddy areas). Prevention, by properly grading the site, is the best remedy. Also, windrows should run down slopes rather than across, making it easier for the water to run off rather than accumulate between windrows. If ponding occurs and odors are released from the pools, adding pulverized limestone may be helpful. Pollution of surface waters (lakes, streams) is the other major concern with leachate. Although leachate from leaf composting is generally not toxic, it may deplete the dissolved oxygen in the water, possibly even to the point where fish kills could occur. Because of its dark color, it might also lead to a discoloration of the water.

In order to prevent this potential pollution, leachate should not be allowed to enter surface waters without prior treatment. This treatment might consist of simple percolation down into or through the soil, or passage through a sand barrier constructed to intercept any horizontal flow. In passing through the soil or sand, the leachate is both physically filtered and biologically degraded to remove a substantial portion of the pollutants. Contamination of groundwater does not appear to be a problem associated with leaf composting.

With grass clippings, however, leachate may contain high levels of nitrogen. This may pose a problem of nitrogen contamination for both surface and groundwaters, and may not be adequately treated with simple soil or sand filters. Such contamination must be prevented either by limiting the nitrogen in the leachate (through control of the carbon to nitrogen ratio -- by minimizing the amount of grass clippings, for example), or by more sophisticated (and expensive) leachate collection and treatment systems.

Treatment of high-nitrogen leachate on site is not a simple matter. Initially the nitrogen may be in a reduced form (either as ammonia or as organic nitrogen), but under aerobic conditions it will be converted to nitrate. Nitrate is the number one groundwater contaminant both in New Jersey and nationally, mainly as a result of agricultural practices. In theory the nitrate can be removed by cycling back and forth between aerobic and anaerobic conditions (nitrate may be converted to harmless nitrogen gas under anaerobic conditions); by taking it up as a nutrient in plants (either aquatic plants or algae, or through use of the treated leachate in controlled amounts for irrigation of crops); or by incorporating it into the composting of low-nitrogen wastes (such as leaves). Full-scale application of any of these alternatives may be problematic and seasonally limited, and may require large retention or treatment ponds. In some cases, discharge to a municipal sewage treatment plant may be another option.

## COMPOST BIOREMEDIATION AND P2

Compost bioremediation refers to the use of a biological system of micro-organisms in a mature, cured compost to sequester or break down contaminants in water or soil. Micro-organisms consume contaminants in soils, ground and surface waters, and air. The contaminants are digested, metabolized, and transformed into humus and inert by-products, such as carbon dioxide, water, and salts. Compost bioremediation has proven effective in degrading or altering many types of contaminants, such as chlorinated and nonchlorinated hydrocarbons, wood-preserving chemicals, solvents, heavy metals, pesticides, petroleum products, and explosives. Compost used in bioremediation is referred to as "tailored" or "designed" compost in that it is specially made to treat specific contaminants at specific sites.

The ultimate goal in any remediation project is to return the site to its precontamination condition, which often includes revegetation to stabilize the treated soil. In addition to reducing contaminant levels, compost advances this goal by facilitating plant growth. In this role, compost provides soil conditioning and also provides nutrients to a wide variety of vegetation.

Dr. Rufus Chaney, a senior research agronomist at the U.S. Department of Agriculture, is an expert in the use of compost methods to remediate metal-contaminated sites. In 1979, at a denuded site near the Burle Palmerton zinc smelter facility in Palmerton, Pennsylvania, Dr. Chaney began a remediation project to revitalize 4 square miles of barren soil that had been contaminated with heavy metals. Researchers planted merlin red fescue, a metal-tolerant grass, in lime fertilizer and compost made from a mixture of municipal wastewater treatment sludge and coal fly ash. The remediation effort was successful, and the area now supports a growth of merlin red fescue and Kentucky bluegrass. Chaney has also investigated the use of compost to bioremediate soils contaminated by lead and other heavy metals at both urban and rural sites. In Bowie, Maryland, for example, he found a high percentage of lead in soils adjacent to houses painted with lead-based paint. To determine the effectiveness of compost in reducing the bioavailablility of the lead in these soils, Chaney fed both the contaminated soils and contaminated soils mixed with compost to laboratory rats. Although both compost and soil bound the lead, thereby reducing its bioavailability, the compost-treated soil was more effective than untreated soil. In fact, the rats exhibited no toxic effects from the lead-contaminated soil mixed with compost, although rats fed the untreated soil exhibited some toxic effects. In another study, Dr. Lee Daniels and P.D. Schroeder of Virginia Polytechnic Institute, Blacksburg, Virginia, remediated a barren site contaminated with sand tailings and slimes from a heavy mineral mining plant. The application of yard waste compost revitalized the soil for agricultural use. The compost was applied at the rates of 20 tons per acre for corn production and 120 tons per acre for a peanut crop.

Petroleum hydrocarbon contamination is another application area for composting. Soil at the Seymour Johnson Air Force Base near Goldsboro, North Carolina, is contaminated as a result of frequent jet fuel spills and the excavation of underground oil storage tanks (USTs). Remediation of several sites on the base is an ongoing project since materials are continually loaded or removed from USTs, and jets are continually refueled. The base deals with a variety of petroleum contaminants, including gasoline, kerosene, fuel oil, jet fuel, hydraulic fluid, and motor oil. In 1994, the base implemented a bioremediation process using compost made from yard trimmings and turkey manure. Prior remediation efforts at Seymour involved hauling the contaminated soil to a brick manufacturer where it was incinerated at high temperatures. Compared to the costs of hauling, incinerating, and purchasing clean soil, bioremediation with compost saved the base $133,000 in the first year of operation. Compost bioremediation also has resulted in faster cleanups, since projects are completed in weeks instead of months. The remediation process at Seymour includes spreading compost on a 50- by 200-foot unused asphalt runway, and applying the contaminated soil, then another layer of compost. Workers top off the pile with turkey manure. Fungi in the compost produce a substance that breaks down petroleum hydrocarbons, enabling bacteria in the compost to metabolize them. Cleanup managers determine the ratio of soil to compost to manure, based on soil type, contaminant level, and the characteristics of the contaminants present. A typical ratio consists of 75% contaminated soil, 20% compost, and 5% turkey manure. A mechanical compost turner mixes the layers to keep the piles aerated. After mixing, a vinyl-coated nylon tarp covers the piles to protect them from wind and rain, and to maintain the proper moisture and temperature for optimal microbial growth.

## LAND APPLICATIONS

To determine the safety of compost applied to land the EPA concerns itself with two vectors which might cause pollution:

- **Pathogens**: (EPA503.32/33) - *Salmonella* sp. Shall be less than 3 Most Probable Number per 4 gr of dry solids.
- **Heavy metals**: (EPA503.13, see Table 3)

Table 3. Regulatory Maximums for Compost Parts Per Million, Dry Weight.

| **Heavy metal** | ppm |
|---|---|
| **Cadmium** | <0.3 |
| **Selenium** | 3.5 |
| **Copper** | 110 |
| **Lead** | 50 |
| **Mercury** | <0.05 |
| **Nickel** | 50 |
| **Arsenic** | 1.3 |

## COST CONSIDERATIONS

Green and putrescible wastes make up almost half of urban domestic waste. It is therefore theoretically possible to reduce the volume of solid waste to landfill by 50% through composting alone. The real challenge of composting, however, is to produce an economically sustainable, readily marketable product. Quality rather than quantity is the key requirement.

Composting is the controlled biological decomposition of organic materials and takes place spontaneously when they are brought together in large enough concentrations in the presence of sufficient air and moisture. It is a natural process of decay for plant material. Microorganisms reduce dead plant material to its constituent elements, releasing water vapor and carbon dioxide.

Composting requires the control of several variables, such as source material, particle size, moisture content, temperature, and air supply. Generally speaking, the greater the control and precision of these factors, the faster the process and the better the product.

Composting also has a valuable place as a pretreatment process for putrescible materials destined for landfill. This nil-value end use allows a much simplified landfill process to be employed and reduces the costs of landfilling. But for market-focused composting, the development process must be to research and define market requirement, select the most cost-effective procedures to satisfy it, then source suitable raw materials. Where the raw materials are waste products, issues of source separation, containment levels, and delivery methods may mean that the selected process must accommodate the waste processing issues as well, especially odor and environmental controls.

Composting's place in resource recovery will depend on developing and sustaining viable markets and beneficial uses. A vast range of soil amendment, mulch, compost, and potting-mix products can result from a composting operation, but quality and reliable fitness for use must be the driving factors.

Composting is a waste minimization option for the private gardener, but will it work as a systematic resource recovery option? Many people bake their own bread or brew their own beer, but the domestic technologies used would not be suitable for commercial bakeries or breweries. Commercial composting operations handling organic wastes in various climatic conditions to produce quality assured products require adequate capitalization for appropriate process technologies.

Quality compost products begin by selecting and sourcing the raw materials — preferably with the party taking the marketing risk controlling their selection. Often local communities buy or contract a shredder to reduce green wastes and then have difficulty selling this product. A professional composter, with an eye on the requirements of the market, wants to be able to control the process — and that includes the raw materials. For example, visible contaminants such as glass and plastic can seriously affect the product's sales potential. The only effective solution is to remove all plastic, glass, and other foreign matter before composting begins. The alternative is costly removal of foreign matter from mature compost using expensive and not completely effective machinery. Potential invisible contaminants in compost include weed seeds, insect eggs, pesticide residues, heavy metals, and pathogens which may cause diseases in humans, animals and plants. Feedstock may also be infected with spores, molds, and fungi which may cause health problems if inhaled, or spread disease to other plants.

Fortunately, composting generates enough heat to break down common invisible pollutants and organisms if properly controlled and managed. Organic matter, with the addition of moisture and with access to oxygen, will produce temperatures of 60°C or more at the center of the heap. This is a natural pasteurization process which destroys most weed seeds, common pathogens, and organic pesticides.

The first and most important principle of successful municipal composting should be that compost which is unsaleable should not be produced. High-quality compost can be produced only from high-quality materials. Source separation and control of sources for composting feedstock is important in minimizing contamination.

The first requirement, therefore, is that not all the compostable part of municipal waste should be composted — only raw materials which produce high-quality compost. Compost produced from clean metropolitan green wastes is an extremely beneficial product for many soils, which are generally low in humus.

## WASTE MANAGEMENT THROUGH RESOURCE RECOVERY

The application of recycling, reuse, composting, waste-to-energy or other processes to the recovery of material and energy resources unquestionably provides a substantial alternative supply of raw materials and reduces the dependence on virgin feedstocks. These recovered resources are essentially given another life cycle; however, many recovered materials cannot be readily reused in the identical markets or applications. In order for resource recovery to be effective on a long-term basis, viable markets and alternative uses must be carefully planned to ensure the least waste of resources. Recovered products must meet the fundamentals of market resource security, meaning they should meet the requirements of reliable quality, quantity, and price. This is critical for the end user to make the commitment needed to sustain a reliable market.

Recovering materials from waste streams for recycling, for another use or productive life cycle appears most successful at the industrial level. For example, it is logical for plastic converters to collect scrap and trimmings for immediate regrinding into useful feed material. Similar in-house recycling occurs throughout industry, including metals, paper/cardboard, and glass. But these kinds of practices represent *waste minimization* in the context of clean production. On a broader scale there are business to business and consumer to business interdependencies that have an impact on whether or not the economics of resource recovery makes sense.

To provide the momentum for waste reduction on a large scale, many U.S. states have mandated aggressive solid waste reduction goals in the league of 30 to 50% reductions by the year 2010. However, other parts of the world are even more aggressive. The city of Canberra in Australia has set the goal of zero waste by 2010 (Australian Capital Territory 1996). A zero waste goal challenges businesses, householders, and government planners to abandon the assumption that high levels of wasting is acceptable. This redefinition is opening cost saving and revenue generating opportunities for businesses. Businesses that operate more efficiently are stronger financially and more likely to stay in business. Defining waste out of existence is creating economic development opportunities for communities and entrepreneurs. More efficient and less polluting use of resources benefits the environment while it improves the economy. This chapter explores some of the issues that require consideration in establishing viable markets and managing large-scale resource recovery schemes.

## INDUSTRY VERSUS CONSUMER MARKETS

There are many success stories and examples where a business-to-business relationship flourishes on the reliability of one party's waste being an essential raw material to another. The strength and reliability of these relationships reinforce the fundamental issues for postconsumer recycling efforts. Between the two industrial parties, the quantity, quality and price of the waste/raw materials can be readily assessed and controlled. Security of resource for the user can be satisfactorily provided by the waste generator. Operational strategies can be efficiently designed and implemented for the advantage of both parties. For the supplier, a waste becomes a resource, and for the user, a more cost-effective or alternative raw material supply provides an opportunity or a commercial advantage. Such relationships and forms of recycling essentially focus on waste minimization or a logical extension of the concept of clean production. However, post-consumers pose the challenge of *resource security*, which can have an impact on resistance for recycled products to re-enter a second life-cycle market.

Resistance to wide-scale recycle markets stems from economic concerns. For example, since industry made the product, they should be prepared to take it back. Communities will readily collect any material for which there is a viable market. But it costs money to collect and forward, and hence communities should receive at least this amount as a fair return for their effort in collecting it for generators.

Industry can afford to pay a fair price for the materials because they can always pass on the costs to the consumer. Industry's view of the issues generally are that cheap and reliable sources of raw materials are always welcome. Clearly, the supply must be regular in quantity and quality and at a price that demonstrates an advantage over virgin or more traditional supplies. However, if the combined cost of collecting and sorting materials is more than a market will offer, the whole enterprise should be discontinued, or the collecting and sorting processes need to be made more efficient, or the quality should be tailored to attract a commensurate price.

To ensure optimum use of specialist equipment to process secondary resources, an often-adopted strategy for industry is undercapitalisation. If, say, marketing research showed that about 200,000 tons a year of a particular reclaimed resource was potentially available, a plant could be commissioned with a capacity of 100,000 or 150,000 tons a year. The effect of this strategy is to ensure that the selected plant will always run to capacity on the available supply and that the surplus material will tend to keep the price down and the quality up.

## REVIEWING THE TECHNOLOGY OPTIONS

### Waste-to-Energy by Combustion (WTE)

Incineration of wastes can be considered a landfill pretreatment if volume reduction and detoxification is the primary aim. In the context of resource recovery, waste-to-energy involves the addition of power generation equipment to combustion for the recovery of process heat. The main products of incineration are carbon dioxide, water, ash residue, and heat energy. Unfortunately, by-products having environmental importance are also generated, such as sulfur, nitrogen, and chlorinated compounds including dioxins and some heavy metal compounds of lead, mercury, and cadmium.

Combustion equipment must be designed around the *Three T's* of combustion: time, temperature, and turbulence in the presence of oxygen. Systems without these factors in their design usually experience operating and maintenance problems as well as posing environmental hazards. The better a system is at controlling these factors, the lower the environmental impact. Time is usually accounted for by the volume allowed for the combustion chamber. It must be large enough to retain the gas flow for sufficient time to allow complete combustion of the fuel and volatile gases. Temperature is a critical consideration. Organic matter usually oxidizes at a relatively low temperature (600° to 700°C) and usually has enough calorific value for combustion. A few refractory organics need a much higher temperature to achieve full decomposition. Other organic wastes have such a high moisture content that they require a subsidiary fuel for combustion. These moist green wastes are probably more valuable as composts. The higher the temperature, the greater the assurance of complete combustion — and the higher the maintenance and running costs of a facility and often the lower the reliability. For other than the extremes of organic matter, temperatures between 850°C and 950°C are enough for the safe and efficient combustion of organics. Turbulence of the gas flows is necessary to promote mixing of the hot products of combustion and the oxidizing substance, air. Turbulence can be achieved by duct design or by the injection of a substance into the hot gas flow. The conversion of water to steam in a hot gas flow creates good turbulent flow conditions.

Industrial incinerators are integrated systems of raw waste handling and storage equipment, combustion chambers, energy and by-product recovery operations, exhaust-gas cleaning facilities, and effluent and solids discharge control devices.

## Refuse-Derived Fuels

The concept of treating waste products to obtain a cheap, transportable and storable fuel has been around for several decades. In most countries, the quantity of waste products increases during spring, summer, and autumn and reaches a low point in winter. Researchers have always aimed to transform or treat these wastes so they could be stored, transported, and used as a fuel during winter. Waste-to-energy plants often supply district heat in Europe and demand is highest in winter when the availability of normal waste fuel is at its lowest point.

It is technically possible to transform normal waste into pellets or briquettes with increased calorific value and greater bulk density for transport. Refuse-derived fuels (RDF) can be used by themselves but more often they are mixed with another solid fuel such as coal in steam or hot-water generating plants. One form of RDF being used comes from the increase in the number of material recovery facilities (MRFs). One stream from these facilities normally contains contaminated dry combustible matter, an ideal fuel for waste-to-energy plants.

Some industries which incorporate fuel-burning equipment can be used for niche burning. The displacement of normal fuel by RDF is a true waste-to-energy application. Blast furnaces, hot-melt cupolas, and cement kilns are some of the industrial plants using waste fuel. Industry will usually use an alternative fuel only when it is offered at a price premium to compensate for inconvenience. Contaminated petroleum products and plastics are used as fuel in cement kilns only when the price of waste disposal is high and the cost of normal fuel is appreciable.

The choice of adopting waste-to-energy rather than landfill disposal is seldom based only on energy or landfill costs. Even if landfill operators in one region were forced to adopt more stringent standards that exist elsewhere, landfill would still be cheaper than incineration unless landfill costs included a large transport component. It is often cheaper to carry waste over 200 to 400 km to a landfill than to burn it in most of the world.

A combination of factors is leading many entities to adopt waste-to-energy plants:

- Consistent production or availability of a waste product
- Consistent need for high-grade and low-grade energy
- A desire to maintain control over waste products
- A desire to minimize the environmental impacts of a waste product

Modern plants pose little danger of adverse health effects to their neighborhood. The evidence is that the emissions from a well-operated incineration plant complying with the stringent air quality standards are most unlikely to cause any health effects. However, environmental impacts of incineration plants should go beyond health considerations. Other factors include:

- Visual intrusion
- Odor and noise
- Vehicle movement
- Socioeconomic effects

Parts of the waste stream can have potential energy recovered only before or after a period of landfill. Where a reliable end user of the energy is available, the recovery of energy by combustion must be a legitimate option. Much opposition to combustion comes from the potential of waste-to-energy plants to mindlessly consume materials that should have been recycled, reused, composted or put to some higher value use. This view has the potential to deny the valuable role of incineration to recover energy that might otherwise be lost.

### Biofermentation

Biofermentation is the in-vessel fermentation of the organic parts of waste streams to produce methane (for power generation) and simultaneously stabilize putrescible wastes. This process is receiving renewed interest as a method of pretreating and stabilizing putrescible or organic wastes to recover methane. The residues can then be aerobically composted. The energy recovered is hoped to be enough to run the overall plant. As a volume-reduction technique, only about 7 to 10% of the material in the waste stream will be affected by biodegradation without a prior hydrolysis process to convert the ligno-cellulosic material into fermentable sugars.

### Hydrolysis

Hydrolysis converts the cellulose content of ligno-cellulosic wastes (paper and wood) into fermentable sugars so that methane or ethanol can be produced as alternative fuels. The traditional method is for a high temperature and pressure process, in the presence of acid, to break down the cellulose materials. More recently, enzyme hydrolysis (which is basically the industrialization of the natural processes of degradation from the forest floor) and steam explosion hydrolysis have been receiving significant development interest. However, all hydrolysis processes are sensitive to continuity of feedstock in quality and quantity, which make them unsuitable for mixed wastes and more suitable for agricultural residues such as sawdust, straw, or specially grown crops.

### Pyrolysis

Pyrolysis is the process of heating waste materials in the absence of oxygen to produce volatile gases, fuel oils and inert charred residues. It is sensitive to reliability and quality of feedstock if valuable products are to be produced.

## INTEGRATED RESOURCE RECOVERY

One approach that is being considered as a model for large-scale resource recovery and reuse on an economical scale is based on the concept of an eco-industrial park (EIP). This is a community of manufacturing and service businesses seeking enhanced environmental and economic performance through collaboration in managing environmental and resource issues including energy, water, and materials. By working together, the community of businesses seeks a collective benefit that is greater than the sum of the individual benefits each company would realize if it optimized its individual performance only. The goal of an EIP is to improve the economic performance of the participating companies while minimizing their environmental impact. Components of this approach include new or retrofitted design of park infrastructure and plants; pollution prevention; energy efficiency; and inter-company partnering.

Figure 16 illustrates the basic scheme for an integrated resource recovery system as a whole, with all community sources feeding discards into an eco-industrial park anchored by a resource recovery facility. Finance, communications, education, and government agencies support the development of the system. Within the manufacturing sector an industrial ecosystem generates by-product flows between plants as well as into the resource recovery facility and eco-park. The collection and aggregation of smaller quantities of by-products not useful in plant-to-plant flows enables a higher level of overall recovery.

The resource recovery facility itself includes dropoff, sorting, and sales operations which serve collectors, community members, and industries. It can operate at both wholesale and retail levels in both intake and sales functions. The eco-industrial park includes processors of discards, manufacturers, and crafts people using the outputs of processors, and other environmental businesses. Service businesses in the EIP can serve clients in the community as well as firms in the park.

A resource-recovery-focused industry includes reuse, recycling, remanufacturing and composting, as well as the marketing and end use of reclaimed discarded materials. As a vertical industry it involves a wide range of business activities including collection, sorting, and processing of industrial and biological materials; repair, refurbishing, or dismantling of equipment; and wholesale or retail sales. The unifying concept is that discarded materials, goods, and by-products are turned into salable materials and products. Businesses and communities benefit through a reduction in disposal costs, creating new revenues, and by opening new sources of materials and goods. The environment benefits from reduction in demands on limited natural, virgin resources and on the capacity of the environment to accommodate solid waste and pollution.

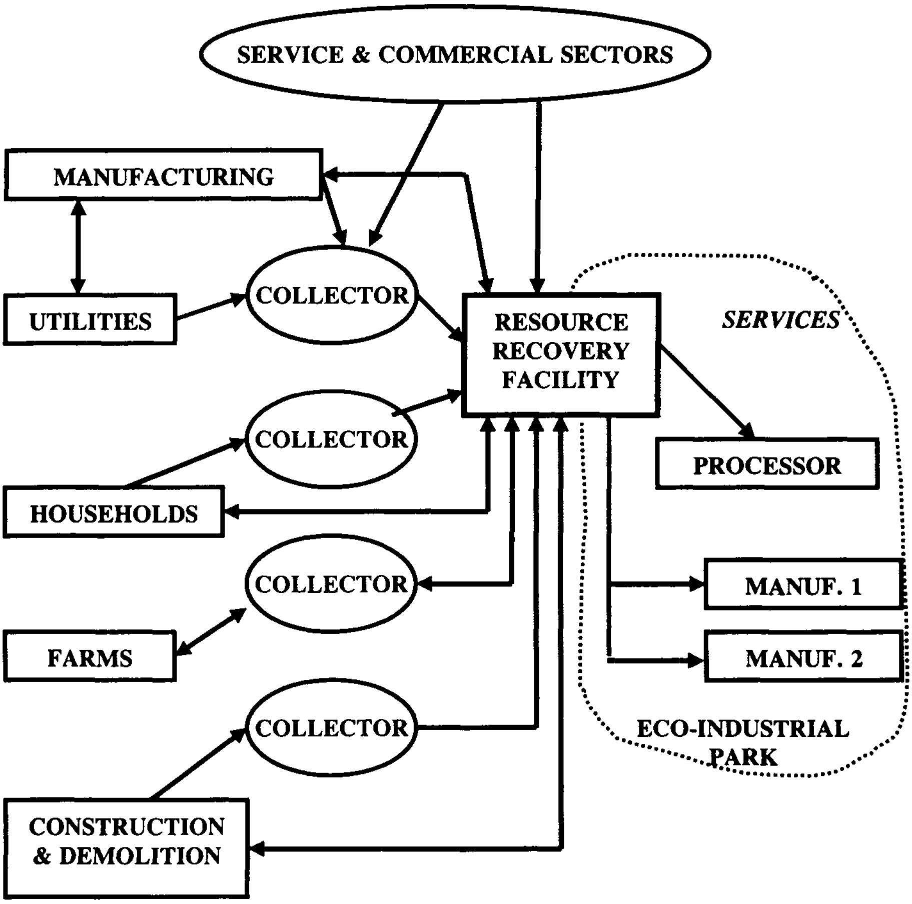


Figure 16. Conceptualized view of an eco-industrial park.

An investment recovery company could be a valuable coordinator of the logistics of materials acquisition, movement, and recycling/reuse by the diverse network of companies involved. It could also manage the resource recovery facility that serves as the entry point for discard resources in the EIP.

The major streams of materials and goods coming through resource recovery companies (and direct connections with other industrial sources in the region) would define the initial set of companies to recruit or develop for the EIP. These would include: manufacturers using recycled feedstocks; remanufacturers of capital or consumer equipment; companies with major supply requirements that could be filled by the outputs of other tenants or plants in the area; and users of reclaimed materials and energy by-products or agriculture and aquaculture firms if there is by-product energy or water available to the site.

Another group of prospective tenants would be those with a broader environmental mission, including manufacturers of renewable energy and energy efficiency equipment; companies pioneering the use of bio-materials; firms providing services and products for sustainable agriculture industry; and industrial ecology and other environmental consultants.

An eco-industrial park offers a combination of economic development and environmental benefits. The resource recovery foundation for an EIP increases the local economic value of these returns, which include:

- Expansion of existing firms and creation of new local businesses
- Job development at a broad range of skill levels and with a good pay range
- Utilization of industrial energy and materials by-products now wasted
- Recovery of economic value of many materials and products households now send as solid waste to landfills
- Utilization of restaurant, agricultural and food processing discards
- An attractive, ecologically designed and landscaped industrial complex
- High environmental standards for the park tenants and the park management

## A SHORT REVIEW

The composition of MSW is broad and contains both organic and inorganic components. Some portion of MSW may be considered hazardous and pose potential threats to public health. Waste management strategies that have proven to be cost effective in industrial settings heavily favor prevention technologies. However, the identical approaches at the municipal level have not always proven effective. On the hierarchy of waste management practices, resource recovery and recycling and waste-to-energy are more readily adaptable to MSW management. The selection of specific technologies that are relied upon in many cases for several decades depends on the technical feasibility of the options considered in relationship to local waste profiles, and requires the application of life-cycle costing tools to evaluate the risks of investments.

Electricity can be produced by burning MSW as a fuel. MSW power plants, also called waste-to-energy (WTE) plants, are designed to dispose of MSW and to produce electricity as a by-product of the incinerator operation. The term MSW describes the stream of solid waste generated by households and apartments, commercial establishments, industries, and institutions. MSW consists of everyday items such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, and batteries. It does not include medical, commercial, and industrial hazardous or radioactive wastes, which must be treated separately.

MSW is managed by a combination of disposal in landfill sites, recycling, and incineration. MSW incinerators often produce electricity in WTE plants. EPA estimates that in 1998 17% of the nation's MSW was burned and generated electricity, 55% was disposed in landfills, and 28% was recovered for reuse. In the United States there are currently two main WTE facility designs. Mass Burn is the most common waste-to-energy technology, in which MSW is combusted directly in much the same way as fossil fuels are used in other direct combustion technologies. Burning MSW converts water to steam to drive a turbine connected to an electricity generator.

There are several types of mass-burn combustion systems. They include refractory, modular, and waterwall furnaces. Waterwall technology is the most widely used and is similar to the furnaces used at coal-burning power plants. In all three systems, untreated MSW is incinerated and the heat that is recovered is converted to steam. The steam can then be passed through a turbine to generate electricity and low-temperature heat suitable for space heating. The technology for producing electricity from high temperature steam and usable heat as a by-product is called *cogeneration* or *combined heat and power* (CHP). The application of this technology results in more efficient use of fuel. Incineration of MSW generally results in a volume reduction of between 80 and 90%, which therefore achieves the environmental benefit of reducing landfill space requirements.

Refuse-derived fuel (RDF) facilities process the MSW prior to direct combustion. The level of precombustion processing varies among facilities, but generally involves shredding of the MSW and removal of metals and other bulky items. The shredded MSW is then used as fuel in the same manner as at mass-burn plants.

Facilities that handle more than 100 tons per day use a continuous feed arrangement. An overhead crane moves the refuse into the furnace. The furnace walls are composed of water-filled tubes, called waterwalls; they absorb heat released during combustion and create steam. A refuse stoker moves and agitates the waste, allowing it to burn thoroughly. Air is forced in above and below the stoker to cool the stoker and provide oxygen. Combustion gases rise from the fuel bed into the upper furnace and flow through the boiler and superheater sections to produce steam. A variation of the mass-fired unit has a furnace without waterwalls. The heat is transferred through a waste heat boiler where the energy is absorbed to create steam. Another mass-burning unit is the rotary kiln, a large steel cylinder supported by rollers. The kiln is sloped and revolves several times a minute. The rotating motion helps to remove moisture from the refuse before it is burned. This process is suitable for wastewater sludge and refuse with a high moisture content.

The advantages of mass-fired waterwall systems are that no processing of waste is required, other than removing large objects to prevent jams. Waterwall systems can handle up to 1000 tons per day and have been used for more than 30 years in Europe, Japan and the United States. The disadvantages are that precise control of the combustion process can be difficult. Refuse glass and clay may cause excessive slagging when melted.

RDF preparation separates different waste into combustible and noncombustible materials. Once separated, the more homogenous combustibles can be burned in a furnace dedicated to the fuel or co-fired with coal or another fuel. RDF preparation separates recyclable secondary materials. Materials such as glass and metals can be sold. Fuel prepared from refuse can be formed into cubes; briquettes, or cylinders called densified RDF (dRDF). This fuel can then be used in more traditional furnaces. Processing RDF into dRDF creates a fuel that is more easily transported and handled. dRDF, being closer in physical and combustional characteristics to coal, can be burned with or instead of coal. Biomass RDF has been successfully applied in parts of Europe with several unique designs.

Reverse-burn gasification is a method of incineration that emits a combustible exhaust gas that can be burned rather than treated. In reverse-burn gasification, wastes are destroyed by conversion to a combustible gas and a dry, inert carbonaceous solid. The process produces nonhazardous water and inorganic salts as by-products. The process has been successful in laboratory-scale operation, although the long-term efficient use of this system is in question.

Burning MSW can generate energy while reducing the volume of waste by up to 90%, which is a major environmental benefit. Ash disposal and the air-polluting emissions from plant combustion operations are the primary environmental impact control issues. MSW contains a diverse mix of waste materials; some are benign, but a portion are highly toxic. Effective environmental management of MSW plants aims to exclude toxics from the MSW-fuel and to control air pollution emissions from the WTE plants. Toxic materials include trace metals such as lead, cadmium and mercury, and trace organics, such as dioxins and furans. Such toxics pose an environmental problem if they are released into the air with plant emissions or if they are dispersed in the soil and allowed to migrate into ground water supplies and work their way into the food chain. The control of such toxics and air pollution are key features of environmental regulations governing MSW fueled electric generation. Burning MSW in WTE plants produces comparatively high carbon dioxide emissions, a contributor to global climate change. The net climate-change impact of these emissions is lessened because a major component of trash is wood, paper, and food wastes that would decompose if not burned. If left to decompose in a solid waste landfill, the material produces methane, which is a major greenhouse gas. Also, WTE plants generate comparatively high rates of nitrogen oxide emissions. The on-site land use impacts are generally equal to those of coal- or oil-fueled plants.

Composting is a form of recycling and is the only technique discussed that may be viewed as approaching P2. The benefits of using compost include:

- Soil enrichment
    - Adds organic bulk and humus to regenerate poor soils
    - Helps suppress plant diseases and pests
    - Increases soil nutrient content and water retention in both clay and sandy soils
    - Restores soil structure after reduction of natural soil microbes by chemical fertilizer
    - Reduces or eliminates the need for fertilizer
    - Combats specific soil, water, and air problems

- Pollution remediation
    - Absorbs odors and degrades volatile organic compounds
    - Binds heavy metals and prevents them from migrating to water resources or being absorbed by plants
    - Degrades, and in some cases, completely eliminates wood preservatives, petroleum products, pesticides, and both chlorinated and nonchlorinated hydrocarbons in contaminated soils

- Pollution prevention
    - Avoids methane production and leachate formation in landfills by diverting organics for composting
    - Prevents pollutants in stormwater runoff from reaching water resources

  - Prevents erosion and silting on embankments parallel to creeks, lakes, and rivers
  - Prevents erosion and turf loss on roadsides, hillsides, playing fields, and golf courses

- Economic benefits
  - Results in significant cost savings by reducing the need for water, fertilizers, and pesticides
  - Produces a marketable commodity and a low-cost alternative to standard landfill cover and artificial soil amendments
  - Extends municipal landfill life by diverting organic materials from the waste stream
  - Provides a less costly alternative to conventional bioremediation techniques

Within the resource recovery area a range of technologies are available to complete the recycling loop or add value to reprocessed materials, but a key factor in every case is that the viability of any process or option should be determined by deducting recovery and processing costs from the market price. If this process is subsidized for political purposes to ensure its viability, it is effectively consuming a greater value of production cost than it is generating. This is wasteful in economic and environmental terms.

Because of the *undercapitalization* requirement for major investment in certain recycling capacity, it is essential that a range of markets be encouraged. Such markets would have trickle-down values such that lesser grades of material would go to less sensitive uses. The current position in glass and PET is therefore unstable as the market for both commodities is far too centralized and the lack of alternatives could be a major impediment.

Avoided landfill credits may provide additional income; however, resource recovery is generally constrained less by low landfill gate fees, than by the resource security requirements of any investor to develop the process, infrastructure, and markets for the available materials.

With local communities driven by demand for recycling, a predictable (and perhaps avoidable) imbalance exists between supply and demand for recovered resources. This inefficiency is manifesting itself as a cost to the community and industry which is much higher than it need be.

The most powerful motivation for the general public to recycle is considered to be the ability to make a personal contribution to the quality of the environment. Social pressure to conform is also a strong influence. Materials are recovered from the municipal waste streams for recycling more because they are obvious or easy to isolate than because there is sustained demand for them as essential raw materials. Most plastics, papers, cardboards, metals or glasses are technically recyclable, but few qualify on economic grounds because the combined costs of collection, sorting, transporting, cleaning and reformulating are greater than those of virgin extraction, especially to achieve a comparable quality and usefulness.

This highlights one of the major challenges of waste management/resource recovery: to focus on the development of universal strategies and infrastructure for the collection, sorting, transport, and beneficiation of materials designed for reuse/recycling. Then there will be fewer economic constraints on the technical potential for widespread recycling.

The greatest recycling challenge facing solid waste infrastructure is not in the process of collecting, separating, and supplying resources recovered from the waste stream, but in doing so at a competitive cost, and in marketing the materials at a price, quality, and quantity competitive with virgin materials. Simply collecting obvious materials and hoping someone will pay enough to produce a profit is not recycling. Like any other business venture, it must be carefully planned with the application of life-cycle costing tools.

Several references that provide more in-depth information are provided at the end of this chapter.

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# Chapter 4

# LANDFILL OPERATIONS AND GAS ENERGY RECOVERY

## INTRODUCTION

Throughout Europe and the United States, there is a strong reliance on disposing of waste in landfills. Furthermore, in many developing countries, conditions for waste disposal are still rudimentary. In 1997, for instance, 99% (around 90,000 tons per day) of Brazil's collected waste was being landfilled or simply dumped. Each person in the United Staes generates about 4.5 pounds of waste per day, which is nearly 1 ton per year. Again, most of this waste is deposited in municipal solid waste (MSW) landfills. As MSW decomposes, it produces a blend of several gases, including methane (about 50%).

Landfilling is the oldest and most widely practiced waste disposal option. Modern landfill sites have developed from uncontrolled dumping sites to be an advanced treatment and disposal option designed and managed as engineering projects. In addition, modern purpose-built landfill sites normally incorporate a system for the extraction of landfill gas (arising from the decomposition of bioreactive wastes), from which energy can be recovered. The types of wastes suitable for landfilling include biodegradable wastes, aqueous liquids in limited amounts, inert wastes, and certain special wastes that would not pose toxic threats. Wastes that are generally considered unsuitable for landfilling include volatile liquids or solvents, wastes that would introduce unacceptable contamination into the leachate, and wastes that would interfere with the biological processes in a landfill site.

The advantages of landfilling as a waste disposal option include:

- It costs less than other disposal options
- A wide variety of wastes are suitable for landfill
- It frequently offers the only final disposal route for residues arising from end-of-pipe treatment technologies and other waste management options, such as incineration
- Landfill gas can be collected and utilized for heat and as a low-polluting fuel for energy generation

- Restored land can provide valuable space for wildlife habitat or leisure use

The disadvantages of landfilling include:

- Older sites, constructed before the impacts of leachate and landfill gas were realized, are now sources of pollution with uncontrolled leakages
- There is continued risk of contamination from operational landfill sites
- Some parts of the world are experiencing shortages of suitable landfill sites close to the source of waste generation
- Landfilling achieves a lower conversion of wastes into energy than other solid waste management strategies
- The convenience of landfilling tends to discourage the development of innovative waste management strategies
- Landfilling may produce contaminated land that is unsuitable for some future uses
- Landfilling causes noise pollution, odors, unsightliness, and often heavy vehicle movement adding to air pollution problems

Anaerobic decomposition of organic solid waste in the landfill environment produces landfill gas (LFG). LFG mainly consists of methane and carbon dioxide, both of which are odorless. Trace constituents of other volatiles, often malodorous or toxic gases, are also found in LFG. LFG can migrate through soil into structures located on or near landfills. Since methane presents a fire or explosive threat, LFG must be controlled to protect property, and public health and safety. Also, many jurisdictions require landfill owners/operators to reduce reactive organic gas emissions to improve regional air quality. Thus, engineered solutions are needed to efficiently and safely monitor, collect, and process landfill gas. As noted, a positive side to LFG control is energy recovery. Today's technology allows a landfill owner/operator to recovery the energy in LFG while reducing gas emissions. Revenue from the sale of LFG or electricity generated using LFG as a fuel can offset costs for landfill environmental compliance and/or closure.

This chapter provides an overview of sanitary landfill operations and utilizing landfill gas as a means of energy. The practice has been successfully applied to small-scale operations that generate heat and electricity for on-site use, to relatively large operations that can sell the energy into an off-site grid, thereby offsetting investment and OM&R costs.

## REGULATORY CONSIDERATIONS

The Resource Conservation and Recovery Act (RCRA) establishes landfill design and performance standards under Subtitle D. Subtitle D requires monitoring of landfill gas and establishes performance standards for combustible gas migration control. Landfill owners/operators must:

- Establish LFG monitoring programs. Use of gas monitoring probes is typical.
- Monitor for subsurface migration of combustible gas on a quarterly basis.
- Maintain combustible gas concentrations under 5% in soil at the property line, and under 1.25% in facility structures.
- Mitigate gas hazards if conditions are not in compliance.

The U.S. EPA has proposed control of surface LFG emissions under the Clean Air Act. The New Source Performance Standards (NSPS) will require LFG testing and collection system installations at many sites, even those otherwise in compliance with RCRA Subtitle D. NSPS will require landfill owners/operators to:

- Estimate total LFG emissions using sophisticated gas models, laboratory analyses, and gas pump tests.
- Install comprehensive gas collection systems throughout the landfill at any site shown to have high emissions of non-methane organic compounds.
- Perform long-term operation and recordkeeping on such landfill gas systems.

Other federal agencies also have standards that may affect siting, such as Federal Aviation Administration (FAA) regulations intended to minimize bird hazards to aircraft.

Subtitle D regulations also establish national minimum standards for landfills that receive household waste. These national minimum standards are incorporated into each state's landfill permitting standards. However, states also may impose more restrictive criteria. Under RCRA, the U.S. Environmental Protection Agency (EPA), Washington, D.C., regulates solid waste landfilling with regard to:

- Groundwater quality protection
- Landfill gas controls

- Air pollution control
- Basic operating procedures
- Safety issues
- Flood plains
- Seismic and slope stability
- Disturbance of endangered species
- Surface water discharges
- Site closure and long-term care
- Closure and long-term care financial assistance

State regulations vary widely. Nevertheless, most states require a regulatory body to approve landfill engineering plans. State regulations often specifically address geologic or other factors unique to a region. In addition, state and local governments also regulate other landfill-related issues. These include conditional use zoning, highway issues (heavy loads and traffic), water discharge/water quality control, mining regulations (excavations), building permits, fugitive dust and emissions controls, and closure permits.

All applicable regulations should be considered when planning a landfill. Government standards generally can be classified into engineering design standards and performance standards. Engineering design standards are similar to building codes, which describe how a facility must be built. For example, a new landfill may be required to have a 6-foot-high fence surrounding the facility.

Design standards are prescriptive and don't offer much flexibility. In contrast, performance standards are applicable over a facility's life and require a certain level of environmental control. For example, the state agency regulating groundwater quality may specify the maximum allowable contaminant concentration that may be present in the groundwater below or adjacent to the site. Site operators must incorporate the necessary control systems to comply with the groundwater standard. Performance standards allow for some design flexibility provided the standard is met.

Despite the pervasiveness of federal, state, and local landfill regulations, these criteria are legally viewed as minimum performance requirements. Therefore, even if all the applicable regulations have been followed, if a problem arises, the landfill developer still may be liable for the legal consequences. Claiming compliance with regulatory standards has not been an effective defense against pollution damage claims. To increase public acceptance and reduce long-term risk, many landfill developers now design facilities that exceed regulatory requirements in some key aspects.

Since October 1979, federal regulations promulgated under Subtitle D of RCRA, which regulates the siting, design, construction, operation, monitoring, and closure of MSW landfills, have required controls on migration of methane in landfill gas. These regulations do not address other components of landfill gas. In 1991, EPA issued standards for landfill design and performance that apply to MSW landfills active on or after October 9, 1993. The standards require methane monitoring and establish performance standards for methane migration control. Monitoring requirements must be met at landfills not only during their operation, but also for a period of 30 years after closure. Landfills affected by RCRA Subtitle D are required to control gas by establishing a program to periodically check for methane emissions and prevent off-site migration. Landfill owners and operators must ensure that the concentration of methane gas does not exceed:

- 25% of the EL (explosion limit) for methane in the facilities' structures (1.25% by volume)
- The LEL (lower explosion limit) for methane at the facility boundary (5% by volume)

Permitted limits on methane levels reflect the fact that methane is explosive within the range of 5% to 15% concentration in air. If methane emissions exceed the permitted limits, corrective action (i.e., installation of a landfill gas collection system) must be taken. The Subtitle D RCRA regulations for MSW landfills can be found in 40 CFR Part 258.

Under NSPS/EG of the CAA, EPA requires affected landfills to collect and control landfill gas. The NSPS/EG target reductions in the emissions of landfill gas due to odor, possible health effects, and safety concerns. The rules use NMOCs (which contribute to local smog formation) as a surrogate for total landfill gas to determine if control is required. Landfills meeting certain design capacity and emissions criteria are required to collect landfill gas and either flare it or use it for energy. Landfills that meet both of the following criteria must collect and control landfill gas emissions.

- Capacity: design capacity greater than or equal to 2.5 Mg and 2.5 million cubic meters.
- Emissions: annual NMOC emission rate greater than or equal to 50 Mg.

The basic requirements are the same for both existing and new landfills. Existing landfills are defined as landfills that received waste after November 8, 1987, and began construction before May 30, 1991. These are regulated through the EG. New landfills are defined as landfills that began construction, reconstruction, or modification on or after May 30, 1991. These are subject to the NSPS. The CAA regulations (NSPS/EG) for MSW landfills can be found in 40 CFR Part 60, Subparts Cc and WWW. State plans and a federal plan to implement the EG for existing landfills can be found in 40 CFR Part 62.

## THE COMPOSITION OF LANDFILL GAS

Landfill gas is usually referred to as natural gas or methane; however there are notable distinctions among these three terms. In addition, an often-used term *landfill methane* is deceiving as it implies that landfill gas is simply methane. Methane is a hydrocarbon gas whose chemical formula is $CH_4$. It is a greenhouse gas and it is explosive. It is generated by the decomposition of organic matter. Natural gas is approximately 80 to 99% methane, with the remainder being mostly other hydrocarbons (ethane, propane, butane, etc.) as well as some nitrogen, oxygen, water, $CO_2$, sulfur, and various contaminants.

Table 1. Composition of Landfill Gas

| **Constituent Gas** | **Concentration in LFG** | |
|---|---|---|
| | **Range** | **Average** |
| Methane ($CH_4$) | 35 to 60% | 50% |
| Carbon dioxide ($CO_2$) | 35 to 55% | 45% |
| Nitrogen ($N_2$) | 0 to 20% | 5% |
| Oxygen ($O_2$) | 0 to 2.5% | $<1\%$ |
| Hydrogen sulfide ($H_2S$) | 1 to 1,700 ppmv | 21 ppmv |
| Halides | NA | 132 ppmv |
| Water vapor ($H_2O$) | 1 to 10% | NA |
| Nonmethane organic compounds (NMOCs) | 237 to 14,294 ppmv | 2,700 ppmv |

NA, Not available; ppmv, parts per million by volume.

Note: Highest values occur in perimeter wells.

Sources: G.J. Sandelli, *Demonstration of Fuel Cells to Recover Energy from Landfill Gas. Phase I Final Report: Conceptual Study,* EPA-600-R-92-007, prepared for the U.S. Environmental Protection Agency by International Fuel Cells Corporation (Washington, D.C., January 1992); M. Doorn, J. Pacey, and D. Augenstein, *Landfill Gas Energy Utilization Experience: Discussion of Technical and Non-Technical Issues, Solutions, and Trends*, EPA-600/R-95-035, prepared for the Air and Energy Engineering Research Laboratory, USEPA by E.H. Pechan and Associates, Inc. (Washington, D.C., March 1995).

Table 1 provides a typical compositional breakdown of landfill gas. Landfill gas is approximately 50% methane. The remainder of landfill gas is mostly carbon dioxide with varying amounts of nitrogen, oxygen and assorted contaminants known as *nonmethane organic compounds* or NMOCs. NMOCs usually make up less than 1% of landfill gas. Many of these are toxic chemicals, such as benzene, toluene, chloroform, vinyl chloride, carbon tetrachloride, and 1,1,1 trichloroethane. At least 41 of these are halogenated compounds. Many others are nonhalogenated toxic chemicals. When halogenated chemicals (chemicals containing halogens - typically chlorine, fluorine, or bromine) are combusted in the presence of hydrocarbons, they can recombine into highly toxic compounds such as dioxins and furans, which are extremely toxic and pose long-term health risks even from low levels of exposure. Burning at high temperatures does not eradicate or minimize the problem as dioxins are formed at low temperatures and can be formed as the gases are cooling down after the combustion process.

Bacteria decompose landfill waste in four phases. The composition of the gas produced changes with each of the four phases of decomposition. Landfills often accept waste over a 20- to 30-year period, so waste in a landfill may be undergoing several phases of decomposition at once. This means that older waste in one area might be in a different phase of decomposition than more recently buried waste in another area. During the first phase of decomposition, aerobic bacteria — bacteria that live only in the presence of oxygen — consume oxygen while breaking down the long molecular chains of complex carbohydrates, proteins, and lipids that make up organic waste. The primary by-product of this process is carbon dioxide. Nitrogen content is high at the beginning of this phase, but declines as the landfill moves through the four phases. Phase I continues until available oxygen is depleted. Phase I decomposition can last for days or months, depending on how much oxygen is present when the waste is disposed of in the landfill. Oxygen levels will vary according to factors such as how loose or compressed the waste was when it was buried.

Phase II decomposition starts after the oxygen in the landfill has been used up. Using an anaerobic process (a process that does not require oxygen), bacteria convert compounds created by aerobic bacteria into acetic, lactic, and formic acids and alcohols such as methanol and ethanol. The landfill becomes highly acidic. As the acids mix with the moisture present in the landfill, they cause certain nutrients to dissolve, making nitrogen and phosphorus available to the increasingly diverse species of bacteria in the landfill. The gaseous byproducts of these processes are carbon dioxide and hydrogen. If the landfill is disturbed or if oxygen is somehow introduced into the landfill, microbial processes will return to Phase I.

Phase III decomposition starts when certain kinds of anaerobic bacteria consume the organic acids produced in Phase II and form acetate, an organic acid. This process causes the landfill to become a more neutral environment in which methane-producing bacteria begin to establish themselves. Methane-and acid-producing bacteria have a symbiotic, or mutually beneficial, relationship. Acid-producing bacteria create compounds for the methanogenic bacteria to consume. Methanogenic bacteria consume the carbon dioxide and acetate, too much of which would be toxic to the acid-producing bacteria.

Phase IV decomposition begins when both the composition and production rates of landfill gas remain relatively constant. Phase IV landfill gas usually contains approximately 45% to 60% methane by volume, 40% to 60% carbon dioxide, and 2% to 9% other gases, such as sulfides. Gas is produced at a stable rate in Phase IV, typically for about 20 years; however, gas will continue to be emitted for 50 or more years after the waste is placed in the landfill. Gas production might last longer, for example, if greater amounts of organics are present in the waste, such as at a landfill receiving higher than average amounts of domestic animal waste.

The rate and volume of landfill gas produced at a specific site depend on the characteristics of the waste (e.g., composition and age of the refuse) and a number of environmental factors (e.g., the presence of oxygen in the landfill, moisture content, and temperature). The more organic waste present in a landfill, the more landfill gas (e.g., carbon dioxide, methane, nitrogen, and hydrogen sulfide) is produced by the bacteria during decomposition. The more chemicals disposed of in the landfill, the more likely NMOCs and other gases will be produced either through volatilization or chemical reactions. Generally, more recently buried waste (i.e., waste buried less than 10 years) produces more landfill gas through bacterial decomposition, volatilization, and chemical reactions than does older waste (buried more than 10 years). Peak gas production usually occurs from 5 to 7 years after the waste is buried. Methane will be produced only when oxygen is no longer present in the landfill. The presence of moisture (unsaturated conditions) in a landfill increases gas production because it encourages bacterial decomposition. Moisture may also promote chemical reactions that produce gases. As the landfill's temperature rises, bacterial activity increases, resulting in increased gas production. Increased temperature may also increase rates of volatilization and chemical reactions. The box on the following page provides more detailed information about how these variables affect the rate and volume of landfill gas production.

## LANDFILL DESIGN CONSIDERATIONS

Landfill design is communicated to regulatory officials through several documents. The landfill design package should include plans, specifications, a design report, and an operator's manual -- all of which are submitted to regulatory agencies. A general cost estimate also should be developed, even though it may be a rough estimate.

Plans and specifications typically include:

- A base map showing existing site conditions with contour intervals of 1 foot to 5 feet, and a scale of 1 inch equal to 50 feet to 1 inch equal to 200 feet
- A site preparation plan designing fill and stockpile areas, and site facilities
- A development plan showing initial excavated and final completed contours in filling areas
- Construction details illustrating site facilities
- Cross sections illustrating phased development of the landfill at several interim points
- A completed site plan including final site landscaping and other improvements

Additionally, a design report typically includes four major sections:

1. A site description, which includes existing site size, topography, slopes, surface water, utilities, roads, structures, land use, soil, groundwater, exploration data, bedrock and climatological information
2. Design criteria, which include solid waste types, volumes, and fill-area dimensions, and all calculations
3. Operational procedures, which include site preparations, solid waste unloading, handling and covering, as well as equipment and personnel requirements
4. Environmental safeguards, including the control of leachate, surface water, gas, blowing paper, odor and vectors

Waste characteristics are also critical to the design and operation of the gas recovery system of the landfill. These will provide important design information for determining operating procedures. Waste type affects the handling techniques, and waste quantity determines site lifetime, daily operating procedures, and cover requirements. A waste characterization study should precede landfill siting work, but additional information may be needed while the facility is being designed. For example, certain waste types may be used as daily cover or on-site road base. When preparing a profile of the wastes that will be received at the new landfill, pay attention to sources that may be unknowingly mixing hazardous waste with solid waste. In suspicious cases, hazardous waste testing procedures may be necessary. Systematic load checking during site operation also should be planned. The types and number of vehicles that transport solid waste to the site should be tabulated, too. Traffic information will be useful for later analysis of roadways and access points.

The design basis is a tabulation of the general performance requirements that the facility must satisfy to achieve project goals. It includes the facility's capacity, waste flow rates, traffic counts and principal environmental controls. Tabulating the design basis in this manner communicates to the project design team and others, such as regulatory review specialists, about the nature and size of the proposed landfill. The design basis may require revisions if unforeseen circumstances cause significant changes in the landfill plan.

## SITE LAYOUT CONSIDERATIONS

The landfill's layout will be strongly influenced by the site's geology. The potential for gas and leachate migration and the suitability of the soil for landfill base and cover material should be a particular concern. The site layout begins with geotechnical information, which includes data on the surrounding site geology, hydrology, and soils. These data usually are collected during the site selection process, then supplemented during subsequent investigation. Soil-boring logs and other data describing subsurface formations and groundwater conditions are diagrammed to present an interpretation of the subsurface conditions at the planned. Soil-boring logs help to show the extent of each formation extrapolated between the boreholes. The depths to bedrock and the groundwater table also are shown. Many more boring logs and additional cross sections at regular coordinate intervals in several (minimum of two) directions typically are required to properly locate the waste disposal area within the developing site.

The base map usually shows the landfill location in relation to surrounding communities, roads and other features. A site map shows:

- Contour lines drawn at 2- or 5-foot intervals
- Clearly delineated property lines
- Easements and rights-of-ways
- Utility corridors, buildings, wells, roads and other features
- Drainage ways
- Neighboring property ownership and land uses

Contour maps show drainage patterns adjacent to and through possible disposal sites. Areas with excessive slope or direct overland flow from a site to surface waters must be carefully evaluated. Subsurface formations and groundwater conditions will influence the landfill's design features in the leachate collection system and liner requirements. A formation's geotechnical characteristics will determine its suitability as a construction material.

Site plans should describe landfill development phases in chronological order. Landfills usually are planned to be developed, constructed, and operated in phases of 1 to 2 years each. Dividing the project into phases minimizes the amount of open landfill surface and reduces the potential for precipitation to accumulate. As each phase is completed, that landfill portion can be closed and final cover material can be placed over the waste. Another phasing advantage is that it makes premature landfill closure, in the event of an environmental problem, more practical and economical. In a well-planned development, the landfill's end-use can be implemented in the completed sections while other areas remain open for disposal.

Concurrent with plan development for liners, covers, service roads and embankments, soil cut-and-fill balances must be calculated. The best designs minimize soil transfer at the site. Substantial volumes of earth will be required for cover material and possibly for liners. Some regulatory agencies mandate screening berms or fence construction around the landfill's active areas. The extra soil needed for berm construction must be accounted for when planning excavation work. The berm height will depend on the sight lines into the landfill from adjacent areas.

The site plan should chronologically illustrate the developing landfill's features. The landfill's enduse can begin on completed sections while other areas in the landfill still are being used for disposal. Phasing diagrams show the landfill's evolution at different stages through the site's life. Phases should be developed for key times in sufficient detail to ensure that the operator knows what is to be done at any point. The engineers and management must be assured that the site is proceeding according to plan so that contracts can be let or finances arranged for construction. Regulatory bodies also must be assured that landfill operators are following the plan and that the site will be completed as designed at the agreed-upon time. The dimensions of each phase are determined by several factors. Generally, each phase accommodates 2 to 3 years of refuse volume.

## DESIGN PHASES

When practical, design phases should be laid out so that excavated soil is immediately used. When stockpiling is necessary, the work should be organized so that stockpiled soil is undisturbed until needed or used to surcharge completed areas. Stockpiled soil should be covered whenever possible to prevent wind and precipitation erosion. After completing the phasing diagrams and earthwork balances, a table should be prepared to summarize the waste disposal and earth volumes that will be contained within each landfill phase.

The operating plan should detail the configuration of the landfill's working face and helps to define terms. The "working face" is the area presently being worked, with new refuse being deposited and compacted into it. Once the working face has been completed and daily cover material provided, it is a completed cell, or "daily cell." A "lift" is composed of the adjacent daily cells that form one layer of the landfill. Lift thicknesses generally are 8 to 20 feet. Larger landfills that accept more refuse per day have higher lift thicknesses. "Daily cover material" is applied over the working face and can extend over the horizontal surface at the top of each daily cell, depending on how long the cover will be exposed to the environment. If the landfill is not expected to receive additional wastes, closure must begin within 30 days of the final receipt of waste.

This closure requirement ensures that a proper cover is installed at the landfill. The minimum width of the working face or daily cell should be at least wide enough to accommodate as many trucks or vehicles as are expected to be at the landfill. Typically, 10 to 15 feet per truck or vehicle is used in designing.

Clearly, it is not a good operating practice to have extremely wide working faces to accommodate the peak flow of trucks that may occur once or twice a day. A trade-off must be made between the width of the working face and the area needed to queue vehicles entering the site during peak hours. The working face should remain as small as possible to avoid attracting birds and creating visual problems for passersby, and to contain blowing paper. Keeping freshly deposited refuse in a well-defined and small working face is a good indication of a well-operated landfill.

## SANITARY LANDFILL DESIGN STEPS

The following is a summary of the steps generally applied to sanitary landfill designs (Source: Conrad et al., 1981 with additions by the authors, Solid Waste Landfill Design and Operation Practices, EPA Draft Report, 1981):

1. Determine solid waste quantities and characteristics:
    a. Existing
    b. Projected
2. Compile information for potential sites:
    a. Performance of boundary and topographic surveys
    b. Preparation of base maps of existing conditions on and near sites (property boundaries, topography and slopes, surface water, wetlands, utilities roads, structures, residences, and land use).
    c. Compile hydrogeological information and preparation of location map: Soils (depth, texture, structure, bulk density, porosity, permeability, moisture, ease of excavation, stability, pH, and CATION exchange capacity), bedrock (depth, type, presence of fractures, and location of surface outcrops), groundwater (average depth, seasonal fluctuations, hydraulic gradient and direction of flow, rate of flow, quality, and uses).
    d. Compile climatological data: Precipitation, evaporation, temperature, number of freezing days, and wind direction.
    e. Identify regulations (federal, state, local) and design standards: Loading rates, frequency of cover, distances to residences, roads, surface water and airports, monitoring, groundwater quality standards, roads, building codes, and contents of application for permit.

3. Design of filling area
    a. Select landfilling method based on site topography, site soils, site bedrock, and site groundwater.
    b. Specify design dimensions: Cell width, depth, length, fill depth, liner thickness. interim cover soil thickness, and final soil cover thickness.
    c. Specify operational features: Use of cover soil, method of cover application, need for imported soil, equipment requirements, and personnel requirements.
4. Design features:
    a. Leachate controls
    b. Gas controls
    c. Surface water controls
    d. Access roads
    e. Special working areas
    f. Special waste handling
    g. Structure utilities
    h. Recycling dropoff
    i. Fencing
    j. Lighting
    k. Washracks
    l. Monitoring wells
    m. Landscaping
5. Prepare design package:
    a. Develop preliminary site plan of fill areas.
    b. Develop landfill contour plans: Excavation plans (including benches), sequential fill plans, completed fill plans, and fire, litter, vector, odor and noise controls.
    c. Compute solid waste storage volume, soil requirement volumes, and site life.
    d. Develop final site plan showing normal fill areas, special working areas, leachate controls, gas controls, surface water controls, access roads, structures, utilities, fencing, lighting, washracks, monitoring wells, landscaping.
    e. Prepare elevation plans with cross-sections of excavated fill, completed fill, phase development of fill at interim points.
    f. Preparation of construction details: Leachate controls, gas controls, surface water controls, access roads, structures, monitoring wells.
    g. Prepare ultimate land use plan.
    h. Prepare cost estimate.
    i. Prepare design report.
    j. Prepare environmental impact assessment.
    k. Submit application and obtaining required permits.
    l. Prepare operator's manual.

## GAS CONTROL

Once gases are produced under the landfill surface, they generally move away from the landfill. Gases tend to expand and fill the available space, so that they move, or "migrate," through the limited pore spaces within the refuse and soils covering the landfill. The natural tendency of landfill gases that are lighter than air, such as methane, is to move upward, usually through the landfill surface. Upward movement of landfill gas can be inhibited by densely compacted waste or landfill cover material (e.g., by daily soil cover and caps). When upward movement is inhibited, the gas tends to migrate horizontally to other areas within the landfill or to areas outside the landfill, where it can resume its upward path. Basically, the gases follow the path of least resistance. Some gases, such as carbon dioxide, are denser than air and will collect in subsurface areas, such as utility corridors. Three main factors influence the migration of landfill gases: diffusion (concentration), pressure, and permeability. Gases can travel off-site and into neighboring buildings, posing indoor air quality threats such as odors or exposures to inhalation hazards, or even fire and explosion. For these reasons gas control is needed.

Landfills install gas control measures because of regulatory requirements. Regulations have been developed to reduce health and environmental impacts from landfill gas emissions through the reduction of ozone precursors (volatile organic compounds and nitrogen oxides), methane, NMOCs, and odorous compounds. States may also have state specific landfill regulations, which must be as strict as or stricter than the federal regulations. Odor complaints or potential safety and health concerns may also prompt landfill gas collection. Sulfide emissions are a common source of landfill odor complaints. At older landfills or at smaller landfills exempt from federal and state regulations, uncontrolled releases of landfill gases can pose potential safety and health concerns (e.g., explosion hazards). In such cases, the landfill might implement landfill gas control measures, even if they are not required by federal or state regulations. Some landfills have also implemented voluntary gas collection and control or treatment systems to recover landfill gas for energy production.

The primary objective of a landfill gas control plan is to prevent people from being exposed to landfill gas emissions. This goal can be achieved either by collecting and treating landfill gas at the landfill or by preventing landfill gas from entering buildings and homes in the community. Technologies used to control landfill gas at the landfill or in the community can be applied separately or in combination. Landfill gas can be collected by either a passive or an active collection system. A typical collection system, either passive or active, is composed of a series of gas collection wells placed throughout the landfill. The number and spacing of the wells depend on landfill-specific characteristics, such as waste volume, density, depth, and area. As gas is generated in the landfill, the collection wells offer preferred pathways for gas migration. Most collection systems are designed with a degree of redundancy to ensure continued operation and protect against system failure. Redundancy in a system may include extra gas collection wells in case one well fails.

*Passive gas collection systems* use existing variations in landfill pressure and gas concentrations to vent landfill gas into the atmosphere or a control system. Figure 1 illustrates the main design features. Passive collection systems can be installed during active operation of a landfill or after closure. Passive systems use collection wells, also referred to as extraction wells, to collect landfill gas. The collection wells are typically constructed of perforated or slotted plastic and are installed vertically throughout the landfill to depths ranging from 50% to 90% of the waste thickness. If groundwater is encountered within the waste, wells end at the groundwater table. Vertical wells are typically installed after the landfill, or a portion of a landfill, has been closed. A passive collection system may also include horizontal wells located below the ground surface to serve as conduits for gas movement within the landfill. Horizontal wells may be appropriate for landfills that need to recover gas promptly (e.g., landfills with subsurface gas migration problems), for deep landfills, or for active landfills.

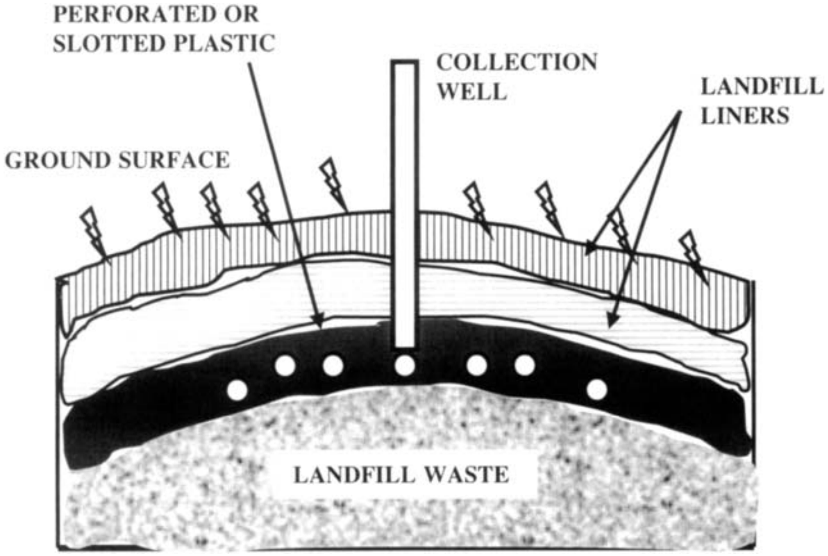

Figure 1. Passive gas collection system.

Sometimes, the collection wells vent directly to the atmosphere. Often, the collection wells convey the gas to treatment or control systems (e.g., flares). The efficiency of a passive collection system partly depends on how well the gas is contained within the landfill. Gas containment can be controlled and altered by the landfill collection system design. Gas can be contained by using liners on the top, sides, and bottom of the landfill. An impermeable liner (e. g., clay or geosynthetic membranes) will trap landfill gas and can be used to create preferred gas migration pathways. For example, installing an impermeable barrier at the top of a landfill will limit uncontrolled venting to the atmosphere by causing the gas to vent through collection wells rather than the cover. The efficiency also depends on environmental conditions, which may or may not be controlled by the system design. When the pressure in the landfill is inadequate to push the gas to the venting device or control device, passive systems fail to remove landfill gas effectively. High barometric pressure results in outside air entering the landfill through passive vents that are not routing gas to control devices. For these reasons, passive collection systems are not considered reliable enough for use in areas with a high risk of gas migration, especially where methane can collect to explosive levels in buildings and confined spaces. It is fairly common for landfills to flare gas because of odor concerns, for example, even if not the landfill is not subject to regulatory requirements.

*Active collection systems* are considered the most effective means of landfill gas collection. Active gas collection systems include vertical and horizontal gas collection wells similar to passive collection systems. Unlike the gas collection wells in a passive system, however, wells in the active system should have valves to regulate gas flow and to serve as sampling ports. Sampling allows the system operator to measure gas generation, composition, and pressure. Refer to Fig. 2 for key features. Active gas collection systems include vacuums or pumps to move gas out of the landfill and piping that connects the collection wells to the vacuum. Vacuums or pumps pull gas from the landfill by creating low pressure within the gas collection wells. The low pressure in the wells creates a preferred migration pathway for the landfill gas. The size, type, and number of vacuums required in an active system to pull the gas from the landfill depend on the amount of gas being produced. With information about landfill gas generation, composition, and pressure, a landfill operator can assess gas production and distribution changes and modify the pumping system and collection well valves to most efficiently run an active gas collection system. The system design should account for future gas management needs, such as those associated with landfill expansion. An effective active gas collection system incorporates the following design elements:

- Gas-moving equipment, including vacuums and piping, capable of handling the maximum landfill gas generation rate.

- Collection wells placed to capture gas from all areas of the landfill. The number and spacing between each extraction well depends on the waste type, depth, and compaction; the pressure gradients created by the vacuums; and the moisture content of the gas.

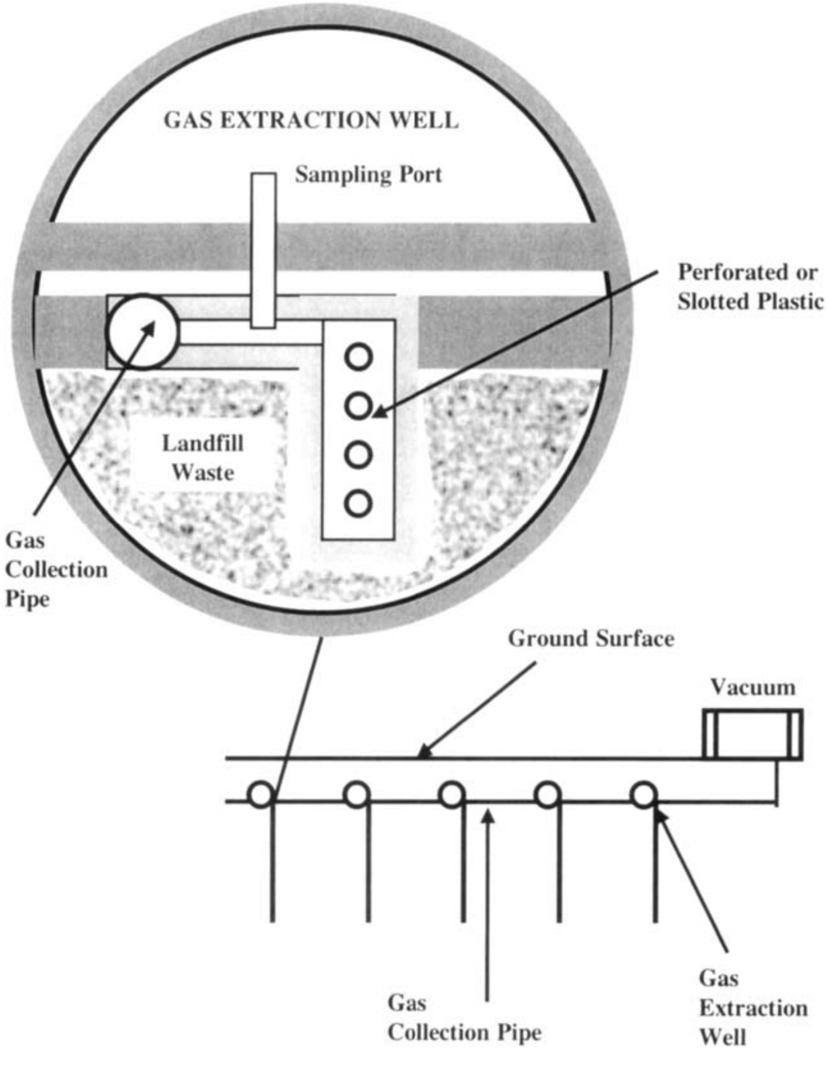

Figure 2. Active gas collection system design.

- The ability to monitor and adjust flow from individual extraction wells. Inclusion of a valve, pressure gauge, condenser, and sampling port at each collection well allows a landfill operator to monitor and adjust pressure and to measure gas generation and content. Some passive gas collection systems simply vent landfill gas to the atmosphere without any treatment before release. This may be appropriate if only a small quantity of gas is produced and no people live or work nearby. More commonly, however, the collected landfill gas is controlled and treated to reduce potential safety and health hazards.

## EXPLOSION AND OTHER HAZARDS

Landfill gas may form an explosive mixture when it combines with air in certain proportions. The following conditions must be met for landfill gas to pose an explosion hazard:

- **Gas production.** A landfill must be producing gas, and this gas must contain chemicals that are present at explosive levels.
- **Gas migration.** The gas must be able to migrate from the landfill. Underground pipes or natural subsurface geology may provide migration pathways for landfill gas. Gas collection and treatment systems reduce the amount of gas that is able to escape from the landfill.
- **Gas collection in a confined space.** The gas must collect in a confined space to a concentration at which it could potentially explode. A confined space might be a manhole, a subsurface space, a utility room in a home, or a basement. The concentration at which a gas has the potential to explode is defined in terms of its lower and upper explosive limits (LEL and UEL). The concentration level at which gas has the potential to explode is called the explosive limit. The potential for a gas to explode is determined by its lower explosive limit (LEL) and upper explosive limit (UEL). The LEL and UEL are measures of the percent of a gas in the air by volume. At concentrations below its LEL and above its UEL, a gas is not explosive. However, an explosion hazard may exist if a gas is present in the air between the LEL and UEL and an ignition source is present.

Methane is the constituent of landfill gas that is likely to pose the greatest explosion hazard. Methane is explosive between its LEL of 5% by volume and its UEL of 15% by volume. Because methane concentrations within the landfill are typically 50% (much higher than its UEL), methane is unlikely to explode within the landfill boundaries. As methane migrates and is diluted, however, the methane gas mixture may be at explosive levels. Also, oxygen is a key component for creating an explosion, but the biological processes that produce methane require an anaerobic, or oxygen-depleted, environment. At the surface of the landfill, enough oxygen is present to support an explosion, but the methane gas usually diffuses into the ambient air to concentrations below the 5% LEL. In order to pose an explosion hazard, methane must migrate from the landfill and be present between its LEL and UEL.

Other landfill gas constituents (e.g., ammonia, hydrogen sulfide, and NMOCs) are flammable. However, because they are unlikely to be present at concentrations above their LELs, they rarely pose explosion hazards as individual gases. For example, benzene (an NMOC that may be found in landfill gas) is explosive between its LEL of 1.2% and its UEL of 7.8%. However, benzene concentrations in landfill gas are very unlikely to reach these levels. If benzene were detected in landfill gas at a concentration of 2 ppb (or 0.0000002% of the air by volume), then benzene would have to collect in a closed space at a concentration 6 million times greater than the concentration found in the landfill gas to cause an explosion hazard.

Table 2 provides a summary of the potential explosion hazards posed by the important constituents of landfill gas. Methane is the most likely landfill gas constituent to pose an explosion hazard. Other flammable landfill gas constituents are unlikely to be present at concentrations high enough to pose an explosion hazard. However, the flammable NMOCs do contribute to total explosive hazard when combined with methane in a confined space.

Table 2. Potential Explosion Hazards from Common Landfill Gas Components

| **Component** | **Potential to pose an explosion hazard** |
|---|---|
| Methane | Methane is highly explosive when mixed with air at a volume between its LEL of 5% and its UEL of 15%. At concentrations below 5% and above 15%, methane is not explosive. At some landfills, methane can be produced at sufficient quantities to collect in the landfill or nearby structures at explosive levels. |
| Carbon dioxide | Carbon dioxide is not flammable or explosive. |
| Nitrogen dioxide | Nitrogen dioxide is not flammable or explosive. |
| Oxygen | Oxygen is not flammable, but is necessary to support explosions. |
| Ammonia | Ammonia is flammable. Its LEL is 15% and its UEL is 28%. However, ammonia is unlikely to collect at a concentration high enough to pose an explosion hazard. |
| NMOCs | Potential explosion hazards vary by chemical. For |

| Component | Potential to pose an explosion hazard |
|---|---|
| | example, the LEL of benzene is 1.2% and its UEL is 7.8%. However, benzene and other NMOCs alone are unlikely to collect at concentrations high enough to pose explosion hazards. |
| Hydrogen sulfide | Hydrogen sulfide is flammable. Its LEL is 4% and its UEL is 44%. However, in most landfills, hydrogen sulfide is unlikely to collect at a concentration high enough to pose an explosion hazard. |

Landfill gas poses an asphyxiation hazard only if it collects in an enclosed space (e.g., a basement or utility corridor) at concentrations high enough to displace existing air and create an oxygen-deficient environment. The Occupational Safety and Health Administration (OSHA) defines an oxygen-deficient environment as one that has less than 19.5% oxygen by volume. Ambient air contains approximately 21% oxygen by volume. Health effects associated with oxygen-deficient environments are described in Table 3. Any of the gases that make up landfill gas can, either individually or in combination, create an asphyxiation hazard if they are present at levels sufficient to create an oxygen-deficient environment.

Carbon dioxide, which comprises 40% to 60% of landfill gas, may pose specific asphyxiation hazard concerns. Because it is denser than air, carbon dioxide that has escaped from a landfill and collected in a confined space, such as a basement or an underground utility corridor, may remain in the area for hours or days after the area has been opened to the air (e.g., after a manhole cover has been removed or a basement door opened). Carbon dioxide is colorless and odorless and therefore not readily detectable. Carbon dioxide concentrations of 10% or more can cause unconsciousness or death. Lower concentrations may cause headache, sweating, rapid breathing, increased heartbeat, shortness of breath, dizziness, mental depression, visual disturbances, or shaking. The seriousness of these symptoms depends on the concentration and duration of exposure. The response to carbon dioxide inhalation varies greatly even in healthy normal individuals.

In assessing the public health issues of migrating landfill gas, environmental health professionals should investigate the presence of buried utility lines and storm sewers on or adjacent to the landfill. These structures not only provide a pathway for migrating gases, but also pose a special asphyxiation problem for utility workers who fail to follow confined space entry procedures prescribed by OSHA. On-site or adjacent residences and commercial buildings with basements or insulated (or sealed) crawl spaces should also be investigated for potential asphyxiation hazards.

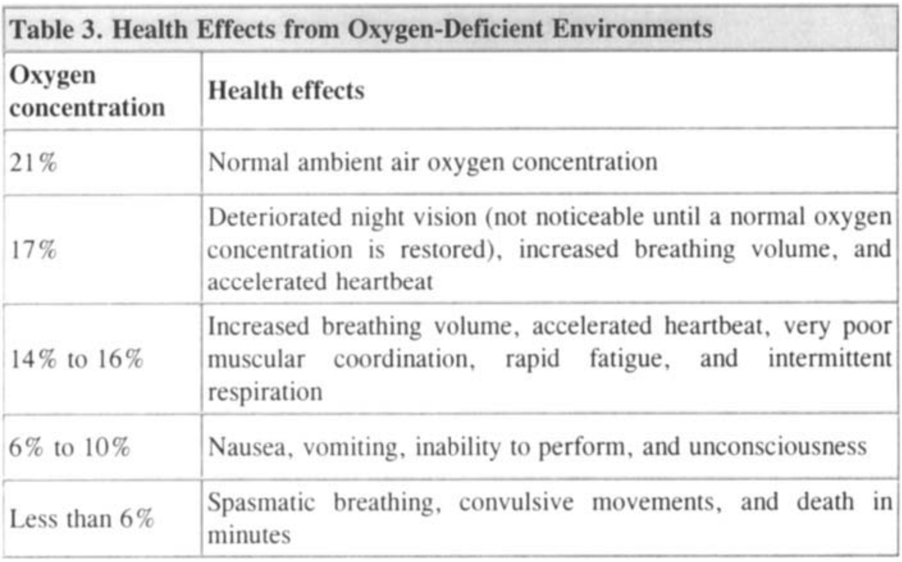

**Table 3. Health Effects from Oxygen-Deficient Environments**

| Oxygen concentration | Health effects |
|---|---|
| 21% | Normal ambient air oxygen concentration |
| 17% | Deteriorated night vision (not noticeable until a normal oxygen concentration is restored), increased breathing volume, and accelerated heartbeat |
| 14% to 16% | Increased breathing volume, accelerated heartbeat, very poor muscular coordination, rapid fatigue, and intermittent respiration |
| 6% to 10% | Nausea, vomiting, inability to perform, and unconsciousness |
| Less than 6% | Spasmatic breathing, convulsive movements, and death in minutes |

Landfill odors often prompt complaints from community members. People may also have concerns about health effects associated with these odors and other emissions coming from the landfill. People in communities near landfills are often concerned about odors emitted from landfills. They say that these odors are a source of undesirable health effects or symptoms, such as headaches and nausea. At low-level concentrations—typically associated with landfill gas— it is unclear whether it is the constituent itself or its odors that trigger a response. Typically, these effects fade when the odor can no longer be detected. Landfill gas odors are produced by bacterial or chemical processes and can emanate from both active or closed landfills. These odors can migrate to the surrounding community. Potential sources of landfill odors include sulfides, ammonia, and certain NMOCs, if present at concentrations that are high enough. Landfill odors may also be produced by the disposal of certain types of wastes, such as manures and fermented grains. The following are major landfill gases generated:

- **Sulfides.** Hydrogen sulfide, dimethyl sulfide, and mercaptans are the three most common sulfides responsible for landfill odors. These gases produce a very strong rotten-egg smell—even at very low concentrations. Of these three sulfides, hydrogen sulfide is emitted from landfills at the highest rates and concentrations. Humans are extremely sensitive to hydrogen sulfide odors and can smell such odors at concentrations as low as 0.5 to 1 part per billion (ppb). At levels approaching 50 ppb, people can find the odor offensive. Average concentrations in ambient air range from 0.11 to 0.33 ppb. According to information collected by the Connecticut

Department of Health, the concentration of hydrogen sulfide in ambient air around a landfill is usually close to 15 ppb.

- **Ammonia.** Ammonia is another odorous landfill gas that is produced by the decomposition of organic matter in the landfill. Ammonia is common in the environment and an important compound for maintaining plant and animal life. People are exposed daily to low levels of ammonia in the environment from the natural breakdown of manure and dead plants and animals. Because ammonia is commonly used as a household cleaner, most people are familiar with its distinct smell. Humans are much less sensitive to the odor of ammonia than they are to sulfide odors. The odor threshold for ammonia is between 28,000 and 50,000 ppb. Landfill gas has been reported to contain between 1,000,000 and 10,000,000 ppb of ammonia, or 0.1% to 1% ammonia by volume (Zero Waste America n.d.). Concentrations in ambient air at or near the landfill site are expected to be much lower.
- **NMOCs.** Some NMOCs, such as vinyl chloride and hydrocarbons, may also cause odors. In general, however, NMOCs are emitted at very low (trace) concentrations and are unlikely to pose a severe odor problem.

Table 4 lists some of the common landfill gas components and their odor thresholds.

Table 4. Common Landfill Gas Components and Their Odor Thresholds.

| **Component** | **Odor description** | **Odor threshold (parts per billion)** |
|---|---|---|
| Hydrogen sulfide | Strong rotten egg smell | 0.5 to 1 |
| Ammonia | Pungent acidic or suffocating odor | 1000 to 5000 |
| Benzene | Paint-thinner-like odor | 840 |
| Dichloroethylene | Sweet, ether-like, slightly acrid odor | 85 |
| Dichloromethane | Sweet ,chloroform-like odor | 205,000 to 307,000 |
| Ethylbenzene | Aromatic odor like benzene | 90 to 600 |
| Toluene | Aromatic odor like benzene | 10,000 to 15,000 |
| Trichloroethylene | Sweet, chloroform-like odor | 21,400 |

| Component | Odor description | Odor threshold (parts per billion) |
|---|---|---|
| Tetrachloroethylene | Sweet, etheror chloroform-like odor | 50,000 |
| Vinyl chloride | Faintly sweet odor | 10,000 to 20,000 |

## FLARING PRACTICES

Combustion is the most common technique for controlling and treating landfill gas. Combustion technologies such as flares, incinerators, boilers, gas turbines, and internal combustion engines thermally destroy the compounds in landfill gas. Over 98% destruction of organic compounds is typically achieved. Methane is converted to carbon dioxide, resulting in a large greenhouse gas impact reduction. Combustion or flaring is most efficient when the landfill gas contains at least 20% methane by volume. At this methane concentration, the landfill gas will readily form a combustible mixture with ambient air, so that only an ignition source is needed for operation. At landfills with less than 20% methane by volume, supplemental fuel (e.g., natural gas) is required to operate flares, greatly increasing operating costs. When combustion is used, two different types of flares can be chosen: open or enclosed flares.

*Open flame flares* (e.g., candle or pipe flares), the simplest flaring technology, consist of a pipe through which the gas is pumped, a pilot light to spark the gas, and a means to regulate the gas flow. The simplicity of the design and operation of an open flame flare is an advantage of this technology. Disadvantages include inefficient combustion, aesthetic complaints, and monitoring difficulties. Sometimes, open flame flares are partially covered to hide the flame from view and improve monitoring accuracy.

*Enclosed flame flares* are more complex and expensive than open flame flares. Nevertheless, most flares designed today are enclosed, because this design eliminates some of the disadvantages associated with open flame flares. Enclosed flame flares consist of multiple burners enclosed within fire- resistant walls that extend above the flame. Unlike open flame flares, the amount of gas and air entering an enclosed flame flare can be controlled, making combustion more reliable and more efficient.

*Other enclosed combustion technologies* such as boilers, process heaters, gas turbines, and internal combustion engines can be used not only to efficiently destroy organic compounds in landfill gas, but also to generate useful energy or electricity, as described later in this chapter.

There are limited data comparing emissions from landfill gas flares to energy producing combustion devices (which includes boilers, turbines and internal combustion engines). According to very limited data in a 1995 EPA report, carbon monoxide and $NO_x$ emissions are highest from internal combustion engines and lowest from boilers. Flares and gas turbines are somewhere in the middle.

Flaring of landfill gas is done either in a candle flare or a shrouded flare. A candle flare is an open air flame. With such, there is no reliable means to monitor for dioxins or other toxic emissions. Shrouded flares involve enclosing the flame in an insulated cylindrical shroud which can be anywhere from 16 to 60 feet tall. While dioxins can be tested for in such flares, it is possible that enclosing the flare will keep the postcombustion temperature in dioxin-formation range, resulting in increased dioxin emissions. Essentially, this is a lose-lose situation. Most shrouded landfill gas flares have exit temperatures of around 1,400°F, well above the dioxin formation range (which end around 752°F). In such cases, dioxins will be formed in midair as the exhaust hits the cooler background air after leaving the stack.

Dioxin emissions data are also very sparse. Flares are known to generate more dioxin than internal combustion engines or boiler mufflers. There is high variability in dioxin emissions from landfill gas burners (based on composition of waste dumped and also on the combustion technology - internal combustion engines are much more variable). Burning landfill gas is dirtier than burning natural gas. Whether using an internal combustion engine or a gas turbine, burning landfill gas to produce energy emits more pollution per kilowatt hour than natural gas does.

## LANDFILL GAS ENERGY SYSTEMS

Landfill gas is formed when the waste deposited in landfills breaks down as a result of the action of microbes. It consists of a mixture of carbon dioxide and methane (in roughly equal quantities), with a large number of trace components. The methane content of the gas (typically around 40 to 60% by volume) makes it a potential fuel. Landfill gas is collected through a series of wells drilled into the waste. A wide variety of designs of wells and collection systems are available. The choice will depend to some extent on site-specific factors, such as type and depth of waste.

Gas collection for energy production can often complement environmental protection measures in force at landfill sites. There is a potential risk to the local and global environment from the escape of landfill gas, and its control is often required to comply with environmental legislation. A well-designed landfill site and gas collection system can ensure integration of effective environmental protection and energy recovery.

The common types of engine used to combust landfill gas and convert it into energy are gas turbines, dual-fuel (compression ignition) engines and spark ignition engines. Engine sizes available range from a few hundred kilowatts to several megawatts. Fuel conversion efficiency for the generating sets can range from 26% (typically for gas turbines) to 42% (for dual-fuel engines). Landfill gas to energy projects can be used to produce electricity, combined heat and power, or heat only.

In general, emissions from landfill gas combustion will include (at different concentrations) all the pollutants produced by flaring off landfill gas at sites that do not have gas utilization equipment, but at different concentrations. These emissions include particulates, traces of heavy metals and organic compounds such as dioxins. Emissions of some pollutants (e.g. carbon monoxide) are less than those from flaring, because of the more controlled combustion conditions employed in energy recovery schemes. Using landfill gas for energy generation provides an additional incentive to maximize gas collection at a site and so reduces uncontrolled methane emissions. While some noise is generated by the gas utilization equipment, appropriate siting and design can keep noise levels within acceptable limits.

Landfills install gas collection systems to prevent the problems with gas migration. Gas migration off-site can cause explosions. Also the release of the methane contributes to global warming problems and the release of the toxic contaminants can cause cancer and present other health risks to communities.

In addition to flairing, the other options for dealing with landfill gas (once collected) are as follows:

1. boilers for making thermal energy
2. Internal combustion engine for generating electricity
3. Gas turbine for generating electricity
4. Fuel cell for generating electricity
5. Conversion of the methane to methyl alcohol
6. Cleanup sufficient to allow the gas to be piped to other industries or into the natural gas lines

*Boilers* are among the cheapest options. They produce thermal energy or heat, not electricity. Boilers are generally less sensitive to landfill gas contaminants and therefore require less cleanup than other alternatives. Boilers have the lowest $NO_x$ and carbon monoxide emissions of the combustion technologies. Landfill gas use in boilers brings in the issue of piping the gas to local industries. While boilers themselves may not require much cleanup of the gas, the pipelines do require some cleanup, since corrosive compounds in the gas (particularly the acids and hydrogen sulfide -- $H_2S$) can damage the pipelines. Among the concerns with this option are the integrity of the pipeline, liability issues, and the economic support of neighboring polluting industries which might use the gas.

*Internal combustion engines* are the dirtiest technology for burning landfill gas. They emit the most carbon monoxide and $NO_x$ and they may be the largest dioxin source of the available technologies.

*Gas turbines* are somewhere in the middle in terms of carbon monoxide and $NO_x$ emissions. There isn't enough data on dioxin emissions from landfill gas turbines to provide an extensive comparison.

*Fuel cells* are the most expensive technology, and they are still largely experimental. EPA describes fuel cells as "potentially one of the cleanest energy conversion technologies available." In order not to poison the fuel cells, halogenated contaminants must first be removed and destroyed, for example by pyrolysis.

One option is to convert the methane recovered from landfills into *methyl alcohol* or methanol. Other novel ideas include converting the carbon dioxide in landfill gas to dry ice for sale to industry.

The concept of cleaning up the landfill gas to pipeline quality, while environmentally friendly, is not cost-effective. Since natural gas prices are so low, this is not expected to be economical anytime soon. It also requires a high degree of cleaning and filtering the gas. To the extent that the gas is not adequately filtered, the landfill gas will be degrading the quality of the natural gas by adding more contaminants to the system.

## LIFE CYCLE COST CONSIDERATIONS

The advantages of energy recovery from landfill gas include decreased emissions of methane, NMOCs, and toxics (e.g., benzene, carbon tetrachloride, and chloroform). Although carbon dioxide ($CO_2$) emissions increase with energy recovery, the net atmospheric balance is a positive one because $CO_2$ emissions are significantly less radiative, which means that the greenhouse effect is less than methane emissions.

The average size of a landfill gas energy recovery project is about 3 megawatts, with typically over 95% availability. The number of commercial energy recovery projects has grown from a handful in the 1980s to more than 130 in 1990s. Even though there has been a large increase in projects, there are more than 700 landfills across the U.S. that could install landfill gas energy recovery systems. About 30 of the original conversion and direct use projects initiated in the 1970s and 1980s have had to shut down due to more competitive market conditions. Therefore, although the advantages of landfill gas energy recovery are significant from an environmental standpoint, there are few successful commercial projects relative to the number of MSW landfills because of prevailing market conditions and the array of other barriers that confront project developers. According to M. Doorn, J. Pacey, and D. Augenstein (see *Landfill Gas Energy Utilization Experience: Discussion of Technical and Non-Technical Issues, Solutions, and Trends*, EPA-600/R-95-035, prepared by E.H. Pechan and Associates, Inc., for the Air and Energy Engineering Research Laboratory, USEPA, Washington, D.C., March 1995), the principle barriers to gas recovery and conversion to energy include:

- Low oil and gas prices (current and projected future)
- Need for expensive new, sometimes untested, technology (e.g., fuel cells)
- High transportation costs (e.g., dedicated pipelines have to be built for relatively small supplies of gas)
- High debt-service rates for projects that generate electricity or pipeline-quality gas
- Limited or unstable marketplace
- Obtaining third-party project financing at reasonable cost (financing is difficult, time-consuming, and proportionately more costly for small projects than for large ones)
- Difficulties obtaining air permits, especially for projects located in ozone, nitrogen oxide, and carbon monoxide nonattainment areas, because air boards and utilities often have lengthy permit processes and contract negotiations
- Difficulties in negotiating power contracts with local utilities because they are primarily interested in purchasing low-cost power without considering environmental externalities (e.g., offsets from power plants using fossil fuel)
- Unforeseen costs resulting from compliance with new air quality rules and regulations, and declining energy revenues that cannot be adjusted to offset new costs
- Taxation by some states (e.g., California) on LFG extraction and energy conversion facilities
- Difficulties in complying with overlapping federal and state energy policies and environmental regulations that may affect these projects

The most significant barrier is low oil and natural gas prices, which make recovery and conversion, with its high initial capital costs, lack of economies of scale, and high transportation costs, uncompetitive in many situations. Table 5 provides a comparison of current costs for different landfill gas energy recovery technologies.

Table 5. Comparison of Costs for Energy Recovery Technologies (1992 Dollars, Unless Otherwise Noted)

| **Technology/use** | **Capital costs (dollars per kilowatt)** | **O&M costs (dollars per kilowatt-hour)** |
|---|---|---|
| Internal combustion engine/electricity generation | 900 to 1200 | 0.013 to 0.020 |
| Gas turbine/electricity generation | 1000 to 1500 | 0.01 to 0.015 |
| Steam turbine/electricity generation | 900[a] | 0.001[a] |
| Boiler/direct heat | 1000 to 1500 | 0.005 to 0.018 |
| Organic rankine/heat recovery | 1000 to 1500 | 0.005 |
| Fuel cell/electricity generation | 3000+[b] | NA |

[a] 1993 dollars.

[b] 1995 dollars, using 1995 technology.

NA = not available.

Sources: T.D. Williams, "Making Landfill Gas an Asset," *Solid Waste and Power* (July/August 1992), p. 22; and C.E. Anderson, "Selecting Electrical Generating Equipment for Use with Landfill Gas," *Proceedings of the SWANA 16th Annual Landfill Gas Symposium* (Louisville, KY, March 1993).

Although LLC studies do not appear in the literature, in general the most economical options for landfill gas utilization are direct uses such as process heat and boiler fuel, where the end users are in relatively close proximity (no more than 1 or 2 miles) to the landfill, and whose gas supply needs closely match production at the landfill. In the United States, end users are infrequently located near landfills and rarely require continuous fuel in the amounts produced; however this is not always the case in other countries. This situation can be found more frequently in Central and Eastern Europe. Boiler fuel is the most typical direct use and can be attractive when conventional equipment can be retrofitted with minimal modifications. Boilers are generally less sensitive to landfill gas trace constituents and therefore require less cleanup than other alternatives. End-use options include industrial applications such as kilns, lumber drying, oil refining, hotel heating, and cement manufacturing. These are likely economically attractive candidates because of the continuous need and availability of the fuel.

## ELECTRICITY GENERATION

As noted earlier, the primary applications for landfill gas electricity generation are internal combustion engines, gas turbines, and fuel cells. Most of the operating landfill energy recovery projects sell electricity under contract to a utility. Internal combustion engines are economical where the supply of gas is enough to produce 1 to 3 megawatt-hours. Turbines are most economical at sites with output of over 3 megawatt-hours. The advantages of internal combustion engines include comparatively low capital costs (between $950 and $1250 per kilowatt), good efficiency, a high degree of standardization, and portability, which facilitates transportation from one landfill site to another. A major disadvantage with internal combustion engines is emissions. There are two types of internal combustion engines, each having distinct emissions characteristics. Stoichiometric combustion engines generate high nitrous oxides ($NO_x$) emissions. Lean-burn engines generate lower $NO_x$ and CO emissions, so they are better suited for applications where these emissions are a concern.

There are several disadvantages in using gas-fed turbines. They typically have parasitic energy losses of 17% of gross output. By comparison, internal combustion engines only have about 7%. Other disadvantages include poor turndown performance compared to internal combustion engines, and difficulties may occur when they are operated at less than a full load. Additional problems are combustion chamber melting, corrosion, and accumulation of deposits on turbine blades.

Fuel cells may become attractive because of their higher energy efficiency, negligible emissions impact, and suitability for all landfill sizes. Fuel cells have low labor and maintenance costs. At present, however, economic and technical disadvantages make fuel cells clearly uncompetitive with more conventional applications. This includes the high capital cost of designing an landfill gas cleanup process that can remove the trace constituents from the gas since fuel cells require a higher grade of gas purification than other options. There is also a very high capital investment required, costing about $3,000 per kilowatt using state-of-the-art technology. Because of continued advances in fuel cell technology and the possibility of more stringent future emissions requirements that may make other technologies more costly, fuel cells will could eventually become competitive.

## NONCOMBUSTION TECHNOLOGIES

Noncombustion technologies were developed in the 1990s as an alternative to combustion, which produces compounds that contribute to smog, including nitrogen oxides, sulfur oxides, carbon monoxide, and particulate matter.

Noncombustion technologies fall into two groups: energy recovery technologies and gas-to-product conversion technologies. Regardless of which noncombustion technology is used, the landfill gas must first undergo pretreatment to remove impurities such as water, NMOCs, and carbon dioxide. Numerous pretreatment methods are available to address the impurities of concern for a specific landfill. After pretreatment, the purified landfill gas is treated by noncombustion technology options.

As noted. energy recovery technologies use landfill gas to produce energy directly. Currently, the phosphoric acid fuel cell (PAFC) is the only commercially available noncombustion energy recovery technology. Other types of fuel cells (molten carbonate, solid oxide, and solid polymer) are still under development. The PAFC system consists of landfill gas collection and pretreatment, a fuel cell processing system, fuel cell stacks, and a power conditioning system. Several chemical reactions occur within this system to create water, electricity, heat, and waste gases. The waste gases are destroyed in a flare.

*Gas-to-product conversion* technologies focus on converting landfill gas into commercial products, such as compressed natural gas, methanol, purified carbon dioxide and methane, or liquefied natural gas. The processes used to produce each of these products varies, but each includes landfill gas collection, pretreatment, and chemical reactions and/ or purification techniques. Some of the processes use flares to destroy gaseous wastes.

Noncombustion energy recovery systems are not used as widely as combustion-based systems. Fuel cells are a promising new technology for producing energy from landfill gas that does not involve combustion. This technology has been demonstrated and in the future may become more economically competitive with other options. One option that does not involve combustion of landfill gas at or near the landfill is purifying the landfill gas to remove constituents other than methane, producing a high British thermal unit (Btu) gas that can be sold as pipeline quality natural gas. Although the high-Btu gas is eventually combusted, it would not contribute to any emissions near the landfill. Another option is using compressed landfill gas as a vehicle fuel.

Both combustion and noncombustion energy recovery systems have three basic components: (1) a gas collection system; (2) a gas processing, treatment, and conversion system; and (3) a means to transport the gas or final product to the user. Gas is collected from the landfill by the use of active vents. It is then transported to a central point for processing. Processing requirements vary, depending on the gas composition and the intended use, but typically include a series of chemical reactions or filters to remove impurities. For direct use of landfill gas in boilers, minimal treatment is required. For landfill gas injection into a natural gas pipeline, extensive treatment is necessary to remove carbon dioxide. At a minimum, the gas is filtered to remove any particles and water that may be suspended in the gas stream.

Below are some examples of how gas collected from landfills is being reused for power.

- In Raleigh, North Carolina, Ajinomoto Pharmaceutical Company has used landfill gas as fuel in boilers at its facility since 1989. The steam produced by the boilers is used to heat the facility and warm pharmaceutical cultures. This project has prevented pollution equivalent to removing more than 23,000 cars from the road.
- In Pittsburgh, Pennsylvania, Lucent Technologies saves $100,000 a year on fuel bills by using landfill gas to generate steam for space heating and hot water.
- The City of Riverview, Michigan, works with the local utility, Detroit Energy, to recover landfill gas and create electricity with two gas turbines. The project generates enough power to meet the energy needs of more than 3700 homes.
- The Los Angeles County Sanitation District in California has succeeded in turning landfill gas into a clean alternative vehicle fuel. Landfill gas is compressed to produce enough fuel per day to run an 11-vehicle fleet, ranging from passenger vans to large on-road tractors.
- Pattonville High School in Maryland Heights, Missouri, is located within 1 mile of a municipal solid waste landfill. The landfill supplies methane gas to heat the 40000-square-foot high school, saving the Pattonville School District thousands of dollars in annual heating costs. Pattonville High School was the first high school to use landfill gas as its source of heat.

## FEEDSTOCK CHEMICALS FOR MANUFACTURING

This approach involves the use of expensive cleanup, purification, and processing equipment to bring the gas to the quality standards of alternative feedstocks, such as natural gas. Using landfill gas as a chemical manufacturing feedstock remains largely uneconomical as long as the price of conventional feedstocks (e.g., natural gas) remains low. Other disadvantages are high transportation costs and a need for proximity to the end user. Landfill sites have found that gas pipelines cannot exceed 1 or 2 miles to be cost-effective. Potential uses for the feedstock include production of methanol and diesel fuels.

## PIPELINE-QUALITY GAS

This option involves the conversion of landfill gas from a medium heating value gas into high heating value gas for local gas distribution networks or, in compressed form, for vehicular fuel. This option remains uneconomical as long as the prices of natural gas and oil remain relatively low. Disadvantages include the need for a more thorough and expensive purification process than in some other options (but the same as in feedstock for chemical manufacturing processes and fuel cell applications), high transportation costs, and need for proximity to the end-user.

## A SHORT REVIEW

Landfill gas is the single largest source of man-made methane emissions in the United States, contributing to almost 40% of methane emissions each year. Consequently, a growing trend at landfills is to use recovered methane gas from landfills as an energy source. Collecting landfill gas for energy use greatly reduces the risk of explosions, provides financial benefits for the community, conserves other energy resources, and potentially reduces the risk of global climate change. Currently in the U.S., approximately 325 landfill gas energy recovery projects prevent emissions of over 150 billion cubic feet of methane per year (or more than 300 billion cubic feet of landfill gas). Approximately 220 of these projects generate electricity, producing a total of more than 900 megawatts per year. Another 68 projects are under construction in 2001, and more than 150 additional projects are in the planning stages. Previous studies by EPA and the Electric Power Research Institute estimate that up to 750 of the landfills in the United States could profitably recover and use their methane emissions. There are several technologies that enable the use of landfill gas to be recovered and applied to the generation of energy, however, many of these have been only partially successful at the local level. In general, the poor quality of landfill gas makes it costly to rely upon it as a form of green energy, and the capital investments are high for large-scale applications. Because landfill gas contains toxic constituents, end-of-pipe treatment technologies must be heavily relied upon in order to purify and concentrate the gas to a sufficiently high heating value.

This brings one to realize that P2 must play a more dominant role in reducing the environmental impacts of landfill gas. Doing nothing is simply not an option because off-site gas migration can lead to the risk of fire, explosions, and greenhouse gases. In order for P2 to have a broad impact, such things as phasing out of halogens in industrial use must be implemented aggressively. This is a way in which we can stop chlorine, fluorine and bromine pollution and the organohalogens (dioxins, furans, etc.) that come with them. The technology of landfilling itself needs to be re-examined. There are communities in the United States which are recycling 80 to 90% of their waste. It is the act of mixing materials together that makes waste on a large scale. Source separation and recycling minimizes and can even prevent this.

## RECOMMENDED RESOURCES

General information about landfill emissions and emissions monitoring can be found in the following resources. In addition, state and federal environmental officials are an excellent resource for site- specific insights.

1. Information related to the CAA regulations for municipal solid waste landfills and landfill emissions estimation can be found at http://www.epa.gov/ttn/atw/landfill/landflpg.html. The actual regulatory text, which includes emissions estimation, testing, and monitoring requirements, can be found in 40 CFR Part 60, Subparts Cc and WWW.

2. EPA maintains a Web site (http://www.epa.gov/ttn/emc), with general information about emissions sampling methodologies; some of this information is specific to emissions monitoring at landfills.

3. EPA. Guidance on Collection of Emissions Data to Support Site-specific Risk Assessments at Hazardous Waste Combustion Facilities, EPA/ 530-D-98-002, 1998.

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# Chapter 5

# VOLUME REDUCTION TECHNOLOGIES

## INTRODUCTION

There are a wide range of technology options to select from for volume reduction purposes. These include incineration, size reduction, composting, concentrating techniques, and drying. Municipal solid waste disposal generally relies upon the first three, but industry often has unique applications and utilizes incineration, size reduction, concentrating methods, and drying more frequently. Among these technology groups, incineration (unless coupled with energy production), drying, size reduction, and concentrating techniques for the most part represent treatment practices. In other words, they are within the end-of-pipe category of options for waste management. They can be applied to incrementally improve environmental performance and achieve savings in operational costs for handling and disposing of large volumes of wastes, but they are not applied as source reduction methods. They can be effectively applied in pollution prevention and waste minimization projects as ancillary techniques, and hence the operational experiences in standard treatment practices provide useful guidelines. Composting also is not source reduction, but it is a form of recycling.

## SIZE REDUCTION

As received, most solid waste has a low bulk density and is composed of a wide variety of objects in all sizes and shapes. This is especially the case for MSW. Solid waste shredding machines are not capable of destroying waste matter, but only of converting it into a form more easily and economically handled for processing. Hammer mills in one adaptation or another are the most commonly used size reduction machine.

The machines are variously called shredders, crushers, pulverizers, mills, and hoggers. Shredder is the most frequently used term. At one time, both capacity and durability posed important limitations to the application of waste shredders on a large scale. This is no longer true. Today, shredders are in service which can nuggetize two complete automobiles per minute. Capacities of the largest waste shredders exceed 100 tons/hr.

The most common shredder design consists of a welded steel frame protected on the interior with abrasion-resistant steel alloy liners. Within the frame, there is a power-driven rotor with rows of pivoted manganese steel hammers.

For handling oversize bulky waste and other hard refuse, hammers are free to pivot back under impact to give relief from overload or shock. A series of sizing grates are positioned below the rotor. The violent hammer action reduces the material to a size that will pass through openings in the grates. Maximum product size can be controlled by installing grates with large or small openings. Figure 1 illustrates key features found in a hammer mill.

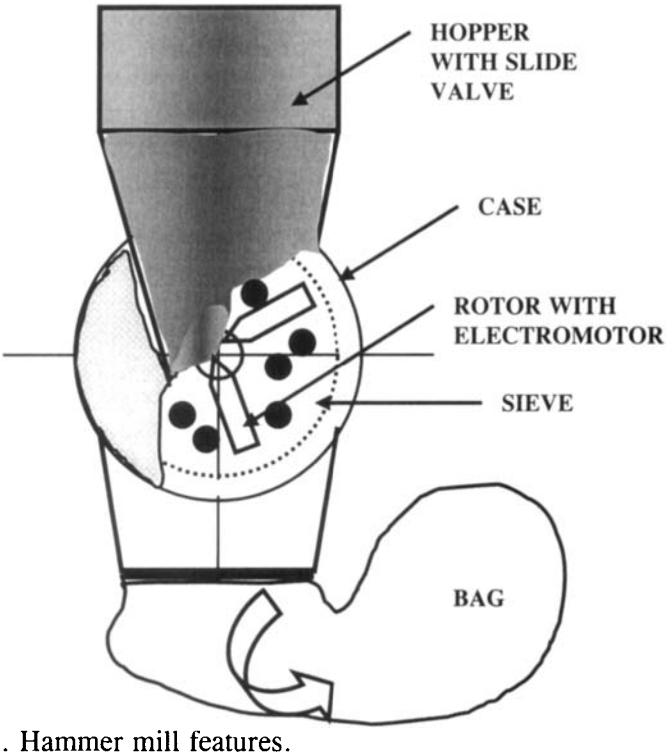


Figure 1. Hammer mill features.

Characteristics of shredded waste differ somewhat from those of other materials which are processed in shredders and hammer mills. With many materials, it is possible to arrive at a screen analysis or size degradation which tells the size of the particles produced, as well as the relative quantity of the various size particles. However, because of the variety of materials contained in solid waste and seasonal variations which can be expected, a quantitative analysis of size degradation is almost impossible.

Shredder size should be selected to allow for anticipated surges in the rate of material feed. In addition to processing the hourly tonnage of materials, a refuse shredder must be sized to accommodate the largest pieces anticipated. Size reduction machines consume power in proportion to the feed rate and to the degree to which material is reduced. Little or no shock loading will occur when processing small pieces of wood, paper, corrugated board, bottles, plastic, and assorted organic matter. However, where a shredder must handle oversize bulky waste such as rubber tires, mattresses, refrigerators, stoves, tree limbs, furniture, packing crates, and demolition lumber, the power source and the drive train must be designed to withstand shock loading. For most solid waste applications, a motor is selected to provide between 12 and 20 horsepower per ton of refuse per hour. Shredder output is characterized by the maximum particle size though much of the product will be far smaller. Arbitrarily specifying a small final product will mean increasing shredder size, cost, power requirements, and cost of maintenance over the operating life of the installation. Shredder output can range from as large as 10 in. for landfilling to as small as 1 in. for composting.

To reduce the cost per ton of MSW handling, many communities have installed transfer stations. At the transfer station, small payload collection trucks are unloaded and quickly returned to neighborhood route service. Refuse is shredded to reduce bulk and improve handling characteristics. Compaction immediately after shredding can reduce the waste to one-third of its original volume.

Shredders can help a waste incineration plant operate more effectively. Even when physical size of the waste is not the limiting factor, firing theory indicates that more efficient combustion will occur when solid waste material is first shredded.

Modern high-capacity composting operations would not be possible without the use of shredding machines. In these plants, shredders reduce waste to a size which can be quickly decomposed by bacterial action. Composting plants operate best with a relatively fine particle size.

The process is speeded if fibrous material is also opened. To produce the required fineness at high material flow rates, composting operations usually employ two shredders in series. Following bacterial decomposition, a third shredder may be used to thoroughly mix the compost and to break up any agglomerates not destroyed in the digester tank. Output size from the secondary refuse shredder operation will usually be on the order of 1 in.

Shredding is also used in conjunction with sanitary landfilling operations. When deposited in a landfill, waste shredded to a maximum size of 6 to 10 in. will not support combustion, will not support vermin, will not produce odor, and will not provide a breeding ground for insects.

Reduced volume of the shredded waste leads to prolonged life of the landfill site. Materials such as rubber tires and demolition lumber which could not previously be effectively compacted into a landfill present no problem after shredding. The effective life of the landfill site is prolonged from two to three times that normally expected, and the expense for covering the site daily with topsoil is eliminated.

## CONCENTRATING METHODS

Concentrating methods are most often applied in industrial and wastewater treatment applications, where sludges are recovered during various treatment stages. By reducing the volume of sludge to be disposed of, savings for transport and ultimate disposal can be achieved. In wastewater treatment applications these methods are more commonly refered to as *dewatering*.

The objective of *dewatering* (also called *sludge thickening*) is to concentrate the sludge, and make it as dry as economically possible for post processing and disposal purposes. There are both mechanical and thermal techniques for achieving this. This section only describes mechanical methods.

Among the mechanical processes used to dewater sludge are belt filter presses and drum filters (vacuum technologies), pressure filter presses, and centrifugation.

### VACUUM FILTRATION

The vacuum filter for dewatering sludge is a drum over which is laid the filtering medium consisting of a cloth of cotton, wool, nylon, Dynel, fiberglass, or plastic; a stainless-steel mesh, or a double layer of stainless-steel coil springs. The drum with horizontal axis is set in a tank with about one-quarter of the drum submerged in conditioned sludge. Valves and piping are so arranged that, as a portion of the drum rotates slowly in the sludge, a vacuum is applied on the inner side of the filter medium, drawing out water from the sludge and holding the sludge against it. The application of the vacuum is continued as the drum rotates out of the sludge and into the atmosphere. This pulls water away from the sludge, leaving a moist mat or cake on the outer surface. This mat is scraped, blown, or lifted away from the drum just before it enters the sludge tank again. The common measure of performance of vacuum filters is the rate in pounds per hour of dry solids filtered per square foot of filter surface. For various sludge this rate may vary from a low of 2.5 for activated sludge to a high of 6 to 11 for the best digested primary sludge. The moisture content in the sludge cake also varies with the type of sludge, from 80 to 84% for raw activated sludge to 60 to 68% for well-digested primary sludge. While operating costs, including conditioning of sludge for vacuum filtration, are usually higher than with sludge beds, filtration has the advantage of requiring much less area, is independent of seasons and weather conditions, and can eliminate the necessity for digestion, since raw sludge can be dewatered sufficiently to be incinerated.

Proper care may prolong of the life of the material used as the filter. Such care includes washing of the filter material with the spray jets after every period of use, removal of grease and fats with warm soap solution if clogged, treatment with diluted hydrochloric acid for removal of lime encrustations, and maintenance of the scraper blade in careful adjustment to the filter drum to prevent tearing of the filter material.

## CHEMICAL USE

Diluted ferric chloride solutions (10 to 20%) usually give better results in the conditioning of the sludge. A high-calcium lime is preferable or sludge filtration work. One should avoid excessive use of chemicals. The quantities of chemicals used for conditioning can be frequently reduced by careful control of the mixing and flocculation equipment. The maintenance of a uniform vacuum is necessary for satisfactory operation. Loss or fluctuations in vacuum usually indicate a break in the filter material, poorly conditioned sludge, or uneven distribution of the sludge solids in the filter pan.

## ROTARY DRUM PRECOAT FILTER

This machine is used to polish solutions having traces of contaminating insolubles, so it is not a dewatering machine per se, but its use is often integrated into the process. To polish the solution, the drum deck is precoated with a medium of a known permeability and particle size that retains the fines and produces a clear filtrate. The following materials are used to form the precoat bed: diatomaceous earth (or diatomite) consisting of silicaceous skeletal remains of tiny aquatic unicellular plants; perlite consisting of glassy crushed and heat-expanded rock of volcanic origin; and cellulose consisting of fibrous lightweight and ashless paperlike medium. Special ground wood has also become popular in recent years because it is combustible and reduces the high cost of disposal. There are manufacturers nowadays that grind, wash, and classify special timber to permeabilities, which can suit a wide range of applications. These materials when related to precoating are wrongly called filter aids since they do not aid filtration but serve as a filter medium in an analogy to the filter cloth on a conventional drum filter.

The *precoat filter* is similar in appearance to a conventional drum filter but its construction is very different. The scraper blade on conventional drum filters is stationary and serves mainly to deflect the cake while it is back-blown at the point of discharge. The scraper on a precoat filter, which is also called the *doctor blade*, moves slowly toward the drum and shaves off the blinding layer of the contaminants together with a thin layer of the precoating material. This movement continuously exposes a fresh layer of the precoat surface so that when the drum submerges into the tank it is ready to polish the solution. The blade movement mechanism is equipped with a precision drive having an adjustable advance rate of 1 to 10 mm/hr. The selected rate is determined by the penetration of fines into the precoat bed, which in turn depends on the permeability of the filter aid. Once the entire precoat is consumed the blade retracts at a fast rate so that the filter is ready for a new precoating cycle. The cake discharges on conventional drum filters by blow-back; hence a section of the main valve's bridge setting is allocated for this purpose. On precoat filters the entire drum deck is subjected to vacuum; therefore, there are two design options:

- A conventional valve that is piped, including its blow-back section, to be open to vacuum during polishing. When the precoat is consumed its blow-back section is turned on to remove the remaining precoat heel over the doctor blade.
- A valveless configuration in which there is no bridge setting and the sealing

between the rotating drum and the stationary outlet is by circumferential O-rings rather than by a face seal used on conventional valves.

The flow scheme for a conventional precoat filter station typically looks like that shown in Figure 2. The doctor blade discharge configuration for this machine is illustrated in Figure 3.

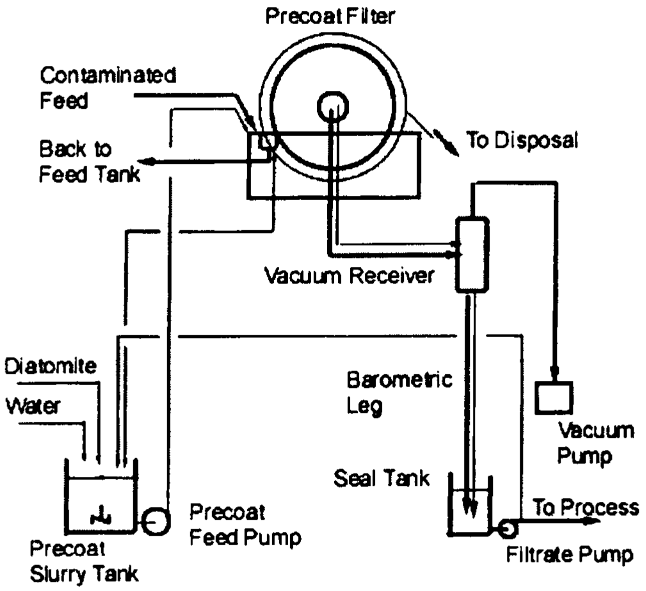


Figure 2. Precoat drum filter flow scheme for polishing operations.

## PRESSURE FILTRATION

Pressure filtration is a process similar to vacuum filtration where sludge solids are separated from the liquid. Leaf filters probably are the most common type of unit. As in vacuum filtration, a porous medium is used in leaf filters to separate solids from the liquid. The solids are captured in the media pores; they build up on the media surface; and they reinforce the mediium in its solid-liquid separation action. Sludge pumps provide the energy to force the water through the medium. Lime, aluminum chloride, aluminum chlorohydrate, and ferric salts have been commonly used to condition sludge prior to pressing.

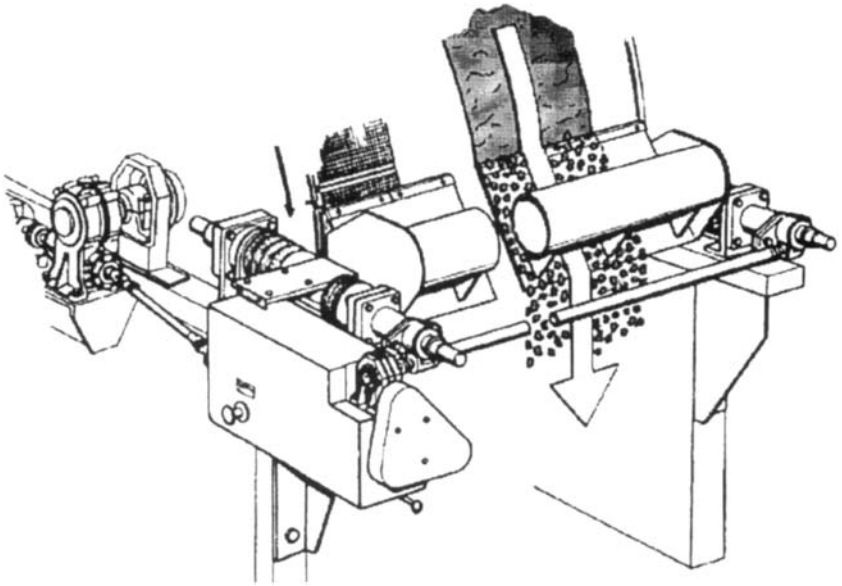


Figure 3. Doctor blade discharge for precoat filter.

The successful use of ash precoating is also prevalent. Minimum chemical costs are supposed to be the major advantage of press filters over vacuum filters. Leaf filters represent an attempt to dewater sludge in a small space quickly. But, when compared to other dewatering methods, they have major disadvantages, including (1) batch operation and (2) high operation and maintenance costs. Some other types of pressure filters include hydraulic and screw presses, which while effective in dewatering sludges, have the major disadvantage of usually requiring a thickened sludge feed. Sludge cakes containing as high as 75% solids using pressure filtration have been reported.

## CENTRIFUGE DEWATERING

Centrifuges are machines that separate solids from the liquid through sedimentation and centrifugal force. In a typical unit sludge is fed through a stationary feed tube along the centerline of the bowl through a hub of the screw conveyor. The screw conveyor is mounted inside the rotating conical bowl. It rotates at a slightly lower speed than the bowl. Sludge leaves the end of the feed tube, is accelerated, passes through the ports in the conveyor shaft, and is distributed to the periphery of the bowl. Solids settle through the liquid pool, are compacted by centrifugal force against the walls of the bowl, and are conveyed by the screw conveyor to the drying or beach area of the bowl. The beach area is an inclined section of the bowl where further dewatering occurs before the solids are discharged. Separated liquid is discharged continuously over adjustable weirs at the opposite end of the bowl. The important process variables are: (1) feed rate, (2) sludge solids characteristics, (3) feed consistency, (4) temperature, and (5) chemical additives. Machine variables are: (1) bowl design, (2) bowl speed, (3) pool volume, and (4) conveyor speed. Two factors usually determine the success or failure of centrifugation: cake dryness and solids recovery. The effect of the various parameters on these two factors are listed below:

| **To increase cake dryness:** | **To increase solids recovery:** |
|---|---|
| 1. Increase bowl speed | 1. Increase bowl speed |
| 2. Decrease pool volume | 2. Increase pool volume |
| 3. Decrease conveyor speed | 3. Decrease conveyor speed |
| 4. Increase feed rate | 4. Decrease feed rate |
| 5. Decrease feed consistency | 5. Increase temperature |
| 6. Increase temperature | 6. Use flocculants |
| 7. Do not use flocculants | 7. Increase feed consistency |

Centrifugation has some inherent advantages over vacuum filtration and other processes used to dewater sludge. It is simple, compact, totally enclosed, flexible, can be used without chemical aids, and the costs are moderate. Industry particularly has accepted centrifuges in part because of their low capital cost, simplicity of operation, and effectiveness with difficult-to-dewater sludges. The most effective centrifuges to dewater waste sludges are horizontal or cylindrical conical, solid-bowl machines. Basket centrifuges dewater sludges effectively but liquid clarification is poor. Disk-type machines do a good job of clarification but their dewatering capabilities leave much to be desired. Centrifuges are being installed in more and more wastewater treatment plants for the following reasons: (1) the capital cost is low in comparison with other mechanical equipment, (2) the operating and maintenance costs are moderate, (3) the unit is totally enclosed so odors are minimized, (4) the unit is simple and will fit in a small space, (5) chemical conditioning of the sludge is often not required, (6) the unit is flexible in that it can handle a wide variety of solids and function as a thickening as well as a dewatering device, (7) little supervision is required, and (8) the centrifuge can dewater some industrial sludges that cannot be handled by vacuum filters.

The poor quality of the centrate is a major problem with centrifuges. The fine solids in centrate recycled to the head of the treatment plant sometimes resist settling and as a result, their concentrations in the treatment system gradually build up. The centrate from raw sludge dewatering can also cause odor problems when recycled. Flocculants can be used to increase solids captures, often to any degree desired, as well as to materially increase the capacity (solids loading) of the centrifuges. However, the use of chemicals nullifies the major advantage claimed for centrifuges - moderate operating costs. As noted, three basic types of centrifuges are disk-nozzle, basket, and solid bowl. The latter two types have been used extensively for both dewatering and thickening. The disk-nozzle centrifuge is seldom used for dewatering sludge, but is used more for sludge thickening in the industrial sector. Because the solid-bowl design has undergone major improvements throughout the history of its use, this method is used more than any other to dewater sludge. Because of recent improvements in solid-bowl centrifuge design, solid concentrations can reach 35%.

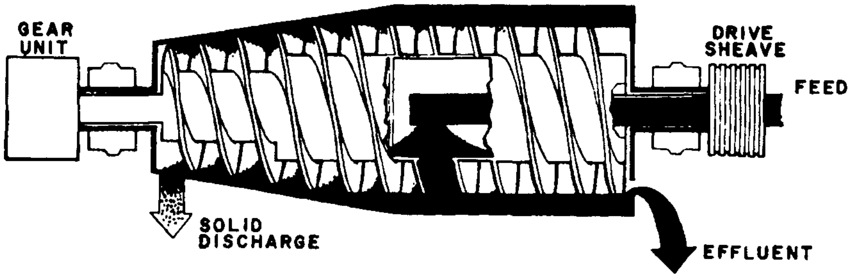


Figure 4. Continuous solid-bowl centrifuge.

The solid-bowl conveyor centrifuge operates with a continuous feed and discharge rates. It has a solid-walled imperforated bowl, with a horizontal axis of rotation. These centrifuges are enclosed, so they have a limited odor potential compared with other dewatering methods. The laydown area, access area, and centrifuge required space for a large machine (200 m to 700 gpm of sludge feed) is approximately 400 ft$^2$. Compared to other mechanical dewatering machines, this space is significantly smaller. An example of a continuous horizontal solid-bowl centrifuge is illustrated in Figure 4. It consists of a cylindrical rotor with a truncated cone-shaped end and an internal screw conveyor rotating together. The screw conveyor often rotates at a rate of 1 or 2 rpm below the rotor's rate of rotation. The suspension enters the bowl axially through the feed tube to a feed accelerated zone, then passes through a feed port in the conveyor hub into the pond. The suspension is subjected to centrifugal force and thrown against the bowl wall where the solids are separated. The clarified suspension moves toward the broad part of the bowl to be discharged through a port. The solid particles being scraped by the screw conveyor are carried in the opposite direction (to the small end of the bowl) across discharge ports through which they are ejected continuously by centrifugal force. As in any sedimentation centrifuge, the separation takes place in two stages: settling (Figure 4, in the right part of the bowl), and thickening or pressing out of the sediment (left-hand side of the bowl).

Because the radius of the solid discharge port is usually less than the radius of the liquid overflow at the broader end of the bowl, part of the settled solids is submerged in the pond. The remainder, closer to the center, is inside the free liquid interface, where they can drain before being discharged. The total length of the settling and pressing-out zones depends on the dimensions of the rotor. Their relative length can be varied by changing the pond level through suitable adjustment of the liquid discharge radius. When the pond depth is lowered, the length of the pressing-out zone increases with some sacrifice in the clarification effectiveness. The critical point in the transport of solids to the bowl wall is their transition across the free liquid interface, where the buoyancy effect of the continuous phase is lost. At this point, soft amorphous solids tend to flow back into the pond instead of discharging. This tendency can be overcome by raising the pond level so that its radius is equal to, or less than, that of the solids discharge port. In reality, there are no dry settled solids. The solids form a dam, which prevents the liquid from overflowing. The transfer of solids becomes possible because of the difference between the rotational speed of the screw conveyor and that of the bowl shell. The flights of the screw move through the settled solids and cause the solids to advance. To achieve this motion, it is necessary to have a high circumferential coefficient of friction on the solid particles with respect to the bowl shell and a low coefficient axially with respect to the bowl shell and across the conveyor flights. These criteria may be achieved by constructing the shell with conical grooves or ribs and by polishing the conveyor flights. The conveyor or differential speed is normally in the range of 0.8 to 5% of the bowl's rotational speed.

The required differential is achieved by a two-stage planetary gear box. The gear box housing carrying two ring gears is fixed to, and rotates with, the bowl shell. The first-stage pinion is located on a shaft that projects outward from the housing. This arrangement provides a signal that is proportional to the torque imposed by the conveyor. If the shaft is held rotationally (for example, by a torque overload release device or a shear pin), the relative conveyor speed is equivalent to the bowl rotative speed divided by the gear-box ratio. Variable differential speeds can be obtained by driving the pinion shaft with an auxiliary power supply or by allowing it to slip forward against a controlled braking action. Both arrangements are employed when processing soft solids or when maximum retention times are needed on the pressing out zone. The solids-handling capacity of this type centrifuge is established by the diameter of the bowl, the conveyor's pitch, and its differential speed. Feed ports should be located as far from the effluent discharge as possible to maximize the effective clarifying length. Note that the feed must be introduced into the pond to minimize disturbance and resuspension of the previously sedimented solids. As a general rule, the preferred feed location is near the intercept of the conical and cylindrical portions of the bowl shell. The angle of the sedimentation section with respect to the axis of rotation is typically in the range of 3° to 15°. A shallow angle provides a longer sedimentation area with a sacrifice in the effective length for clarification.

In some designs, a portion of the conveyor flights in the sedimentation area is shrouded (as with a cone) to prevent intermixing of the sedimented solids with the free supernatant liquid in the pond through which they normally would pass. In other designs, the clarified liquid is discharged from the front end via a centrifugal pump or an adjustable skimmer that sometimes is used to control the pond level in the bowl. Some displacement of the adhering virgin liquor can be accomplished by washing the solids retained on the settled layer, particularly if the solids have a high degree of permeability. Washing efficiency ranges up to 90% displacement of virgin liquor on coarse solids. Some configurations enable the settled layer to have two angles; comparatively steep in the wetted portion (10 to 15°) and shallow in the dry portion (3 to 5°). A wash is applied at the intersection of these angles, which, in effect, forms a constantly replenished zone of pure liquid through which the solids are conveyed. The longer section of a dry shallow layer provides more time for drainage of the washed solids. In either washing system, the wash liquid that is not carried out with the solids fraction returns to the pond and eventually discharges along with the effluent virgin liquor.

### *Disk-Bowl Centrifuges*

Disk-bowl centrifuges are used widely for separating emulsions, clarifying fine suspensions, and separating immiscible liquid mixtures. Although these machines are generally not applied to wastewater applications and are more usually found in food processing, they can find niche applications in water treatment. More sophisticated designs can separate immiscible liquid mixtures of different specific gravities while simultaneously removing solids. Figure 5 illustrates the physical separation of two liquid components within a stack of disks. The light liquid phase builds up in the inner section, and the heavy phase concentrates in the outer section.

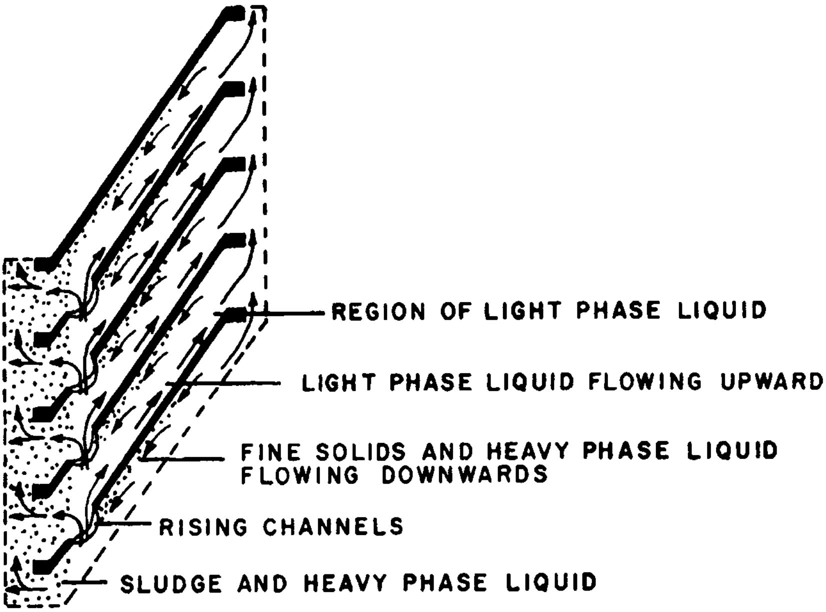


Figure 5. Separation is achieved by use of stack disks.

The dividing line between the two is referred to as the *separating zone*. For the most efficient separation, this is located along the line of the rising channels, which are a series of holes in each disk, arranged so that the holes provide vertical channels through the entire disk set. These channels also provide access for the liquid mixture into the spaces between the disks. Centrifugal force causes the two liquids to separate, and the solids move outward to the sediment-holding space.

The position of the separating zone is controlled by adjusting the back pressure of the discharged liquids or by means of exchangeable ring dams. Figure 6 illustrates the main features of a disk-bowl centrifuge, which includes a seal ring (1); a bowl (2) with a bottom (13); a central tube (18), the lower part of which has a fixture (16) for disks; a stack of truncated cone disks (17), frequently flanged at the inside and outer diameters to add strength and rigidity; collectors (3 and 4) for the products of separation; and a feed tank (5) with a tube (6).

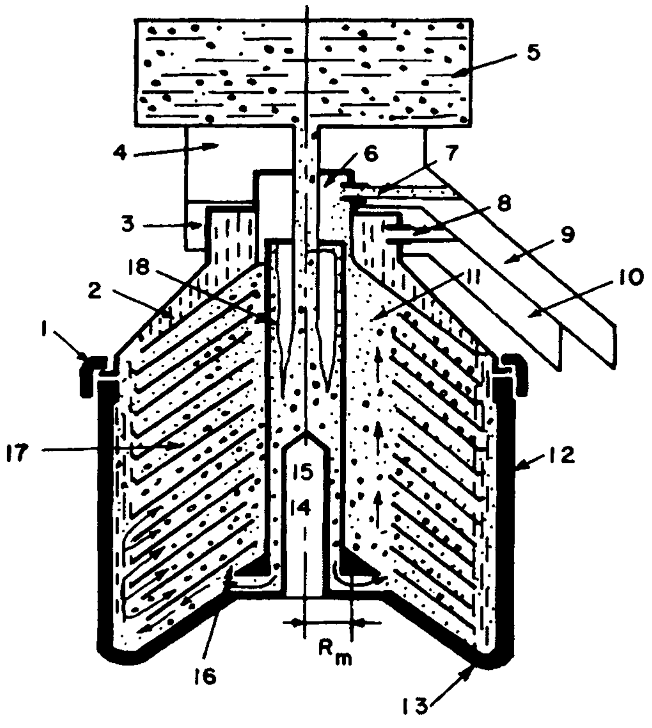


Figure 6. Details of disk-bowl centrifuge.

The bowl is mounted to the tube (14) with a guide in the form of a horizontal pin. This arrangement allows the bowl to rotate along with the shaft. The suspension is supplied from the feed tank (5) through the fixed tube (6), to the central tube (18), which rotates together with the bowl and allows the liquid to descend to the bottom. In the lower part of the bowl, the suspension is subjected to centrifugal force and, thus, directed toward the periphery of the bowl. The distance between adjacent disks is controlled by spacers that usually are radial bars welded to the upper surface of each disk. The suspension may enter the stack at its outside diameter or through a series of vertical channels cut through the disks, as described earlier. The suspension is lifted up through vertical channels formed by the holes in the disks and distributed simultaneously under the action of centrifugal force into the spacings between the disks. These spacings are of tight tolerances and can range from 0.3 to 3 mm.

Because of its larger diameter, the disk bowl operates at a lower rotational speed than its tubular counterpart. Its effectiveness depends on the shorter path of particle settling. The maximum distance a particle must travel is the thickness of the spacer divided by the cosine of the angle between the disk wall and the axis of rotation. Spacing between disks must be wide enough to accommodate the liquid flow without promoting turbulence and large enough to allow sedimented solids to slide outward to the grit-holding space without interfering with the flow of liquid in the opposite direction.

The disk angle of inclination (usually in the range of 35° to 50°) generally is small to permit the solid particles to slide along the disks and be directed to the solids-holding volume located outside of the stack. Dispersed particles transfer from one layer to the other; therefore, the concentration in the layers and their thickness are variables. The light component from the spacing near central tube (18) falls under the disk; then it flows through the annular gap between tube (18) and the cylindrical end of the dividing disk, where it is ejected through the port (7) into the circular collector (4) and farther via the funnel (9) on being discharged to the receiver. The heavier product is ejected to the bowl wall and raised upward. It enters the space between the outside surface of the dividing disk and the cone cover (2), then passes through the port (8) and is discharged into the collector (3). From there, the product is transferred to the funnel (10).

## THICKENERS

Thickening is practiced in order to remove as much water as possible before final dewatering of the sludge. It is usually accomplished by floating the solids to the top of the liquid (floatation) or by allowing the solids to settle to the bottom (gravity thickening). Other methods of thickening include centrifuging, gravity belts, and rotary drum thickening. These processes offer a low-cost means of reducing the volumetric loading of sludge to subsequent steps.

In the flotation thickening process air is injected into the sludge under pressure. The resulting air bubbles attach themselves to sludge solids particles and float them to the surface of an open tank. The sludge forms a layer at the top of the tank which is removed by a skimming mechanism. This process increases the solids concentration of activated sludge from 0.5 to 1% to 3 to 6%.

Gravity thickening has been widely used on primary sludge for many years because of its simplicity and inexpensiveness. In gravity thickening, sludge is concentrated by the gravity-induced settling and compaction of sludge solids. It is essentially a sedimentation process. Sludge flows into a tank that is similar to the circular clarifiers used in primary and secondary sedimentation. The solids in the sludge settle to the bottom where a scraping mechanism removes them to a hopper. The type of sludge being thickened has a major effect on performance. The best results can be achieved with primary sludge. Purely primary sludge can be thickened from 1 to 3% up to 10% solids. As the proportion of activated (secondary) sludge increases, the thickness of settled solids decreases.

There are various designs for sludge thickeners and any standard textbook on wastewater treatment technology will provide the reader with further details. There are a variety of technologies from which to select for sludge dewatering operations. Each has its own set of advantages, disadvantages, and limitations in operating ranges.

Selection greatly depends on the volumes and nature of the sludge. Table 1 provides a relative comparison between the principal mechanical dewatering techniques.

Table 1. Advantages and Disadvantages of Mechanical Thickening Technologies

| Technology or method | Advantages | Disadvantages |
|---|---|---|
| Gravity | Simple<br>Low operating and maintenance costs<br>Low operator attention and moderate training requirements<br>Minimal power consumption | Potential for obnoxious and harmful odors<br>Thickened sludge concentration limited for WAS<br>High space requirements for WAS |
| Dissolved air flotation | Effective for WAS<br>Can work without conditioning chemicals<br>Relatively simple equipment components | Relatively high power consumption<br>Thickening solids concentration limited<br>Potential for obnoxious and harmful odors<br>High space requirements |
| Centrifugation | Low space requirements<br>Effective for WAS<br>Minimum housekeeping and odor problems<br>Highly thickened concentrations available | Best suited for continuous operations<br>Sophisticated maintenance requirements<br>Relatively high power consumption<br>Relatively high capital cost |
| Rotating drum filter | Low space requirements<br>Low capital cost<br>Relatively low power consumption<br>High solids capture achievable | Can be polymer dependent<br>Sensitive to polymer type<br>Housekeeping requirements high<br>Potential for obnoxious and harmful odors<br>Moderate operator attention and training requirements |

| Technology or method | Advantages | Disadvantages |
|---|---|---|
| Gravity belt thickener | Low space requirements<br>Relatively low power consumption<br>Relatively low capital cost<br>Can achieve high thickened concentrations and solids capture with minimum power | Housekeeping requirements high<br>Can be polymer dependent<br>Moderate operator attention and training requirements<br>Potential for obnoxious and harmful odors |

## INCINERATION OF MUNICIPAL SLUDGE

Incineration of municipal wastewater treatment sludge is widely practiced in many parts of the world. Its application is the reduction in the volume and weight of end product to be disposed of. There is a minimum size of sewage treatment plant below which incineration is not economical. There must be enough sludge to necessitate reasonable use of costly equipment. One of the difficulties in operating an incinerator is variations in tonnage and moisture of sludge handled. There are two major incinerator technologies used in this process. They are (1) the multiple hearth incinerator and (2) the fluidized-bed incinerator. An incinerator is usually part of a sludge treatment system which includes sludge thickening, macerations, dewatering (such as vacuum filter, centrifuge, or filter press), an incinerator feed system, air pollution control devices, ash handling facilities, and the related automatic controls. The operation of the incinerator cannot be isolated from these other system components. Of particular importance is the operation of the thickening and dewatering processes because the moisture content of the sludge is the primary variable affecting the incinerator fuel consumption.

Incineration may be thought of as the complete destruction of materials by heat to their inert constituents. This material that is being destroyed is the waste product (i.e., the sludge). Sewer sludge as sludge cake normally contains from 55 to 85% moisture. It cannot burn until the moisture content has been reduced to no more than 30%.

The purpose of incineration is to reduce the sludge cake to its minimum volume, as sterile ash. There are three objectives incineration must accomplish:

- Dry the sludge cake
- Destroy the volatile content by burning
- Produce a sterile residue or ash

There are four basic types of incinerators used in wastewater treatment plants. They are the multiple hearth incinerator, the fluid bed incinerator, the electric furnace, and the cyclonic furnace. Each system has its own distinct method of incineration and while one may be more cost efficient, another may have more of an environmental impact.

Sewage sludge ash is the by-product produced during the combustion of dewatered sewage sludge in an incinerator. Sewage sludge ash is primarily a silty material with some sand-size particles. The specific size range and properties of the sludge ash depend to a great extent on the type of incineration system and the chemical additives introduced in the wastewater treatment process. Two major incineration systems, multiple hearth and fluidized bed, are employed in the United States, with approximately 80% of the incinerators being multiple hearth designs. The multiple-hearth incinerator is a circular steel furnace that contains a number of solid refractory hearths and a central rotating shaft. Rabble arms that are designed to slowly rake the sludge on the hearth are attached to the rotating shaft. Dewatered sludge (approximately 20% solids) enters at the top and proceeds downward through the furnace from hearth to hearth, pushed along by the rabble arms. Cooling air is blown through the central column and hollow rabble arms to prevent overheating. The spent cooling air with its elevated temperature is usually recirculated and used as combustion air to save energy. Flue gases are typically routed to a wet scrubber for air pollution control. The particulates collected in the wet scrubber are usually diverted back into the sewage plant.

Fluidized bed incinerators consist of a vertical cylindrical vessel with a grid in the lower sections to support a bed of sand. Dewatered sludge is injected into the lower section of the vessel above the sand bed and combustion air flows upward and fluidizes the mixture of hot sand and sludge. Supplemental fuel can be supplied by burning above and below the grid if the heating value of the sludge and its moisture content are insufficient to support combustion.

Figure 7 illustrates a simplified flow diagram of a sludge incinerator. The complete system includes sludge pretreatment operations such as sludge thickening (sedimentation) and sludge dewatering (vacuum filter, centrifuge, or filter press), followed by incineration, air pollution control, and ash handling. Sludge dewatering may involve the addition of ferrous chloride, lime, or organic polymers to enhance the dewatering process. Auxiliary fuel is normally needed to maintain the combustion process. The quantity of auxiliary fuel required depends on the heating value of the sludge solids and, primarily, on the moisture content of the incoming feed sludge. Operating temperatures can vary, depending on the type of furnace, but can be expected to range from approximately 650°C (1200°F) to 980°C (1800°F) in the incinerator combustion zone. High operating temperatures above 900°C (1650°F) can result in partial fusion of ash particles and the formation of clinkers, which end up in the ash stream. Lime may also be added to reduce the slagging of sludge during incineration. Incineration of sewage sludge (dewatered to approximately 20% solids) reduces the weight of feed sludge requiring disposal by approximately 85%. There are approximately 170 municipal sewage treatment plant incinerators in the United States, processing approximately 20% of the contry's sludge, and producing between 0.45 million and 0.9 million metric tons (0.5 and 1.0 million tons) of sludge ash on an annual basis.

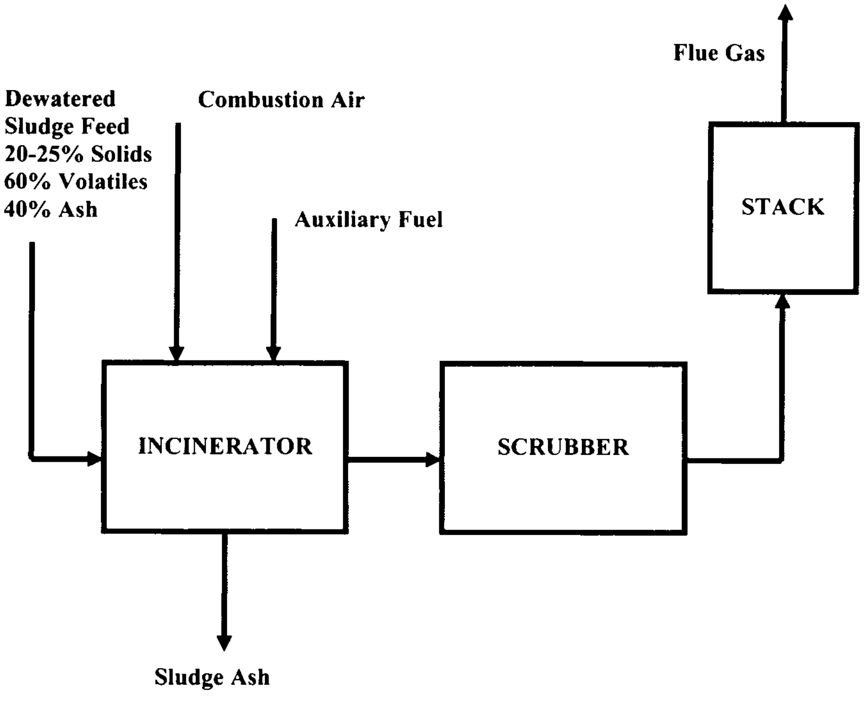


Figure 7. Sewage sludge incineration process.

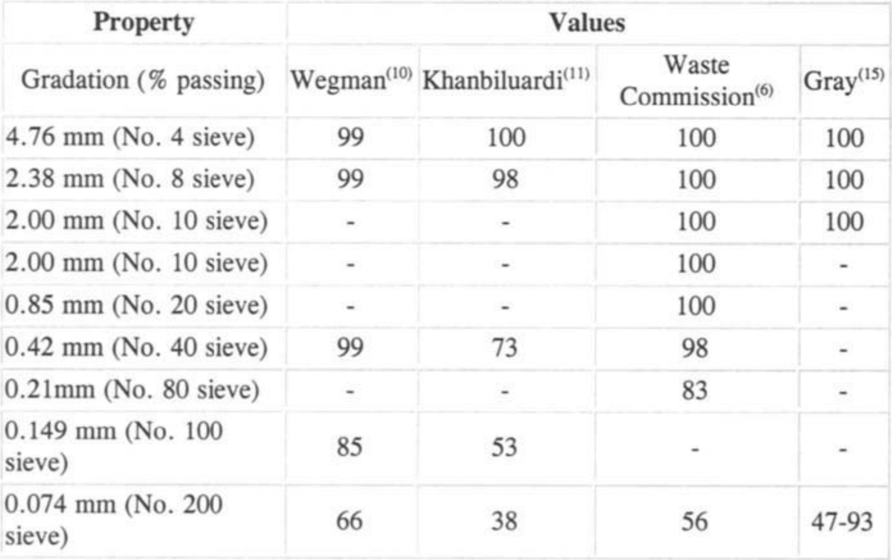
## INCINERATOR ASH PROPERTIES

Table 2 provides lierature reported values of physical property characterization data for sludge ash. Sludge ash is a silty-sandy material. A relatively large fraction of the particles (up to 90% in some ashes) are less than 0.075 mm (No. 200 sieve) in size. Sludge ash has a relatively low organic and moisture content. Permeability and bulk specific gravity properties are not unlike those of a natural inorganic silt. Sludge ash is a nonplastic material.

Sludge ash consists primarily of silica, iron, and calcium. The composition of the ash can vary significantly and depends in great part on the additives introduced in the sludge conditioning operation. There are no specific data available relative to the pozzolanic or cementitious properties of sludge ash, but sludge ash is not expected to exhibit any measurable pozzolanic or cementitious activity. Table 3 lists the range of major elemental concentrations present in sludge ash.

Trace metal concentrations (e.g., lead, cadmium, zinc, copper) found in sludge ash are typically higher than concentrations found in natural fillers or aggregate. This has resulted in some reluctance to use this material; however, recent investigations (leaching tests) suggest that these trace metal concentrations are not excessive and do not pose any measurable leaching problem.

Table 2. Typical Physical Properties of Sewage Sludge Ash



| Property | Values | | | |
|---|---|---|---|---|
| Gradation (% passing) | Wegman(10) | Khanbiluardi(11) | Waste Commission(6) | Gray(15) |
| 4.76 mm (No. 4 sieve) | 99 | 100 | 100 | 100 |
| 2.38 mm (No. 8 sieve) | 99 | 98 | 100 | 100 |
| 2.00 mm (No. 10 sieve) | - | - | 100 | 100 |
| 2.00 mm (No. 10 sieve) | - | - | 100 | - |
| 0.85 mm (No. 20 sieve) | - | - | 100 | - |
| 0.42 mm (No. 40 sieve) | 99 | 73 | 98 | - |
| 0.21mm (No. 80 sieve) | - | - | 83 | - |
| 0.149 mm (No. 100 sieve) | 85 | 53 | - | - |
| 0.074 mm (No. 200 sieve) | 66 | 38 | 56 | 47-93 |

| **Property** | **Values** | | | |
|---|---|---|---|---|
| Gradation (% passing) | Wegman(10) | Khanbiluardi(11) | Waste Commission(6) | Gray(15) |
| - (0.0902 mm) | 10-13 | - | - | 2-13 |
| 0.02 mm | - | - | 20 | - |
| 0.005 mm | - | - | 12 | - |
| >0.001 mm | - | - | 2 | - |
| Loss on Ignition (%) | 1.4(10) | | | |
| Moisture Content (% by Total Weight) | 0.28(11) | | | |
| Absorption (%) | 1.6(6) | | | |
| Specific Gravity | 2.60(10)<br>2.61(6)<br>2.44 - 2.96(15)<br>2.39 - 2.99(2) | | | |
| Bulk Specific Gravity | 1.82(11)<br>1.27 - 1.48(2) | | | |
| Plasticity Index | Nonplastic(10) | | | |
| Permeability (ASTM D2434 - cm/sec) | 4 x $10^{-4}$<br>1 x $10^{-4}$ - 4 x $10^{-4>}$(6) | | | |

Table 3. Typical Range of Elemental Concentrations in Sewage Sludge Ash

| | | **Concentration %** | | | |
|---|---|---|---|---|---|
| **Element** | **Oxide** | **Reported as elemental concentration(2)** | **Reported as elemental concentration(6)** | **Reported as oxides(10,16)** | **Reported as oxides(15)** |
| Silicon (Si) | ($SiO_2$) | 5.6-25.7 | 20 | 27.0 | 14.4-57.7 |
| Calcium (Ca) | (CaO) | 1.4-42.9 | 8 | 21.0 | 8.9-36.9 |
| Iron (Fe) | ($Fe_2O_3$) | 1.0-16.4 | 4 | 8.2 | 2.6-24.4 |
| Aluminum (Al) | ($Al_2O_3$) | 1.1-8.5 | 7 | 14.4 | 4.6-22.1 |
| Magnesium (Mg) | (MgO) | 0.6-1.9 | 2 | 3.2 | 0.8-2.2 |
| Sodium | ($Na_2O$) | 0.1-0.8 | 0.3 | 0.5 | 0.1-0.7 |

| | | Concentration % | | | |
|---|---|---|---|---|---|
| **Element** | **Oxide** | **Reported as elemental concentration**[2] | **Reported as elemental concentration**[6] | **Reported as oxides**[10,16] | **Reported as oxides**[15] |
| (Na) | | | | | |
| Potassium (K) | ($K_2O$) | 0.3-1.6 | 0.5 | 0.6 | 0.07-0.7 |
| Phosphorus | ($P_2O_5$) | 1.2-4.4 | 6 | 20.2 | 3.9-15.4 |
| Sulfur (S) | ($SO_3$) | 0.3-1.2 | - | 0.9 | 0.01-3.4 |
| Carbon (C) | - | 0.6-2.2 | - | - | - |

References at the end of this chapter may be consulted for the sources of data in Tables 2 and 3 as well as additional information.

## MULTIPLE HEARTH INCINERATORS

This incinerator is the most prevalent incinerator technology for the disposal of sewage sludge in the United States because of its low ash discharge. Sludge cake enters the furnace at the top. The interior of the furnace is composed of a series of circular refractory hearths, which are stacked one on top of the other. There are typically five to nine hearths in a furnace. A vertical shaft, positioned in the center of the furnace has rabble arms with teeth attached to them in order to move the sludge through the mechanism. Each arm is above a layer of hearth. Teeth on each hearth agitate the sludge, exposing new surfaces of the sludge to the gas flow within the furnace. As sludge falls from one hearth to another, it again has new surfaces exposed to the hot gas. At the top of the incinerator there is an exit for flue gas, an end product of sludge incineration. At the bottom of the furnace there is an exit for the ashes. Figure 8 illustrates the key design features.

Partially dewatered sludge is fed onto the perimeter of the top hearth. The rabble arms move the sludge through the incinerator by raking the sludge toward the center shaft where it drops through holes located at the center of the hearth. In the next hearth the sludge is raked in the opposite direction.

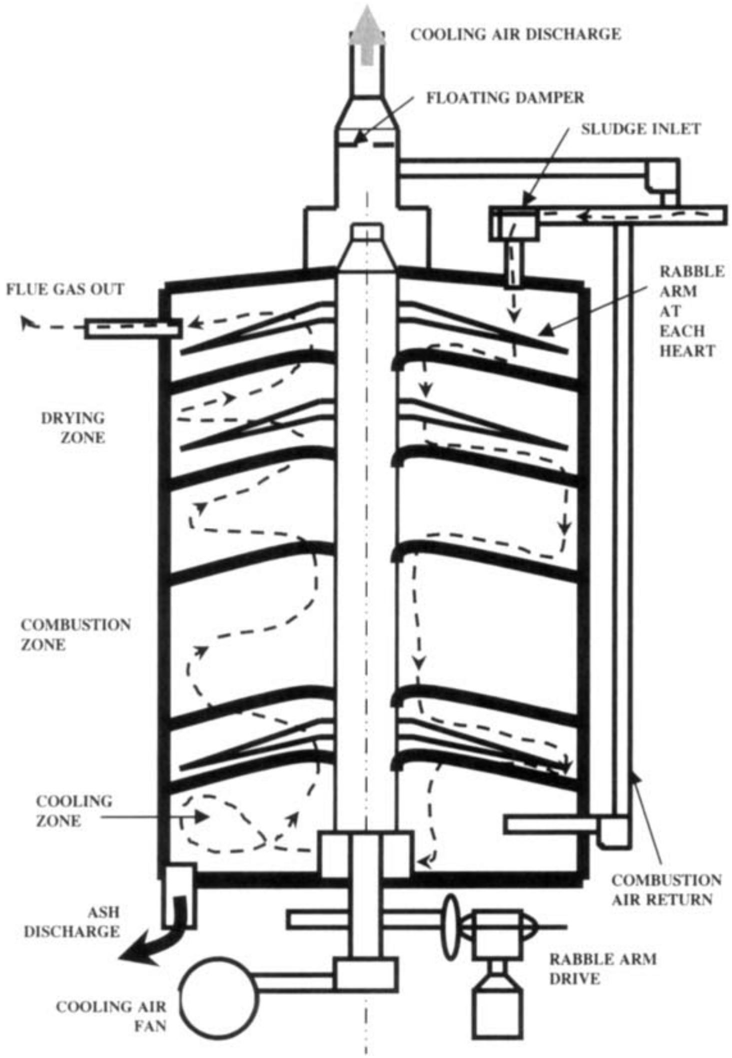


Figure 8. Multiple hearth incinerator.

This process is repeated in all of the subsequent hearths. The effect of the rabble motion is to break up solid material to allow better surface contact with heat and oxygen. A sludge depth of about 1 in. is maintained in each hearth at the design sludge flow rate. Scum may also be fed to one or more hearths of the incinerator. Scum is the material that floats on wastewater. It is generally composed of vegetable and mineral oils, grease, hair, waxes, fats, and other materials that will float. Scum may be removed from many treatment units including preaeration tanks, skimming tanks, and sedimentation tanks. Quantities of scum are generally small compared to those of other wastewater solids. Ambient air is first ducted through the central shaft and its associated rabble arms. A portion, or all, of this air is then taken from the top of the shaft and recirculated into the lowermost hearth as preheated combustion air. Shaft cooling air which is not circulated back into the furnace is ducted into the stack downstream of the air pollution control devices. The combustion air flows upward through the drop holes in the hearths, countercurrent to the flow of the sludge, before being exhausted from the top hearth. Air enters the bottom to cool the ash. Provisions are usually made to inject ambient air directly into the middle hearths as well.

From the standpoint of the overall incineration process, multiple hearth furnaces can be divided into three zones. The upper hearths comprise the drying zone where most of the moisture in the sludge is evaporated. The temperature in the drying zone is typically between 425 and 760°C (800 and 1400°F). Sludge combustion occurs in the middle hearths (second zone) as the temperature is increased to about 925°C (1700°F). The combustion zone can be further subdivided into the upper-middle hearths where the volatile gases and solids are burned, and the lower-middle hearths where most of the fixed carbon is combusted. The third zone, made up of the lowermost hearth(s), is the cooling zone. In this zone the ash is cooled as its heat is transferred to the incoming combustion air.

Multiple hearth furnaces are sometimes operated with afterburners to further reduce odors and concentrations of unburned hydrocarbons. In afterburning, furnace exhaust gases are ducted to a chamber where they are mixed with supplemental fuel and air and completely combusted. Some incinerators have the flexibility to allow sludge to be fed to a lower hearth, thus allowing the upper hearth(s) to function essentially as an afterburner.

Under normal operating condition, 50 to 100% excess air must be added to an MHF in order to ensure complete combustion of the sludge. Besides enhancing contact between fuel and oxygen in the furnace, these relatively high rates of excess air are necessary to compensate for normal variations in both the organic characteristics of the sludge feed and the rate at which it enters the incinerator. When an inadequate amount of excess air is available, only partial oxidation of the carbon will occur, with a resultant increase in emissions of carbon monoxide, soot, and hydrocarbons. Too much excess air, on the other hand, can cause increased entrainment of particulate and unnecessarily high auxiliary fuel consumption.

## FLUIDIZED-BED INCINERATOR

The basic configuration and features of the fluid bed incinerator have already been described. This technology has been around since the early 1960s. In this system, air is introduced at the fluidizing air inlet at pressures of 3.5 to 5 psig. The air passes through openings in the grid supporting the sand and creates fluidization of the sand bed. Sludge cake is introduced into the bed. The fluidizing air flow must be carefully controlled to prevent the sludge from floating on top of the bed.

Fluidization provides maximum contact of air with sludge surface for optimum burning. The drying process is practically instantaneous. Moisture flashes into steam upon entering the hot bed. Some advantages of this system are that the sand bed acts as a heat sink so that after shutdown there is minimal heat loss. With this heat containment, the system will allow startup after a weekend shutdown with need for only 1 or 2 hr of heating. The sand bed should be at least 1200°F when operating.

Fluidized bed technology was first developed by the petroleum industry to be used for catalyst regeneration. These are referred to as fluidized bed combustors (FBCs) and they consist of a vertically oriented outer shell constructed of steel and lined with refractory. Tuyeres (nozzles designed to deliver blasts of air) are located at the base of the furnace within a refractory-lined grid. A bed of sand, approximately 0.75 meters (2.5 feet) thick, rests upon the grid. Two general configurations can be distinguished on the basis of how the fluidizing air is injected into the furnace. In the "hot windbox" design the combustion air is first preheated by passing through a heat exchanger where heat is recovered from the hot flue gases. Alternatively, ambient air can be injected directly into the furnace from a cold windbox.

Partially dewatered sludge is fed into the lower portion of the furnace. Air injected through the tuyeres, at pressures of from 20 to 35 kilopascals (3 to 5 pounds per square inch gauge), simultaneously fluidizes the bed of hot sand and the incoming sludge. Temperatures of 750 to 925°C (1400 to 1700°F) are maintained in the bed. Residence times are typically 2 to 5 s. As the sludge burns, fine ash particles are carried out the top of the furnace. Some sand is also removed in the air stream; sand makeup requirements are on the order of 5% for every 300 hr of operation. Combustion of the sludge occurs in two zones. Within the bed itself (Zone 1), evaporation of the water and pyrolysis of the organic materials occur nearly simultaneously as the temperature of the sludge is rapidly raised. In the second zone (freeboard area), the remaining free carbon and combustible gases are burned. The second zone functions essentially as an afterburner.

Fluidization achieves nearly ideal mixing between the sludge and the combustion air and the turbulence facilitates the transfer of heat from the hot sand to the sludge. The most noticeable impact of the better burning atmosphere provided by a fluidized bed incinerator is seen in the limited amount of excess air required for complete combustion of the sludge. Typically, FBCs can achieve complete combustion with 20 to 50% excess air, about half the excess air required by multiple hearth furnaces. As a consequence, FBC incinerators have generally lower fuel requirements compared to MHF incinerators. Fluidized-bed incinerators most often have venturi scrubbers or venturi/impingement tray scrubber combinations for emissions control.

## ELECTRIC FURNACE

The electric furnace is basically a conveyor belt system passing through a long rectangular refractory lined chamber. Heat is provided by electric infrared heating elements within the furnace. Cooling air prevents local hot spots in the immediate vicinity of the heaters and is used as secondary combustion air within the furnace. The conveyer belt is made of continuous woven wire mesh chosen of steel alloy that will withstand the 1300 to 1500°F temperatures. The sludge on the belt is immediately leveled to 1 in. The belt speed is designed to provide burnout of the sludge without agitation. The first electric infrared furnace was installed in the 1970s, and their use is not common.

Electric infrared incinerators consist of a horizontally oriented, insulated furnace. A woven wire belt conveyor extends the length of the furnace and infrared heating elements are located in the roof above the conveyor belt. Combustion air is preheated by the flue gases and is injected into the discharge end of the furnace. Electric infrared incinerators consist of a number of prefabricated modules, which can be linked together to provide the necessary furnace length. A cross section of an electric furnace is shown in Figure 9. The dewatered sludge cake is conveyed into one end of the incinerator. An internal roller mechanism levels the sludge into a continuous layer approximately 1 in. thick across the width of the belt. The sludge is sequentially dried and then burned as it moves beneath the infrared heating. The ash is discharged into a hopper at the opposite end of the furnace. Preheated combustion air enters the furnace above the ash hopper and undergoes further heating by the exiting ash. The air flow direction is countercurrent to the sludge flow along the conveyor.

Exhaust gases leave the furnace at the end of the feed. The excess air can vary from 20 to 70%. These systems offer the advantage of lower capital cost for smaller systems. High electricity costs in some areas make this technology too costly.

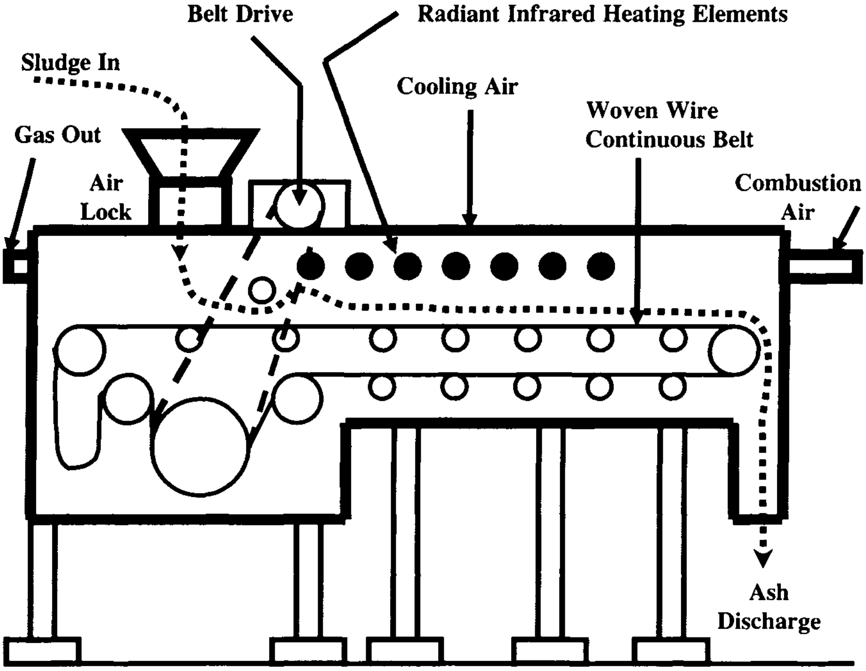


Figure 9. Electric arc furnace.

## CYCLONE FURNACE

The cyclonic furnace is a single hearth unit where the hearth moves and the rabble teeth are stationary. Sludge is moved toward the center of the hearth where it is discharged as ash. The furnace is a refractory lined cylindrical shell with a domed top. The air, heated with the immediate introduction of supplemental fuel, creates a violent swirling pattern which provides good mixing of air and sludge feed. The air, which later turns into flue gas, swirls up vertically in cyclonic flow through the discharge flue in the center of the domed roof. One advantage of these furnaces is that they are relatively small and can be placed in operation, at operating temperature, within an hour.

As ash falls into a wet sump, turbulence is created by the entrance of water. This turbulence is necessary so that the ash doesn't collect and cake up. This water containing the ash is pumped into a holding pond or lagoon, with a residence time of at least 6 hours. During this time, 95% of the ash will have settled to the bottom and the overflow is taken back to the treatment plant. There has to be a minimum of two lagoons with one being used to hold the ash-water discharge and the other for drying. When dry, the ash is hauled to a landfill or used for concrete. Mixing one part of ash to four parts cement will produce a slow-setting concrete with no loss in strength.

## ENVIRONMENTAL IMPACT AND CONTROLS

A serious environmental impact of incineration is on air quality. An incinerator's smoke discharge or flue gas should be colorless. Flue gas is an emission mainly made up of nitrogen, carbon dioxide, and oxygen. There are traces of chloride and sulfides in the gas and if these levels become too high, they could cause the possibility of corrosion. With respect to the color of the discharge again, if there is a significant amount of particulate matter in the emission, it will be detected by color. The stream can range from a black to white appearance and will have a pale yellow to dark brown trail. The discharge should also have no discernable odor and there should be no detectable noise due to incinerator operation at the property line. Unfortunately, colored emissions and odor problems do occur and treatment plants take the proper actions to correct it.

Air pollution controls are critical factors that add significant costs onto these technologies. Sewage sludge incinerators potentially emit significant quantities of pollutants. The major pollutants emitted are: (1) particulate matter, (2) metals, (3) carbon monoxide (CO), (4) nitrogen oxides ($NO_X$), (5) sulfur dioxide ($SO_2$), and (6) unburned hydrocarbons. Partial combustion of sludge can result in emissions of intermediate products of incomplete combustion (PIC), including toxic organic compounds. Uncontrolled particulate emission rates vary widely depending on the type of incinerator, the volatiles and moisture content of the sludge, and the operating practices employed. Generally, uncontrolled particulate emissions are highest from fluidized-bed incinerators because suspension burning results in much of the ash being carried out of the incinerator with the flue gas.

Uncontrolled emissions from multiple hearth and fluidized-bed incinerators are extremely variable, however. Electric incinerators appear to have the lowest rates of uncontrolled particulate release of the three major furnace types, possibly because the sludge is not disturbed during firing. In general, higher airflow rates increase the opportunity for particulate matter to be entrained in the exhaust gases. Sludge with low volatile content or high moisture content may compound this situation by requiring more supplemental fuel to burn. As more fuel is consumed, the amount of air flowing through the incinerator is also increased. However, no direct correlation has been established between airflow and particulate emissions. Metal emissions are affected by metal content of the sludge, fuel bed temperature, and the level of particulate matter control. Since metals which are volatilized in the combustion zone condense in the exhaust gas stream, most metals (except mercury) are associated with fine particulates and are removed as the fine particulates are removed.

Carbon monoxide is formed when available oxygen is insufficient for complete combustion or when excess air levels are too high, resulting in lower combustion temperatures. Emissions of nitrogen and sulfur oxides are primarily the result of oxidation of nitrogen and sulfur in the sludge. Therefore, these emissions can vary greatly based on local and seasonal sewage characteristics. Emissions of volatile organic compounds (VOC) also vary greatly with incinerator type and operation. Incinerators with countercurrent airflow such as multiple hearth designs provide the greatest opportunity for unburned hydrocarbons to be emitted. In the MHF, hot air and wet sludge feed are contacted at the top of the furnace. Any compounds distilled from the solids are immediately vented from the furnace at temperatures too low to completely destroy them. Particulate emissions from sewage sludge incinerators have historically been controlled by wet scrubbers, since the associated sewage treatment plant provides both a convenient source and a good disposal option for the scrubber water.

The types of existing sewage sludge incinerator controls range from low pressure drop spray towers and wet cyclones to higher pressure drop venturi scrubbers and venturi/impingement tray scrubber combinations. Electrostatic precipitators and baghouses are employed primarily where sludge is co-fired with municipal solid waste. The most widely used control device applied to a multiple hearth incinerator is the impingement tray scrubber. Older units use the tray scrubber alone; combination venturi/impingement tray scrubbers are widely applied to newer multiple-hearth incinerators and to fluidized bed incinerators.

Most electric incinerators and many fluidized bed incinerators use venturi scrubbers only. In a typical combination venturi/impingement tray scrubber, hot gas exits the incinerator and enters the precooling or quench section of the scrubber. Spray nozzles in the quench section cool the incoming gas and the quenched gas then enters the venturi section of the control device. Venturi water is usually pumped into an inlet weir above the quencher. The venturi water enters the scrubber above the throat and floods the throat completely. This eliminates build-up of solids and reduces abrasion. Turbulence created by high gas velocity in the converging throat section deflects some of the water traveling down the throat into the gas stream. Particulate matter carried along with the gas stream impacts on these water particles and on the water wall. As the scrubber water and flue gas leave the venturi section, they pass into a flooded elbow where the stream velocity decreases, allowing the water and gas to separate.

Most venturi sections come equipped with variable throats. By restricting the throat area within the venturi, the linear gas velocity is increased and the pressure drop is subsequently increased. Up to a certain point, increasing the venturi pressure drop increases the removal efficiency. Venturi scrubbers typically maintain 60 to 99% removal efficiency for particulate matter, depending on pressure drop and particle size distribution. At the base of the flooded elbow, the gas stream passes through a connecting duct to the base of the impingement tray tower. Gas velocity is further reduced upon entry to the tower as the gas stream passes upward through the perforated impingement trays. Water usually enters the trays from inlet ports on opposite sides and flows across the tray. As gas passes through each perforation in the tray, it creates a jet which bubbles up the water and further entrains solid particles. At the top of the tower is a mist eliminator to reduce the carryover of water droplets in the stack effluent gas. The impingement section can contain from one to four trays, but most systems for which data are available have two or three trays.

## FUEL ECONOMY

When dealing with incinerators, fuel is generally the most expensive part of the process from an operational standpoint. A ratio should be calculated beforehand that represents the amount of fuel used for the amount of sludge inputted. If there is a significant change to the amount of fuel consumed, it could mean that there is a problem in the fuel supply system, or air flow to the incinerator, or that an extensive furnace cleaning is in order.

## COST CONSIDERATIONS

Minimal cost of operation and equipment maintenance is another economic parameter for sludge incineration. Preventive maintenance is the single most important factor in reduction of operating costs. Semiannual or quarterly appointments must be scheduled to allow time for complete furnace checkout and cleaning (referred to as "turnarounds"). Table 4 is a breakdown of the costs of each incinerator. Essentially costs can be related to one basic parameter: the lower the moisture content is in the sludge, the less expensive the incinerator will be to operate. Also, incinerators are bought based on what moisture level of sludge they are going to be effective with. Some incinerators can burn out sludge with 20% moisture levels and some cannot.

Table 4. Estimated Economics for Incineration.

| Type incinerator | Capacity (lbs/hr) | Sludge moisture content (%) | Installed cost (U.S. $) |
|---|---|---|---|
| Multiple Hearth Furnace | 7,000 | 0 | 11,000,000 |
| Fluid Bed Incinerator | 1,000 | 0 | 900,000 |
| | 2,900 | 20 | 1,600,000 |
| Electric Furnace | 2,400 | 30 | 1,3000,000 |
| | 2,400 | 0 | 950,000 |
| Cyclonic Incinerator | 2,000 | 20 | 1,000,000 |

The design cost will be a function of the incinerator cost plus installation, which is normally in the range of 4 to 7%. This cost should be doubled to include engineering services during project construction. It should be noted that with the electric furnace, the power needed to start up results in a large connected load. In areas of the country where there are high demand charges for electric power, this system can be economically impractical.

## INDUSTRY APPROACHES TO SLUDGE VOLUME REDUCTION

When we think of sludge, what automatically comes to mind is sewerage. Water carriage systems of sewerage provide a simple and economical means for removing offensive and potentially dangerous wastes from household and industry. The solution and suspension of solids in the transporting of water produces sewage. Thus, the role of solids and sludge removal at sewage treatment plants is apparent. Sludge removal is complicated by the fact that some of the waste matters go into solution while others are colloidal or become finely divided in their flow through the sewage system. Ordinarily, less than half of such waste remains in suspension in a size or condition that can be separated by being strained out, skimmed off, or settled out. The remainder must then be precipitated out by chemical means, filtered mechanically, or be subjected to biological treatment whereby it is either removed from the water or changed in character so as to be rendered innocuous.

Sewage contains mineral and organic matter in suspension (coarse and fine suspended matter), in colloidal state (very finely dispersed matter), and in solution. Living organisms, notably bacteria and protozoa, find sewage to be an abundant source of food, and their lives' activities result in the decomposition of sewage. Sewage becomes offensive as a result of its own instability together with the objectionable concentration of suspended materials. In addition, the potential presence of disease-producing organisms makes sewage dangerous. Removal or stabilization of sewage matters may be accomplished in treatment works by a number of different methods or by a suitable combination of these methods. While sewage sludge is rich in nutrients and organic matter, offering the potential for applications as a biosolid (next chapter), or has a heating value making it suitable for incineration and possible heat or energy recovery, many industrial sludges are often unsuitable for reuse.

A more common practice with industrial sludge is to try and identify a reclaim value; i.e., if the sludge can be concentrated sufficiently there may be a portion of this waste which is reclaimable or can enter into a recycling market. If instead an enterprise can sell its waste, then some of the costs associated with waste management can be offset. For example, copper is a heavy metal and the sludge is a hazardous waste which is expensive to dispose of. Identifying an off-site recycling market that will take responsibility for this waste, even if they do not pay for it, can reduce or eliminate such costs as stabilizing and concentrating the sludge, as well as transport and tipping fees at the landfill. This option may not, however, eliminate the long-term liabilities associated with the waste if for some reason the reclaimer has an incident in which the hazardous material impacts on a third party. Of concern, however, with any sludge management problem, are the costs for recovery of potentially valuable by-products. There are many situations in industrial settings where large volumes of toxic sludges are generated on a continual basis. As with POTWs, waste management programs tend to focus on volume reduction techniques that reduce the costs for transport and disposal. The mechanical volume reduction techniques described earlier for wastewater treatment operations are equally applicable in these cases. But in some situations, thermal drying methods must be employed in order to achieve significant volume reductions, whether for disposal or reclaiming purposes.

Thermal techniques such as flash drying, the use of drying rooms, rotary kiln driers, and various other methods are costly. Ongoing energy costs as well as OM&R costs contribute to waste management programs. In many situations less passive drying techniques tend to be help reduce these treatment and recovery costs, such as the use of drying beds and lagoons.

The use of drying beds is one of two common methods of dewatering based upon passive thermal energy. Drying beds are generally used for dewatering of well-digested sludges. Attempts to air-dry raw sludge usually result in odor problems. Sludge drying beds consist of perforated or open-joint drainage pipe laid within a gravel base. The gravel is covered with a layer of sand. Partitions around and between the drying beds are generally open to the weather but may be covered with ventilated greenhouse-type enclosures where it is necessary to dewater sludge in wet climates. The drying of sludge on sand beds is accomplished by allowing water to drain from the sludge mass through the supporting sand to the drainage piping and natural evaporation to the air. As the sludge dries, cracks develop in the surface, allowing evaporation to occur from the lower layers which accelerates the drying process.

There are many design variations used for sludge drying beds, including the layout of the drainage piping, thickness and type of materials in the gravel and sand layers, and construction materials used for the partitions. The major variation is whether or not the beds are covered. Any covering structure must be well ventilated. In the past, some beds were constructed with flat concrete bottoms for drainage without pipes, but this construction has not been very satisfactory. Asphalt concrete (blacktop) has been used in some drying beds.

The only sidestream is the drainage water. This water is normally returned to the raw sewage flow to the plant or to the plant headworks. The drainage water is not normally treated prior to return to the plant. Experience is the best guide in determining the depth of sludge to be applied, however, typical application depth is 8 to 12 inches. The condition and moisture content of the sludge, the sand bed area available, and the need to draw sludge from digesters are factors to consider. It is not advisable to apply fresh sludge on top of dried sludge in a bed.

The best time to remove dried sludge from drying beds depends on a number of factors, such as subsequent treatment by grinding or shredding, the availability of drying bed area for application of current sludge production, labor availability, and, of course, the desired moisture content of the dried sludge. Sludge can be removed by shovel or forks at a moisture content of 60%, but if it is allowed to dry to 40% moisture, it will weigh only half as much and is still easy to handle. If the sludge gets too dry (10 to 20% moisture) it will be dusty and will be difficult to remove because it will crumble as it is removed. Many operators of smaller treatment plants use wheelbarrows to haul sludge from drying beds. Planks are often laid on the bed for a runway so that the wheelbarrow tire does not sink into the sand. Wheelbarrows can be kept close to the worker so that the shoveling distance is not great. Most plants use pick-up trucks or dump trucks to transport the sludge from the drying bed. Dump trucks have the advantage of quick unloading.

Where trucks are used, it is best to install concrete treadways in the sludge drying bed wide enough to carry the dual wheels since the drying bed can be damaged if the trucks are driven directly on the sand. The treadways should be installed so that good access is provided to all parts of the beds. If permanent treadways have not been installed, heavy planks may be placed on the sand. Large plants will normally utilize mechanical equipment for handling the dried sludge. Some communities have encouraged public usage of the dried sludge. In some cases users are allowed to remove the sludge from the beds, but this may not be satisfactory in many cases. Local regulations should be reviewed before attempting to establish a public utilization program.

The use of sludge lagoons is a technique that relies both on the settling characteristics of sludge and solar evaporation. The considerable labor involved in sludge drying bed operations may be avoided by the use of sludge lagoons. These lagoons are nothing but excavated areas in which digested sludge is allowed to drain and dry over a period of months or even a year or more. They are usually dug out by bulldozers, or other dirt-moving equipment, with the excavated material used for building up the sides to confine the sludge. Depths may range from 2 to 6 feet. Areas vary, and although drainage is desirable, it is not usually provided. Digested sludge is drawn as frequently as needed, with successive drawings on top of the previous ones until the lagoon is filled. A second lagoon may then be operated while the filled one is drying.

After the sludge has dried enough to be moved, a bulldozer, or a tractor with an end-loader, may be used to scoop out the sludge. In some locations it may be pushed from the lagoon by dozers into low ground for fill. Lagoons may be used for regular drying of sludge, reused after emptying, or allowed to fill and dry, then leveled and developed into lawn. They can also be used as emergency storage when the sludge beds are full or when the digester must be emptied for repair. In the latter case it should be treated with some odor control chemicals, such as hydrated or chlorinated lime.

The size of the lagoon depends upon the use to which it will be put. Lagoons may take the place of sludge beds or provide a place for emergency drawings of sludge, but they may be unsightly and even unwanted on a small plant site. However, they are becoming more popular because they are inexpensive to build and operate.

Although lagoons are simple to construct and operate, there can be problems associated with sizing them. These problems largely arise from uncertainty in estimating the solar evaporative capacity. In semiarid regions evaporation ponds are a conventional means of disposing of wastewater without contamination of ground or surface waters. Evaporation ponds as defined herein will refer to lined retention facilities. Successful use of evaporation for wastewater disposal requires that evaporation equal or exceed the total water input to the system, including precipitation. The net evaporation may be defined as the difference between the evaporation and precipitation during any time period. Evaporation rates are to a great extent dependent upon the characteristics of the water body. Evaporation from small shallow ponds is usually considered to be quite different from that of large lakes, mainly because of differences in the rates of heating and cooling of the water bodies because of size and depth differences. Additionally, in semi-arid regions, hot dry air moving from a land surface over a water body will result in higher evaporation rates for smaller water bodies. The evaporation rate of a solution will decrease as the solids and chemical composition increase. Depending upon its origin, evaporation pond influent may contain contaminates of various amounts and composition. Decreases in evaporation rates compared to fresh water rates can seriously increase the failure potential of ponds designed on fresh water evaporation criteria. Designers of settling ponds and lagoons that rely on evaporation need to know the probability level of their designs being exceeded. Confidence limits for published evaporation normals have not been given, nor have analyses been made of the effects of uncertainty in the estimated normals or of the temporal variation of net evaporation. Definition of the spatial and temporal distribution of parameters such as evaporation and precipitation is difficult in mountainous regions. A concern is that the application of many of the empirical equations, based on climatological data, for estimating evaporation has not been thoroughly tested for high-altitude conditions. In particular, the ability of these equations to define the variability of evaporation is basically unknown. Historically, pan data are the most common means for defining free water evaporation. However, the density of evaporation pan stations is much less than that of weather stations.

Many methods exist for either measuring or estimating evaporative losses from free water surfaces. Evaporation pans provide one of the simplest, least expensive, and most widely used methods of estimating evaporative losses. Long-term pan records are available, providing a potential source of data for developing probabilities of net evaporation. The use of pan data involves the application of a coefficient to measured pan readings to estimate evaporation from a larger water body. Among the most useful methods for estimating evaporation from free water surfaces are the methods which use climatological data. Many of these equations exist, most being based directly upon the a method which was originally intended for open water surfaces, but is now commonly applied to estimates of vegetative, water use.

Monthly evaporation estimates can be made using the Kohler-Nordenson-Fox equation with a pan coefficient of 0.7. The Kohler-Nordenson-Fox equation describes evaporation as the combination of water loss due to radiation heat energy and the aerodynamic removal of water vapor from a saturated surface. The general form for the combination equation is:

$$E = (d/(d+y))\, R_n + (Y/(d+Y))\, E_a$$

where E is the evaporation in inches per day, d is the slope of the saturation vapor pressure curve at air temperature in inches of mercury per degree Fahrenheit, Y is the psychrometric constant in inches of mercury per degree Fahrenheit, $R_n$ is the net radiation exchange expressed in equivalent inches of water evaporated, and $E_a$ is an empirically derived bulk transfer term of the form:

$$E_a = f(u)\, (e_s - e_d)$$

Where f(u) is a wind function and $(e_s - e_d)$ is the vapor pressure deficit. Kohler-Nordenson-Fox evaluated the aerodynamic term using pan data resulting in the form:

$$E_a = (0.37 + 0.0041 U_p)(e_s - e_a)$$

where $e_a$ is in units of inches of water per day, $U_p$ is the wind speed 2 feet above the ground expressed in miles per day, and $e_s$ and $e_a$ are the saturation vapor pressures at mean air and mean dew-point temperatures, respectively (expressed in inches of mercury). For development of the wind function, an adjustment in the psychrometric constant is generally made to account for the sensible heat conducted through the sides and bottom of the evaporation pan. One may also apply as an approximation the following expression for the psychrometric constant:

$$Y = 0.000367P$$

where P is the atmospheric pressure in inches of mercury. My own experience in designing surface lagoons and evaporation ponds over the years, and substantiated in the literature, has been to apply a pan coefficient of 0.7.

Of concern is that very little information often is available concerning the effects of common wastewaters on evaporation rates. As noted, the evaporation rate of a solution will decrease as the solids and chemical concentrations increase. However, the overall effects on evaporation rates of dissolved constituents as well as color changes and other factors of wastewater are largely unknown.

Evaporation from surface ponds is usually based upon estimates of annual net evaporation. Calculation of annual evaporation rates requires estimates during periods when the surface may be frozen. Most studies related to cold weather evaporation have been concerned with snow rather than ice. In general, the evaporation from a snowpack is usually much less than the amount of melting that occurs. Considering the large percentage of the annual evaporation which occurs during the warmer months and the overall uncertainties involved in estimates of evaporation from water surfaces, the amount of evaporation from frozen ponds during winter can reasonably be neglected in calculating annual evaporation. A more important consideration is the evaporation which occurs during winter from ponds which may remain unfrozen because of the introduction of warm wastewater. In these cases, water temperature will influence the evaporation rates. However, the low value of the saturation vapor pressure of the air above any water body will limit evaporation. Annual estimates of evaporation herein can be made by applying the Kohler-Nordenson-Fox equation throughout the year. Such estimates should provide near maximum possible evaporation estimates. For lined ponds, evaporation will be confined mainly to the water surface area. Evaporation from the soil and vegetation on the banks surrounding the pond should be minimal. However, for ponds which have appreciable seepage to the surrounding area, evaporation from this area will be dependent upon the type and amount of vegetation, as well as the moisture content of the upper soil layers. Methods foe estimating evaporation and/or evapotranspiration in these instances are readily available, and you can find some of these studies and estimating procedures by doing a Web search.

If water losses from the surrounding area are a major component of the total evaporative losses of the pond, then soil moisture conditions will be expected to be high. Under nonlimiting soil moisture conditions vegetative moisture losses are often defined as "potential" losses. Evaporative losses in this case would not be expected to differ greatly from free water evaporation. The literature recommends in fact that lake evaporation be used as a measure of potential evapotranspiration. Thus, for high soil moisture conditions, evaporation rates calculated for the water surface should be applicable to the surrounding area. The influence upon evaporation of vegetative growth within a pond is uncertain. The literature is inconclusive as to whether vegetation will increase or decrease evaporation compared to an open surface. It appears that the effect may be somewhat dependent upon the size of the water body. Literature studies indicate vegetation will decrease evaporation for extensive surfaces with the effect being less for smaller surface areas. It is very possible, however, that the introduction of vegetation upon the surface of a water body of more limited extent may increase its evaporative water loss, but only while the vegetation remains in a healthy, robust condition. Thus, the effect of the presence of vegetation appears to range from being a water conservation mechanism to that of increasing evaporation. In either case, the potential effects appear to be quite large with reported ratios of vegetative covered to open water evaporation under extreme conditions ranging from 0.38 to 4.5. In most instances, this ratio would be expected to be much closer to unity.

Drying techniques based on passive thermal energy are still costly waste management programs because ultimately there are operating costs associated with the collection, transportation, and disposal of the dried waste. And in the end the long-term liabilities still persist, since there are waste materials that continue forever.

## A SHORT REVIEW

Volume reduction techniques help to reduce the costs of disposal, but they are essentially treatment technologies. Among the range of technologies that are available, some are less costly in terms of operating costs and capital investments than others, but all of them contribute to the overall waste management dilemma of long-term liabilities since there is a final waste form that must be disposed of. Incineration as a technology is very expensive and carries many hidden costs that are associated with the required air pollution controls. When used in industrial applications, the ash is generally hazardous and costly to dispose of. Even in situations where resource recovery may be possible through a volume reduction technique, the investment needs to be examined carefully to assess whether there are long-term financial benefits and reduction of future and long-term liabilities.

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# Chapter 6

# BIOSOLIDS TECHNOLOGIES AND APPLICATIONS

## INTRODUCTION

When wastewater is treated the process produces a semisolid, nutrient-rich by-product known as biosolids. When treated and processed properly, biosolids can be recycled and applied to cropland to improve soil quality and productivity because of the nutrients and organic matter that they contain. Although these solids were historically called sewage sludge, biosolids is the term now used to emphasize the beneficial nature of this recyclable material.

This chapter provides an overview of the technologies applicable to biosolids. Much of the material presented in this chapter is derived from the USEPA document titled Biosolids Generation, Use, and Disposal in the United States (EPA530-R-99-099, Sept. 1999).

## GENERAL INFORMATION AND BACKGROUND

Biosolids often contain approximately 93 to 98% water, plus solids and dissolved substances present in the wastewater or added during wastewater or biosolids treatment processes. The quantity of municipal biosolids produced annually in the United States has grown by nearly 50% since 1972 to levels exceeding 6.9 million dry tons. EPA attributes this largely to the Clean Water Act. Domestic, commercial, and industrial wastewater are collected through an extensive network of sewers and transported to wastewater treatment facilities (POTWs). Prior to the release of wastewater into the municipal sewer network, most industrial plants must pretreat their wastewater to remove certain contaminants (including metals, such as copper, lead, cadmium, and chromium, and other pollutants such as chlorinated hydrocarbons). Over the past 20 years, industrial pretreatment technologies have reduced levels of metals and other pollutants going into POTWs, resulting in noticeable improvements in biosolids quality. At the POTW· before it is discharged into the environment, wastewater undergoes preliminary, primary, secondary, and, in some cases, tertiary treatment steps. The quantity and composition of the biosolids depends on the wastewater composition, the type of wastewater treatment used, and the type of subsequent treatment applied to the biosolids. Even within an individual plant the biosolids quality and quantity can vary because of seasonal variations in the influent wastewater.

In general, higher degrees of wastewater treatment can increase the total volume of biosolids generated. Higher levels of treatment also can increase the concentrations of contaminants in biosolids, because many of the constituents removed from the wastewater end up in the biosolids. Furthermore, wastewater processes that involve the addition of chemicals to precipitate the solids (such as ferric chloride, alum, lime, or polymers) can result in increased concentrations of these chemicals in the biosolids. Other, indirect effects also can occur, such as when alum (as aluminum hydroxide) adsorbs phosphorus or causes trace metals (e.g., cadmium) to precipitate out of the wastewater and into the biosolids.

Industrial pretreatment regulations for wastewater required by federal and state agencies, such as pollution prevention programs can reduce levels of metals and other pollutants in the wastewater treated at POTWs and in the subsequent biosolids produced. Thus, the type of wastewater treatment or pretreatment used affects the characteristics of biosolids, which in turn can affect the types treatment chosen. The marked improvements in biosolids quality from pretreatment and pollution prevention programs can encourage POTWs to process their solids further, such as by composting then. When biosolids achieve the low levels of pollutants that make the widest distribution of biosolids products possible, processes such as composting become more attractive.

## PUBLIC ISSUES CONCERNING THE USE OF BIOSOLIDS

Despite the noted benefits of using recycled biosolids, many still question whether the heavy metals, toxic organic compounds, and pathogens in this material could contaminate soil, water, or food and ultimately cause health problems. This doesn't appear likely. A search of the National Library of Medicine's comprehensive Medline database revealed no scientific article claiming that sewage sludge had caused disease. Conceivably, that negative result could result from inadequate research, but given the long history of concern, "If it was causing a problem, it would make itself apparent, and it hasn't," says Sarah Clark Stuart, a member of the NRC committee and a program officer at the Pew Charitable Trusts in Philadelphia, Pennsylvania. Nationally, biosolids recycling is governed by a regulation of the Clean Water Act known as "Part 503" regulation, issued in 1993 by the Office of Water. The goal of the rule is to maintain or improve environmental quality and protect human health. EPA policies encourage biosolids recycling. Rubin, who says he "wrote the [EPA] regulations" on biosolids recycling, is categorical: "We have yet to receive one documented negative human health case where a biosolids program met all the federal and state requirements, and was used the way it should be used - according to good agricultural practices." Nevertheless, NRC committee member Michael Baram, a professor at Boston University Law School, says he found some sludge applicator workers who blamed their hepatitis B infections on biosolids. Baram believes that indicates that the EPA should have worked with the Occupational Safety and Health Administration and the Food and Drug Administration while writing the biosolids rules.

Whether dumped from trailers, sprayed by manure spreaders, emptied out of bags, or injected into the soil by specialized vehicles, millions of tons of an organic material rich in plant nutrients are being added to U.S. soil each year. The material is biosolids, an inevitable by-product of the sewage treatment plants that serve about 75% of the U.S. population. But because biosolids contain concentrations of most heavy metals as well as some pathogens and toxic organics that are flushed and dumped down residential and industrial drains, the question arises of whether biosolids are safe to be spread on farms and forests. Despite the common misconception that biosolids and sewage are identical, well-treated biosolids resemble sewage about as much as a plastic bag resembles the crude oil from which it originated. Biosolids are made through a series of biological transformations in which most of the complex organic molecules in sewage are decomposed and most of the pathogens killed. Nevertheless, aware that the label "sewage sludge" is enough to arouse public fear and opposition, advocates of sludge recycling coined the term "biosolids" a few years ago. In a 9 December 1996 memo to the EPA's Office of Water employees, EPA Assistant Administrator Robert Perciasepe encourages them to use the term "biosolids" in place of the terms “sludge” and “sewage sludge.” In the memo Perciasepe calls the use of the term biosolids "an important component in accomplishing one of EPA's policy objectives - supporting and encouraging the beneficial use of these residuals of wastewater treatment." Still, whatever it's called, the idea of using the residues of sewerage treatment plants in agriculture is sure to arouse opposition - or at least concern over the impacts on health and the environment.

In the process of treating 182 gallons of sewage per person per day, treatment plants create 7 million dry metric tons of biosolids, mixed in roughly 700 million tons of water, according to the EPA. This number dwarfs total municipal solid waste production, which is 210 million tons annually. Therefore, sewage treatment plants face a monumental problem of how to dispose of or reuse biosolids. According to a 1993 EPA report, Standards for the Use or Disposal of Sewage Sludge, about 2.5 million dry tons of biosolids, or 36% of the total amount, was being recycled on farms, forests, golf courses, and elsewhere in the late 1980s, compared to 24% of municipal solid waste now being recycled. The balance of biosolids was buried in landfills (38%), burned (16%), or surface disposed by other means (10%). Until 1992, millions of tons of biosolids ended up in the Atlantic Ocean. The practice was banned because of public concern over ocean pollution; the banning led to the expanded need for land disposal, which now accounts for 40 to 50% of biosolids disposal. Because biosolids are created whenever sewage is treated, the environmental health effects of land application should be evaluated in comparison to other disposal techniques. Because landfilling and incineration each have health and environmental drawbacks and offer none of the potential benefits of recycling, EPA policies express a preference for land application.

Biosolids are no more optional to an urbanized society than sewage treatment itself, since they are an inevitable by-product of treatment. The first treatment works were crude by today's standards, but spurred by public demands for a cleaner environment, treatment has continually improved. When sewage enters a treatment plant, it runs through a series of tanks where heavy material - the biosolids-to-be - settles to the bottom, and water is skimmed off the top. To minimize environmental damage to a lake or river in which the water is disposed, the effluent is treated to reduce the levels of nitrogen and/or phosphorus, and is often disinfected with ultraviolet light or chlorine. Nationally, 3% of sewage plant wastewater is used for agricultural irrigation, mostly in the Southwest. Although the practice raises health concerns that parallel those of biosolids recycling, a National Research Council (NRC) committee that studied the issue and wrote a report, Use of Reclaimed Water and Sludge in Food Production, found few signs that wastewater was causing disease or pollution.

The most characteristic potential health hazard of biosolids are the wide range of pathogenic microbes carried in sewage. The list includes *Salmonella* and *Shigella* bacteria, the hepatitis A and Coxsackie viruses, the *Giardia* and *Cryptosporidium* protozoans, and helminths (parasitic worms) that cause roundworm, tapeworm, and hookworm. Based on microbial content, Part 503 established two categories of biosolids. To achieve Class A status, with pathogens below detectable levels, a treatment plant can either test directly for pathogens or use one of five specific treatments to kill them, including heating or increasing biosolids alkalinity. Class A biosolids can be applied in the same way as commercial fertilizer, without the restrictions that govern Class B sludge. The process for making Class B sludge, which is produced by most large treatment plants, must be known to reduce indicator microorganisms (including some pathogens) below 2 million colony-forming units of fecal coliform per gram of dry weight. (Fecal coliform, common, nonpathogenic bacteria that originate in the human gut, are considered "indicator organisms" for how effectively the treatment has killed all pathogens.) For Class B, the approved treatments include aerobic or anaerobic digestion, composting, heat treatment, and drying. Treatment can drastically reduce bacterial counts. According to the EPA, raw sewage typically contains about 1 billion fecal coliform bacteria per 100 ml of sewage; treated biosolids range from 30,000 to 6 million per 100 ml. Similarly, 100 ml of raw sewage contains an average of 8000 *Salmonella* bacteria, while treated biosolids range from 3 to 62.

Indicators are used because it's expensive to identify and count microbes in biosolids. But Suresh Pillai, an assistant professor of environmental microbiology at Texas A&M University who has studied pathogens at the 128,000-acre New York City biosolids disposal site in west Texas, says counting fecal coliform can be "misleading and unreliable; it underestimates the actual presence of organisms." Pillai calls the bacterial genus *Clostridium* "a much better indicator of [bacterial] survival and transmission in anaerobically digested sludge."

A key concern with Class B sludge is the eggs of parasitic worms called helminths, which survive sewage treatment and soil processes better than most pathogens. To prevent transmission of helminths and other resistant organisms, farmers must wait before harvesting crops on land that has received Class B sludge. This allows time for many of the organisms to die in the soil.

Pathogens worried the NRC study group, which suggested the "EPA should continue to develop and evaluate effective ways to monitor for specific pathogens in sewage sludge." The NRC panel said that since the Part 503 regulations rely so heavily on processes rather than pathogen tests, "reliability must be a critical element in the design and operation of wastewater treatment plants."

Toxic chemicals that do not volatilize or decompose during treatment tend to concentrate in biosolids, and yet their residues have declined greatly over the past 20 years. For example, benzene was detected in 93% of biosolids samples in a survey during the late 1970s, but in only 3% of samples from the late 1980s. Likewise, detections of organochlorine pesticides (which are no longer on the market) have also declined: chlordane, dieldrin, heptachlor, and hexachlorobenzene were each detected in 16% of the 1970s samples, but in none of the 1980s samples. To develop the Part 503 regulations, the EPA screened about 200 toxic organic compounds. After performing detailed risk analyses on the 22 that seemed most threatening, the agency decided that they appeared so rarely, or at such low concentrations, that they did not need regulation in Part 503. The NRC committee questioned this decision, arguing that the EPA's own methodology indicated that the "concentration [of certain toxic organics] in sewage sludge may exceed the risk-based limits." Because the data showing that toxic organics would not pose a hazard came from the National Sewage Sludge

Survey of the late 1980s, about which some methodological concerns had been raised, the NRC committee urged the EPA to repeat the survey. "I felt the issue should be looked at with a new survey," says Stuart. "Not that I thought that toxic organics were necessarily a health or environmental problem," she said, but to instill confidence in land application, "[I felt the] EPA should try to cover its bases better."

Because it is expensive to remove toxic materials from the vast amount of sewage that passes through treatment plants, the EPA has separate pretreatment regulations to control the discharge of 110 toxic chemicals into sewage systems. In practice, a sewage district may test sewage from industries known to pollute, or the companies may certify that they have plans for preventing pollution.

The EPA took what it called a "risk-based" approach to regulating the 10 heavy metals - including lead, cadmium, zinc, mercury, and copper--it found most frequently in the late 1980s national survey. (Chromium was later deleted due to scant evidence for its toxicity, so part 503 now regulates nine metals.) The EPA postulated 14 pathways by which each metal could move from the biosolids into a person, plant, or animal. Then the agency determined which pathway would be most hazardous, and used that to set the lifetime soil "loading rate" for each metal. When the loading rate is reached, biosolids applications must cease. Part 503 also set ceilings on annual loadings of each metal, and on metal concentration in each biosolids application. Taking lead as an example, the lifetime loading on any field is 300 kg/ha, the maximum annual application is 15 kg/ha, and biosolids "sold or given away in a bag or other container" cannot contain more than 840 mg/kg of the metal.

Pretreatment is also reducing metal content. Between the national surveys of biosolids in the late 1970s and the survey from the late 1980s, the average lead level decreased from 969 mg/kg to 134 mg/kg. Nickel levels decreased from 135.1 mg/kg to 42.7 mg/kg, and cadmium levels from 69.0 mg/kg to 7.0 mg/kg. Bucking the trend, mercury levels rose from 2.8 mg/kg to 5.2 mg/kg, and arsenic levels from 6.7 mg/kg to 9.9 mg/kg.

From a human health standpoint, the real potential threat arises not when a pollutant enters the soil, but when it enters water, air, or food. To prevent runoff in surface water, the EPA and states regulate the slope and location of biosolids applications, and generally forbid application to frozen soil, where runoff is likely. A good, but expensive, method for eliminating runoff is to inject liquid biosolids under the soil surface. At mine reclamation sites, where applications tend to be heavier, berms may be used to trap runoff before it reaches surface waters. Tests for airborne toxic chemicals at the Texas site that receives New York City's biosolids have shown "no significant amount [of pathogens], either within the fields or off-site," says B. L. Harris, associate director of agricultural science at Texas Agricultural Extension Service. Similarly, Pillai reports "no indication that pathogens from the sludge application site are blowing beyond the site."

Although most people consider bad odors more of a nuisance than a health problem, continuous exposure to strong odors, for example those emanating from hog farms, has been shown to adversely affect the health of some people. Some opponents of biosolids recycling have cited odor as a primary incriminating factor. In fact, biosolids can be closer in appearance and scent to good compost than to the smelly animal manure that farmers have always used to rejuvenate their soil. And when biosolids are injected under the soil surface, the process is virtually odorless. But in northwest New Jersey, residents of Harmony Township blame sewage biosolids and other residues for the air they claim smells like diarrhea, vomit, and urine. "People should not have to live this way," says Lois Markle, a teacher and vociferous opponent of the odors, who recently was elected deputy mayor of the township. Markle blames the problem on a farm that accepts biosolids and slaughterhouse and food-processing wastes, and on a biosolids processing plant next door. With two biosolids facilities side by side, Markle charges, the "[New Jersey] Department of Environmental Protection is not [able] to figure out who is making the odor." After years of complaints, the state is suing one of the operators for air-quality violations.

Questions still remain, however - most prominently, how safe is food grown on biosolids-amended soils? This question, prompted by concern among food processors that the public might boycott their products, sparked the NRC study of biosolids application and wastewater reuse. In the most comprehensive report in many years on biosolids recycling, the NRC generally endorsed the EPA's approach, concluding that "while no disposal or reuse option can guarantee complete safety, the use of [biosolids and treated effluent] in the production of crops for human consumption, when practiced in accordance with existing federal guidelines and regulations, presents negligible risk to the consumer, to crop production, and to the environment." However, the committee did suggest that the EPA reconsider its exclusion of toxic organics from Part 503. The NRC group added that as more croplands "reach their regulatory limit of chemical pollutant loading from sludge application, additional information will be needed to assess potential, long-term impacts of sludge on ground water quality and on the sustainability of soils for crop production." However, since less than 2% of total U.S. cropland would be enough to recycle all current biosolids production, and in many cases biosolids can be applied for 100 years before lifetime loading rates are reached, the day of saturation will not soon be reached.

Given that the scientific literature contains no reports of toxicity or disease due to sludge, why does the public still seem frightened? In some cases, it's probably due to regional resentment, a feeling that easterners, or New Yorkers, are dumping their waste on the rest of the country. There is also a fundamental feeling that biosolids are unclean. When those feelings are combined with fear that biosolids are - as, admittedly, was true 20 years ago - carrying unacceptable levels of heavy metals and toxic chemicals, it's easy to understand the "don't dump on me" sentiment. Rubin acknowledges that spills, smells, and slip-ups sabotage public confidence in land application. "If the public feels the aesthetics are bad, or a sloppy operation is going on and nobody cares, they will feel something is wrong with their health."

## BIOSOLIDS TREATMENT

Biosolids generally require additional treatment at the wastewater treatment facility before they are disposed of in order to meet regulatory requirements that protect public health and the environment, facilitate handling, and reduce costs. Biosolids characteristics can determine a municipality's choice of use or disposal methods. Only biosolids that meet certain regulatory requirements for pathogens, vector attraction reduction, and metal content, for example, can be land applied or used as compost. Even those biosolids that are disposed of rather than land applied must meet regulatory requirements. Also, with regard to handling and cost, the water content of biosolids can affect many aspects of biosdids management, such as transportation and the size of treatment and use or disposal operations. Some biosolids treatment processes reduce the volume or mass of the biosolids (such as biosolids digestion processes). The two most common types of biosolids treatment processes are stabilization and dewatering.

Stabilization refers to a number of processes that reduce pathogen levels, odor, and volatile solids content Biosolids must be stabilized to some extent before most types of use or disposal. Major methods of stabilization include alkali (lime) stabilization, anaerobic digestion (digestion of organics by microorganisms in the absence of oxygen), aerobic digestion (digestion of organics by microorganisms in the presence of oxygen), composting, and/or heat drying.

The body of technologies within dewatering removes excess water from biosolids and generally must be performed before biosolids are composted, landfilled, dried (e.g. pelletized or heat dried), or incinerated. A number dewatering processes can be used, including air drying, vacuum filters, plate-and-frame filters, centrifuges, and belt filter presses.

The improved structural characteristics of stabilized biosolids (compared to dewatered biosolids cake without lime stabilization) tends to reduce pathogens and odors, allow for more efficient handling operations, and provide a source of lime to help neutralize acid soils. While lime is most commonly used, other alkaline materials, such as cement kiln dust lime kiln dust, Portland cement, and fly ash, have also been used for biosolids stabilization.

Alkaline stabilization has been implemented using either quicklime (CaO) or hydrated lime [$Ca[OH]_2$]; which is added either to liquid biosolids before dewatering or in a contained mechanical mixer. Traditional lime stabilization processes are capable of producing biosolids meeting the minimum pathogen and vector attraction reduction requirements found in the 40CFR Part 503 rules governing land application of biosolids; sufficient lime is added so the pH of the biosolids/lime mixture is raised to 12.0 or above for a period of 2 hr. The elevated pH helps to reduce biological action and odors.

In the treatment plant, anaerobic or aerobic bacteria metabolize the solids in wastewater and settle to the bottom. When these bacteria have finished, wastewater contains about 1% solids, largely organic material from the decomposing bacteria. In dry-weight composition, biosolids resemble animal manure, typically containing 3% nitrogen (manure contains 1.7 - 7.8%) and 1.5% phosphorus (manure contains 0.3 to 2.3%). Both materials also contain sulfur, calcium, magnesium, potassium, and other elements. When applied to land, the organic matter in biosolids improves the soil's structure, increases its water-holding capacity, and feeds essential soil microorganisms.

Sewage plants have always had to dispose of biosolids; ironically, better treatment removes more solids and thus creates more biosolids. One of the first recycling efforts began in 1926, when Milwaukee began selling dried biosolids to homeowners and landscapers as fertilizer. According to the EPA, about 12% of all recycled biosolids are given or sold to the public in containers. Approximately 9% of recycled biosolids are used to revitalize land that's been damaged, usually by mining. For many years, Chicago's biosolids were spread on former coal strip mines in Fulton County, Illinois, 190 miles southwest of Chicago. About 2,000 acres of damaged land owned by the Metropolitan Sanitary District of Greater Chicago has been returned to agriculture and is leased to farmers, says district soil scientist Scott Nelson. Here and elsewhere, sludge has also been used to rejuvenate spoils heaps - multi-acre piles of acidic rock where nothing had grown decades after mining had stopped. An enormous amount of biosolids--up to 1,000 dry tons per acre - increased the organic content of the heaps, and 70 tons of lime per acre neutralized the acidity. Today the land is prairie, and the runoff of acid mine drainage, which commonly carries toxic chemicals from abandoned strip mines, has practically ceased. In Washington State, Seattle's biosolids are sprayed into forests, a practice that nationwide accounts for about 3% of total biosolids recycling. In forests, terrain is a key restriction to biosolids use. If the land slopes more than 10 - 20%, the biosolids may quickly wash into watercourses.

Fully 67% of recycled biosolids go to farmland, where they are spread on, or injected under, soil. In Wisconsin, where the Madison Metropolitan Sewerage District's "Metrogro" program is often held up as a national model, fields are chosen based on soil type, depth to groundwater and bedrock, and slope. "If there's high permeability, or potential for runoff, we're not allowed to go on them," says David Taylor, a district soil scientist who directed the Metrogro program for many years. Since excess nitrogen pollutes groundwater and surface water, the district applies the amount of biosolids that will supply only enough nitrogen for the next crop. The farmer's $7.50 per acre payment covers application with the district's trucks, tests of the soil, plant tissue, well water, and all required recordkeeping. Although the fee only funds 1 - 2% of the biosolids program, Taylor says it helps present biosolids "as a resource, not a waste." Farmers in the surrounding area seem to approve and have offered about seven times as much land as the district needs for its annual application of 3,000 to 4000 acres per year. The high level of acceptance can be credited to clean biosolids, a 20-year history of monitoring pollutant levels in biosolids, soil, water, and plant tissue, and the district's support for university research on cheaper and cleaner sewage treatment. Importantly, the district has also shouldered the extra expense of injecting sludge into the soil, preventing odor and sight problems that enrage neighbors of some land application projects.

## APPLICATIONS

The rate at which biosolids are applied to land such that the amount of nitrogen required by the food crop, feed crop, fiber crop, cover crop or vegetation grown on the land is supplied over a defined growth period, and such that the amount of nitrogen in the biosolids which passes below the root zone of the crop or vegetation grown to groundwater is minimized. Biosolids can exhibit a wide array of physical and chemical traits. Depending on the extent of dewatering or drying, the solids content of biosolids can range from less than 5% to more than

90%. Chemical characteristics of biosolids vary between treatment plants and, to a limited extent, within the same plant over time. Table 1 lists the typical chemical composition of biosolids as representative examples. Because biosolids may contain trace elements, they are classified by their trace-element content due to their potential impact on public health and the environment.

Table 1: Chemical Properties of Biosolids (Dry Weight Basis)

| Parameter, units | Littleton/Englewood[a] | Fort Collins[b] | Metro Denver[c] |
|---|---|---|---|
| EC[d], dS/m | 11.6 | 5.0 | 12.7 |
| Organic N, % | 2.88 | 4.22 | 6.31 |
| $NH_4$-N, % | 0.47 | 0.40 | 1.35 |
| $NO_3$-N, % | 0.01 | 0.01 | 0.01 |
| Phosphorus (P), % | 2.52 | 1.60 | 2.32 |
| Potassium (K), % | 0.283 | 0.194 | 0.200 |
| Arsenic (As), mg/kg | 4 | 3 | 3 |
| Cadmium (Cd), mg/kg | 6 | 5 | 10 |
| Chromium (Cr), mg/kg | 98 | 40 | 80 |
| Copper (Cu), mg/kg | 558 | 553 | 500 |
| Mercury (Hg), mg/kg | 0.8 | 6.2 | 3.0 |
| Lead (Pb), mg/kg | 45 | 117 | 138 |
| Molybdenum (Mo), mg/kg | 26 | 16 | 31 |
| Nickel (Ni), mg/kg | 85 | 19 | 41 |
| Selenium (Se), mg/kg | 13 | 14 | 4 |
| Zinc (Zn), mg/kg | 942 | 776 | 915 |

a Applied to experimental plots near Bennett, Colorado, in August 1993.
b Applied to experimental plots on the Meadow Springs Ranch near Fort Collins, Colorado, in August 1991.
c Metrogro$^{TM}$ cake chemical analysis, 1993.
d EC is a measure of the soluble salt concentration.

New, aggressive pretreatment programs at the source of generation have dramatically reduced metal concentration in biosolids over the past two decades, minimizing the possibility of environmental damage. The EPA established guidelines regarding the quantity of trace elements in biosolids and the amount that ultimately can be added to soils growing plants (see Table 2). Base metal limits on extensive research regarding the effects of biosolids metals on various pathways of exposure, including plant toxicities and adverse effects on animal and human health. Biosolids are treated to eliminate pathogens (disease-causing organisms) that may reside in wastewater. EPA requires domestic wastewater treatment plants to reduce pathogens and diminish the attraction of insects and animals before biosolids are applied. Applicators may apply Grade 1 biosolids at agronomic rates without restrictions regarding trace metal loading limits.

Table 2. Maximum Trace Element Concentrations Allowed for Grades 1 and 2 mg/kg (Dry Weight Basis)

| Metal | Grade 1 | Grade 2 |
|---|---|---|
| As | 41 | 75 |
| Cd | 39 | 85 |
| Cr | 1200 | 3000 |
| Cu | 1500 | 4300 |
| Pb | 300 | 840 |
| Hg | 17 | 57 |
| Mo | Not finalized | 75 |
| Ni | 420 | 420 |
| Se | 36 | 100 |
| Zn | 2800 | 7500 |

Biosolids contain significant amounts of N, P, and K (Table 1). They also can provide plant micronutrients such as Zn. Many soils exhibit low levels of available Zn and biosolids help alleviate the deficiency of this essential element. The nature of nutrients in biosolids is different from those found in commercial fertilizers. Stabilization of biosolids during waste treatment produces organic N forms that are not available to plants until they are decomposed by soil microorganisms. When added to soils, microorganisms break down biosolids and release 10 to 50% of the organic N as available N (ammonium, $NH_4^+$) in the first year following application. Soil microorganisms rapidly convert the $NH_4^+$ to nitrate ($NO_3^-$). Plants quickly absorb $NO_3^-$. It also is mobile in soils, irrespective of whether it originates from commercial N fertilizer or biosolids.

The mobility of $NO_3^-$ increases the potential for groundwater contamination. In essence, biosolids are slow-release N fertilizers that contain low concentrations of plant nutrients. Frequently, biosolids promote physical changes in soil that are more significant than the plant nutrients they supply.

The greatest challenge in using biosolids for beneficial reuse on crop- and rangeland is to prevent $NO_3^-$ leaching to groundwater. As biosolids' nutrient value may vary depending on the form (i.e., liquid, dewatered, or dried), determining the correct agronomic rate remains a challenge. However, if the agronomic rate is applied under nonirrigated (dryland) cropping in a semiarid environment, where water table depths generally are over 100 feet, the potential for groundwater contamination is negligible. Under irrigated conditions, if agronomic rates of biosolids based on site specific soil-test and crop-management information are applied, groundwater contamination with $NO_3^-$ should not occur. Annual monitoring of residual soil $NO_3$-N levels will help guard against groundwater pollution.

## A SHORT REVIEW

Biosolids applications are often touted as a pollution prevention technology; however in many ways this is an inappropriate labeling for this application. It is a form of recycling that may carry some long-term health risks, depending upon the nature and characteristics of the solids. Conceptually it is a more cost-effective strategy that incineration and straight landfilling, but this in part depends on local market conditions which support the uses of this material. As a form of recycling, it represents a more logical strategy for long-term solid waste management. It is not, however, a preventive strategy as is often presented to the public.

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# Chapter 7

# INDUSTRY PRACTICES

## INTRODUCTION

The last decade has brought about a significant change in industry attitude and practices in the handling of wastes and pollution. The concept of environmental management systems, personified by ISO 14001, the chemical industry's Responsible Care program, and Western Europe's EMAS, have raised the awareness and level of responsibility of industry to act in a more responsible manner that protects the public and preserves the environment. Despite this awareness, industry sectors continue to struggle innocently and in some cases act irresponsibly in their handling of waste and pollution issues.

This chapter provides an overview of industry practices in different heavy manufacturing sectors. The conventional waste handling practices, along with some of the pollution prevention strategies that are being implemented more frequently today, are covered.

## THE CHEMICAL INDUSTRY

The U.S. chemicals and allied products industry consists of some 9125 multinational corporations whose primary business is the development, manufacturing, and marketing of industrial chemicals, pharmaceuticals, and other chemical products. The U.S. chemical industry is vital to the U.S. economy. It produces 1.9 percent of U.S. gross domestic product (GDP). It is the nation's number one exporter. It supplies more than $1 out of every $10 of U.S. exports and consistently runs large international trade surpluses. It is a high-tech, research and development (R&D) oriented industry that is awarded about one out of every eight U.S. patents. It employs more than 1 million persons and it produces more than 70,000 different products. Most importantly, chemicals is a "keystone" industry -- one critical to the global competitiveness of other U.S. industries. Because so many modern products and businesses depend on chemicals, the international competitiveness of other U.S. industries requires a high-tech, globally competitive U.S. chemical industry that can supply new products at prices that give U.S. producers an edge.

Chemicals in many ways can be described as the foundation of a modern, progressive society. They are an integral and ever-increasing part of our complex technological world, making it possible for us to enjoy a high standard of living. Not only do pollution prevention (P2) practices in the chemical process industries (CPI) offer reduced costs in manufacturing operations, but they are essential in developing more efficient and safe means of manufacturing many of the chemical products we have grown to depend on.

## PETROCHEMICAL MANUFACTURING PRACTICES

Natural gas and crude distillates such as naphtha from petroleum refining are used as feedstocks to manufacture a wide range of petrochemicals that are in turn used in the manufacture of consumer goods. Basic petrochemicals are manufactured by cracking, reforming, and other processes, and include olefins (such as ethylene, propylene, butylenes, and butadiene) and aromatics (such as benzene, toluene, and xylenes). The capacity of naphtha crackers is generally of the order of 250,000 to 750,000 metric tons per year (tpy) of ethylene production. Some petrochemical plants also have alcohol and oxo-compound manufacturing units on site. The base petrochemicals or products derived from them, along with other raw materials, are converted to a wide range of products. Among them are:

- Resins and plastics such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), linear low-density polyethylene (LLDPE), polypropylene, polystyrene, and polyvinyl chloride (PVC);
- Synthetic fibers such as polyester and acrylic engineering polymers such as acrylonitrile butadiene styrene (ABS);
- Rubbers, including styrene butadiene rubber (SBR) and polybutadiene rubber (PBR);
- Solvents;

Industrial chemicals, including those used for the manufacture of detergents such as linear alkyl benzene (LAB) and of coatings, dyestuffs, agrochemicals, pharmaceuticals, and explosives.

Chemical compounds manufactured at petrochemical plants include methanol, formaldehyde, and halogenated hydrocarbons. Formaldehyde is used in the manufacture of plastic resins, including phenolic, urea, and melamine resins. Halogenated hydrocarbons are used in the manufacture of silicone, solvents, refrigerants, and degreasing agents.

Olefins (organics having at least one double bond for carbon atoms) are typically manufactured from the steam cracking of hydrocarbons such as naphtha. Major olefins manufactured include ethylene, propylene, butadiene, and acetylene. The olefins manufactured are used in the manufacture of polyethylene, including low-density polyethylene (LDPE) and high-density polyethylene (HDPE), and for polystyrene, polyvinyl chloride, ethylene glycol (used along with dimethyl terphthalate, DMT, as feedstock to the polyester manufacturing process), ethanol amines (used as solvents), polyvinyl acetate (used in plastics), polyisoprene (used for synthetic rubber manufacture), polypropylene, acetone (used as a solvent and in cosmetics), isopropanol (used as a solvent and in pharmaceuticals manufacturing), acrylonitrile (used in the manufacture of acrylic fibers and nitrile rubber), propylene glycol (used in pharmaceuticals manufacturing), and polyurethane. Butadiene is used in the manufacture of polybutadiene rubber (PBR) and styrene butadiene rubber (SBR). Other $C_4$ compounds manufactured include butanol, which is used in the manufacture of solvents such as methyl ethyl ketone.

The major aromatics (organics having at least one ring structure with six carbon atoms) manufactured include benzene, toluene, xylene, and naphthalene. Other aromatics manufactured include phenol, chlorobenzene, styrene, phthalic and maleic anhydride, nitrobenzene, and aniline. Benzene is generally recovered from cracker streams at petrochemical plants and is used for the manufacture of phenol, styrene, aniline, nitrobenzene, sulfonated detergents, pesticides such as hexachlorobenzene, cyclohexane (an important intermediate in synthetic fiber manufacture), and caprolactam, used in the manufacture of nylon. Benzene is also used as a solvent.

The main uses of toluene are as a solvent in paints, rubber, and plastic cements and as a feedstock in the manufacture of organic chemicals, explosives, detergents, and polyurethane foams. Xylenes (which exist as three isomers) are used in the manufacture of DMT, alkyd resins, and plasticizers. Naphthalene is mainly used in the manufacture of dyes, pharmaceuticals, insect repellents, and phthalic anhydride (used in the manufacture of alkyd resins, plasticizers, and polyester).

The largest user of phenol in the form of thermosetting resins is the plastics industry. Phenol is also used as a solvent and in the manufacture of intermediates for pesticides, pharmaceuticals, and dyestuffs. Styrene is used in the manufacture of synthetic rubber and polystyrene resins. Phthalic anhydride is used in the manufacture of DMT, alkyd resins, and plasticizers such as phthalates. Maleic anhydride is used in the manufacture of polyesters and, to some extent, for alkyd resins. Minor uses include the manufacture of malathion and soil conditioners. Nitrobenzene is used in the manufacture of aniline, benzidine, and dyestuffs and as a solvent in polishes. Aniline is used in the manufacture of dyes, including azo dyes, and rubber chemicals such as vulcanization accelerators and antioxidants.

## SOLID WASTES

Petrochemical plants generate significant amounts of solid wastes and sludges, some of which are hazardous because of the presence of toxic organics and heavy metals. Spent caustic and other hazardous wastes may be generated in significant quantities; examples are distillation residues associated with units handling acetaldehyde, acetonitrile, benzyl chloride, carbon tetrachloride, cumene, phthalic anhydride, nitrobenzene, methyl ethyl pyridine, toluene diisocyanate, trichloroethane, trichloroethylene, perchloroethylene, aniline, chlorobenzenes, dimethyl hydrazine, ethylene dibromide, toluenediamine, epichlorohydrin, ethyl chloride, ethylene dichloride, and vinyl chloride.

Petrochemical plants are typically large and complex, and the combination and sequence of products manufactured are often unique to the plant. Specific pollution prevention practices or source reduction measures are best determined by a dedicated technical staff. However, there are a number of broad areas where improvements are often possible, and site-specific emission reduction measures in these areas should be designed into the plant and targeted by plant management. A good practice target for a petrochemical complex is to reduce total organic emissions (including VOCs) from the process units to 0.6% of the throughput. Target maximum levels for air releases, per ton of product, are, for ethylene, 0.06 kg; for ethylene oxide, 0.02 kg; for vinyl chloride, 0.2 kg; and for 1,2-dichloroethane, 0.4 kg. Control of air emissions normally includes the capturing and recycling or combustion of emissions from vents, product transfer points, storage tanks, and other handling equipment. Catalytic cracking units should be provided with particulate removal devices. Particulate removal technologies include fabric filters, ceramic filters, wet scrubbers, and electrostatic precipitators. Gaseous releases are minimized by condensation, absorption, adsorption (using activated carbon, silica gel, activated alumina, and zeolites), and, in some cases, biofiltration and bioscrubbing (using peat or heather, bark, composts, and bioflora to treat biodegradable organics), and thermal decomposition.

Petrochemical waste waters often require a combination of treatment methods to remove oil and other contaminants before discharge. Separation of different streams (such as stormwater) is essential to minimize treatment requirements. Oil is recovered using separation techniques. For heavy metals, a combination of oxidation/reduction, precipitation, and filtration is used. For organics, a combination of air or steam stripping, granular activated carbon, wet oxidation, ion exchange, reverse osmosis, and electrodialysis is used. A typical system may include neutralization, coagulation/flocculation, flotation/sedimentation/filtration, biodegradation (trickling filter, anaerobic, aerated lagoon, rotating biological contactor, and activated sludge), and clarification. A final polishing step using filtration, ozonation, activated carbon, or chemical treatment may also be required. Examples of pollutant loads that can be achieved are COD, less than 1 kg per 100 tons of ethylene produced; suspended solids, less than 0.4 kg/100 t; and dichloroethane less than 0.001 kg/100 t.

For solid and hazardous wastes, combustion (preceded in some cases by solvent extraction) of toxic organics is considered an effective treatment technology for petrochemical organic wastes. Steam stripping and oxidation are also used for treating organic waste streams. Spent catalysts are generally sent back to the suppliers. In some cases, the solid wastes may require stabilization to reduce the leachability of toxic metals before disposal of in an approved, secure landfill.

The generation of sludges should be minimized. Sludges must be treated to reduce toxic organics to nondetectable levels. Wastes containing toxic metals should be stabilized before disposal.

## CHLOR-ALKALI PLANTS

There are three basic processes for the manufacture of chlorine and caustic soda from brine: the mercury cell, the diaphragm cell, and the membrane cell. Among these technologies, the membrane cell is the most modern and has both economic and environmental advantages. The other two processes generate hazardous wastes containing mercury or asbestos. Mercury cell technology is being phased out in worldwide production.

In the membrane process, the chlorine (at the anode) and the hydrogen (at the cathode) are kept apart by a selective polymer membrane that allows the sodium ions to pass into the cathodic compartment and react with the hydroxyl ions to form caustic soda. The depleted brine is dechlorinated and recycled to the input stage. As noted already, the membrane cell process is the preferred process for new plants. Diaphragm processes may be acceptable, in some circumstances, but only if nonasbestos diaphragms are used. The energy consumption in a membrane cell process is of the order of 2200 to 2500 kilowatt-hours per metric ton (kWh/t), as compared with 2400 to 2700 kWh/t of chlorine for a diaphragm cell process.

The major waste stream from the process consists of brine muds - the sludges from the brine purification step. The sludge is likely to contain magnesium, calcium, iron, and other metal hydroxides, depending on the source and purity of the brines. The muds are normally filtered or settled, the supernatant is recycled, and the mud is dried and then landfilled. Chlorine is a highly toxic gas, and strict precautions are necessary to minimize risk to workers and possible releases during its handling. Major sources of fugitive air emissions of chlorine and hydrogen are vents, seals, and transfer operations. Acid and caustic waste waters are generated in both the process and the materials recovery stages of the operation. The following pollution prevention measures should be considered in plant operations:

Use metal rather than graphite anodes to reduce lead and chlorinated organic matter.

- Resaturate brine in closed vessels to reduce the generation of salt sprays.
- Use noncontact condensers to reduce the amount of process wastewater.
- Scrub chlorine tail gases to reduce chlorine discharges and to produce hypochlorite.
- Recycle condensates and waste process water to the brine system.
- Recycle brine wastes, if possible.

For the chlor-alkali industry, an emergency preparedness and response plan is mandatory for potential uncontrolled chlorine and other releases. Carbon tetrachloride is sometimes used to scrub nitrogen trichloride (formed in the process) and to maintain its levels below 4% to avoid fire and explosion. Substitutes for carbon tetrachloride may have to be used, as the use of carbon tetrachloride may be banned in the near future because of its carcinogenicity. Implementation of cleaner production processes and pollution prevention measures can yield both economic and environmental benefits. The primary treatment technologies afforded to this manufacturing include the following: Caustic scrubber systems should be installed to control chlorine emissions from condensers and at storage and transfer points for liquid chlorine. Sulfuric acid used for drying chlorine should be neutralized before discharge. Brine muds should be discharged to lined settling ponds (or the equivalent) to prevent contamination of soil and groundwater. Effluents should be controlled for pH by neutralization. Settling and filtration are performed to control total suspended solids. Dechlorination of waste waters is performed using sulfur dioxide or bisulfite.

Daily monitoring for parameters other than pH (for effluents from the diaphragm process) is recommended. The pH in the liquid effluent should be monitored continuously. Chlorine monitors should be strategically located within the plant to detect chlorine releases or leaks on a continuous basis. Monitoring data should be analyzed and reviewed at regular intervals and compared with the operating standards so that any necessary corrective actions can be taken. Records of monitoring results should be kept in an acceptable format. The results should be reported to the responsible authorities and relevant parties, as required.

Preference should be given to the membrane process because it is less polluting characteristics over other technologies. In addition, the following pollution prevention measures should be considered for use with the membrane technology:

- Use metal instead of graphite anodes
- Resaturate brine in closed vessels
- Recycle brine wastes
- Scrub chlorine from tail gases to produce hypochlorite
- Provide lined settling ponds for brine muds

## AGRO-INDUSTRY CHEMICALS

Mixed fertilizers contain two or more of the elements nitrogen, phosphorus, and potassium (NPK), which are essential for good plant growth and high crop yields. This subsection briefly addresses the production of ammonium phosphates (monoammonium phosphate, or MAP, and diammonium phosphate, or DAP), nitrophosphates, potash, and compound fertilizers.

Ammonium phosphates are produced by mixing phosphoric acid and anhydrous ammonia in a reactor to produce a slurry. This is referred to as the mixed acid route for producing NPK fertilizers; potassium and other salts are added during the process. The slurry is sprayed onto a bed of recycled solids in a rotating granulator, and ammonia is sparged into the bed from underneath. Granules pass to a rotary dryer followed by a rotary cooler. Solids are screened and sent to storage for bagging or for bulk shipment.

Nitrophosphate fertilizer is made by digesting phosphate rock with nitric acid. This is the nitrophosphate route leading to NPK fertilizers; as in the mixed-acid route, potassium and other salts are added during the process. The resulting solution is cooled to precipitate calcium nitrate, which is removed by filtration methods. The filtrate is neutralized with ammonia, and the solution is evaporated to reduce the water content. The process of prilling may follow. The calcium nitrate filter cake can be further treated to produce a calcium nitrate fertilizer, pure calcium nitrate, or ammonium nitrate and calcium carbonate. Nitrophosphate fertilizers are also produced by the mixed-acid process, through digestion of the phosphate rock by a mixture of nitric and phosphoric acids.

Potash (potassium carbonate) and sylvine (potassium chloride) are solution-mined from deposits and are refined through crystallization processes to produce fertilizer. Potash may also be dry-mined and purified by flotation.

Compound fertilizers can be made by blending basic fertilizers such as ammonium nitrate, MAP, DAP, and granular potash; this route may involve a granulation process.

The principal pollutants from the production of MAP and DAP are ammonia and fluorides, which are given off in the steam from the reaction. Fluorides and dust are released from materials-handling operations. Ammonia in uncontrolled air emissions has been reported to range from 0.1 to 7.8 kilograms of nitrogen per metric ton (kg/t) of product, with phosphorus ranging from 0.02 to 2.5 kg/t product (as phosphorous pentoxide, $P_2O_5$).

In nitrophosphate production, dust will also contain fluorides. Nitrogen oxides $NO_x$ are given off at the digester. In the evaporation stage, fluorine compounds and ammonia are released. Unabated emissions for nitrogen oxides from selected processes are less than 1000 milligrams per cubic meter ($mg/m^3$) from digestion of phosphate rock with nitric acid, 50-200 ($mg/m^3$) from neutralization with ammonia, and 30-200 $mg/m^3$ from granulation and drying. Dust is the primary air pollutant from potash manufacturing.

The volumes of liquid effluents from mixed fertilizer plants are reported to range from 1.4 to 50 cubic meters per metric ton ($m^3/t$) of product. Where water is used in scrubbers, the scrubbing liquors can usually be returned to the process. Effluents can contain nitrogen, phosphorus, and fluorine; the respective ranges of concentrations can be 0.7-15.7 kg/t of product (as N), 0.1-7.8 kg/t of product (as $P_2O_5$), and 0.1-3.2 kg/t of product.

Generally, there is little solid waste from a fertilizer plant, since dust and fertilizer spillage can be returned to the process. However, wastewater treatment operations will create toxic sludges that ultimately must be disposed of.

Materials handling and milling of phosphate rock should be carried out in closed buildings. Fugitive emissions can be controlled by, for example, hoods on conveying equipment, with capture of the dust in fabric filters. In the ammonium phosphate plant, the gas streams from the reactor, granulator, dryer, and cooler should be passed through cyclones and scrubbers, using phosphoric acid as the scrubbing liquid, to recover particulates, ammonia, and other materials for recycling. In the nitrophosphate plant, nitrogen oxide ($NO_x$) emissions should be avoided by adding urea to the digestion stage. Fluoride emissions should be prevented by scrubbing the gases with water. Ammonia should be removed by scrubbing. Phosphoric acid may be used for scrubbing where the ammonia load is high. The process water system should be balanced, if necessary, by the use of holding tanks to avoid the discharge of an effluent.

Additional pollution control devices beyond the scrubbers, cyclones, and baghouses that are an integral part of the plant design and operations are generally not required for mixed fertilizer plants. Good housekeeping practices are essential to minimize the amount of spilled material. Spills or leaks of solids and liquids should be returned to the process. Liquid effluents, if any, need to be controlled for TSS, fluorides, phosphorus, and ammonia. An effluent discharge of less than 1.5 $m^3/t$ product as $P_2O_5$ is realistic, but use of holding ponds makes feasible a discharge approaching zero. In many countries outside of the United States, wastewater treatment discharges are often used for agricultural purposes and may contain heavy metals. Of particular concern is the cadmium content.

## NITROGENOUS FERTILIZER PLANTS

An important class of fertilizers is based on the production of ammonia, urea, ammonium sulfate, ammonium nitrate (AN), calcium ammonium nitrate (CAN), and ammonium sulfate nitrate (ASN). The manufacture of nitric acid used to produce nitrogenous fertilizers typically occurs on site and is therefore included here. Ammonia ($NH_3$) is produced from atmospheric nitrogen and hydrogen from a hydrocarbon source. Natural gas is the most commonly used hydrocarbon feedstock for new plants; other feedstocks that have been used include naphtha, oil, and gasified coal. Natural gas is favored over the other feedstocks from an environmental perspective.

Ammonia production from natural gas includes the following processes: desulfurization of the feedstock; primary and secondary reforming; carbon monoxide shift conversion and removal of carbon dioxide, which can be used for urea manufacture; methanation; and ammonia synthesis. Catalysts used in the process may include cobalt, molybdenum, nickel, iron oxide/chromium oxide, copper oxide/zinc oxide, and iron.

Urea fertilizers are produced by a reaction of liquid ammonia with carbon dioxide. The process steps include solution synthesis, where ammonia and carbon dioxide react to form ammonium carbamate, which is dehydrated to form urea; solution concentration by vacuum, crystallization, or evaporation to produce a melt; formation of solids by prilling (pelletizing liquid droplets) or granulating; cooling and screening of solids; coating of the solids; and bagging or bulk loading. The carbon dioxide for urea manufacture is produced as a by-product from the ammonia plant reformer.

Ammonium sulfate is produced as a caprolactam by-product from the petrochemical industry, as a coke by-product, and synthetically through reaction of ammonia with sulfuric acid. Only the third process is covered in our discussion. The reaction between ammonia and sulfuric acid produces an ammonium sulfate solution that is continuously circulated through an evaporator to thicken the solution and to produce ammonium sulfate crystals. The crystals are separated from the liquor in a centrifuge, and the liquor is returned to the evaporator. The crystals are fed either to a fluidized bed or to a rotary drum dryer and are screened before bagging or bulk loading.

Ammonium nitrate is made by neutralizing nitric acid with anhydrous ammonia. The resulting 80 to 90% solution of ammonium nitrate can be sold as is, or it may be further concentrated to a 95 to 99.5% solution (melt) and converted into prills or granules. The manufacturing steps include solution formation, solution concentration, solids formation, solids finishing, screening, coating, and bagging or bulk shipping. The processing steps depend on the desired finished product. Calcium ammonium nitrate is made by adding ammonia calcite or dolomite to the ammonium nitrate melt before prilling or granulating. Ammonium sulfate nitrate is made by granulating a solution of ammonium nitrate and ammonium sulfate. The production stages for nitric acid manufacture include vaporizing the ammonia; mixing the vapor with air and burning the mixture over a platinum/rhodium catalyst; cooling the resultant nitric oxide (NO) and oxidizing it to nitrogen dioxide ($NO_2$) with residual oxygen; and absorbing the nitrogen dioxide in water in an absorption column to produce nitric acid ($HNO_3$). Because of the large quantities of ammonia and other hazardous materials handled on site, an emergency preparedness and response plan is required.

Emissions to the atmosphere from ammonia plants include sulfur dioxide ($SO_2$), nitrogen oxides ($NO_x$), carbon monoxide (CO), carbon dioxide ($CO_2$), hydrogen sulfide ($H_2S$), volatile organic compounds (VOCs), particulate matter, methane, hydrogen cyanide, and ammonia. The two primary sources of pollutants, with typical reported values, in kilograms per ton (kg/t) for the important pollutants, are as follows:

- Flue gas from primary reformer: $CO_2$: 500 kg/t $NH_3$, $NO_x$: 0.6-1.3 kg/t $NH_3$ as $NO_2$, $SO_2$: less than 0.1 kg/t; CO: less than 0.03 kg/t.
- Carbon dioxide removal: $CO_2$: 1200 kg/t.

Nitrogen oxide emissions depend on the process features. Nitrogen oxides are reduced, for example, when there is low excess oxygen, with steam injection; when postcombustion measures are in place; and when low-$NO_x$ burners are in use. Other measures will also reduce the total amount of nitrogen oxides emitted. Concentrations of sulfur dioxide in the flue gas from the reformer can be expected to be significantly higher if a fuel other than natural gas is used. Energy consumption ranges from 29 to 36 gigajoules per metric ton (GJ/t) of ammonia. Process condensate discharged is about 1.5 cubic meters per metric ton ($m^3$/t) of ammonia. Ammonia tank farms can release upward of 10 kg of ammonia per ton of ammonia produced. Emissions of ammonia from the process have been reported in the range of less than 0.04 to 2 kg/t of ammonia produced.

In a urea plant, ammonia and particulate matter are the emissions of concern. Ammonia emissions are reported as recovery absorption vent (0.1 to 0.5 kg/t), concentration absorption vent (0.1 to 0.2 kg/t), urea prilling (0.5 to 2.2 kg/t), and granulation (0.2 to 0.7 kg/t). The prill tower is a source of urea dust (0.5-2.2 kg/t), as is the granulator (0.1 to 0.5 kg/t).

Particulate matter are the principal air pollutant emitted from ammonium sulfate plants. Most of the particulates are found in the gaseous exhaust of the dryers. Uncontrolled discharges of particulates may be of the order of 23 kg/t from rotary dryers and 109 kg/t from fluidized-bed dryers. Ammonia storage tanks can release ammonia, and there may be fugitive losses of ammonia from process equipment.

The production of ammonium nitrate yields emissions of particulate matter (ammonium nitrate and coating materials), ammonia, and nitric acid. The emission sources of primary importance are the prilling tower and the granulator. Total quantities of nitrogen discharged are in the range of 0.01-18.4 kg/t of product. Values reported for calcium ammonium nitrate are in the range of 0.13 to 3 kg nitrogen per ton of product.

Solid wastes are principally spent catalysts that originate in ammonia production and in the nitric acid plant. Other solid wastes are not normally of environmental concern. It is important to note that hot ammonium nitrate, whether in solid or in concentrated form, carries the risk of decomposition and is unstable and may even detonate under certain circumstances. Special precautions are therefore required in its manufacture. Implementation of cleaner production processes and pollution prevention measures can yield both economic and environmental benefits. The following describes production-related targets that can be achieved by measures such as those described above. The numbers relate to the production processes before the addition of pollution control measures.

## PHOSPHATE FERTILIZER PLANTS

Phosphate fertilizers are produced by adding acid to ground or pulverized phosphate rock. If sulfuric acid is used, single or normal, phosphate (SSP) is produced, with a phosphorus content of 16 to 21% as phosphorous pentoxide ($P_2O_5$). If phosphoric acid is used to acidulate the phosphate rock, triple phosphate (TSP) is the result. TSP has a phosphorus content of 43 to 48% as $P_2O_5$.

SSP production involves mixing the sulfuric acid and the rock in a reactor. The reaction mixture is discharged onto a slow-moving conveyor in a den. The mixture is cured for 4 to 6 weeks before bagging and shipping.

Two processes are used to produce TSP fertilizers: run-of-pile and granular. The run-of-pile process is similar to the SSP process. Granular TSP uses lower-strength phosphoric acid (40%, compared with 50% for run-of-pile). The reaction mixture, a slurry, is sprayed onto recycled fertilizer fines in a granulator. Granules grow and are then discharged to a dryer, screened, and sent to storage.

Phosphate fertilizer complexes often have sulfuric and phosphoric acid production facilities. Sulfuric acid is produced by burning molten sulfur in air to produce sulfur dioxide, which is then catalytically converted to sulfur trioxide for absorption in oleum. Sulfur dioxide can also be produced by roasting pyrite ore. Phosphoric acid is manufactured by adding sulfuric acid to phosphate rock. The reaction mixture is filtered to remove phosphogypsum, which is discharged to settling ponds or waste heaps.

Fluorides and dust are emitted to the air from the fertilizer plant. All aspects of phosphate rock processing and finished product handling generate dust, from grinders and pulverizers, pneumatic conveyors, and screens. The mixer/reactors and dens produce fumes that contain silicon tetrafluoride and hydrogen fluoride. Liquid effluents are not normally expected from the fertilizer plant, since it is feasible to operate the plant with a balanced process water system. The fertilizer plant should generate minimal solid wastes.

In a fertilizer plant, the main source of potential pollution is solids from spills, operating upsets, and dust emissions. It is essential that tight operating procedures be in place and that close attention be paid to constant cleanup of spills and to other housecleaning measures. Product will be retained, the need for disposal of waste product will be controlled, and potential contamination of stormwater runoff from the property will be minimized. The discharge of sulfur dioxide from sulfuric acid plants should be minimized by using the double-contact, double-absorption process, with high-efficiency mist eliminators. Spills and accidental discharges should be prevented by using well-bounded storage tanks, by installing spill catchment and containment facilities, and by practicing good housekeeping and maintenance. Residues from the roasting of pyrites may be used by the cement and steel manufacturing industries. In the phosphoric acid plant, emissions of fluorine compounds from the digester/reactor should be minimized by using well-designed, well-operated, and well-maintained scrubbers. Design for spill containment is essential for avoiding inadvertent liquid discharges. An operating water balance should be maintained to avoid an effluent discharge.

The management of phosphogypsum tailings is a major problem because of the large volumes and large area required and because of the potential for release of dust and radon gases and of fluorides and cadmium in seepage. The following measures will help to minimize the impacts:

- Maintain a water cover to reduce radon gas release and dust emissions.
- Where water cover cannot be maintained, keep the tailings wet or revegetate to reduce dust. (Note, however, that the revegetation process may increase the rate of radon emissions.)
- Line the tailings storage area to prevent contamination of groundwater by fluoride. Where contamination of groundwater is a concern, a management and monitoring plan should be implemented.
- Phosphogypsum may find a use in the production of gypsum board for the construction industry.

Implementation of cleaner production processes and pollution prevention measures can yield both economic and environmental benefits. The following production-related targets can be achieved by measures such as those described above. The numbers relate to the production processes before the addition of pollution control measures. In sulfuric acid plants that use the double-contact, double-absorption process, emissions levels of 2 to 4 kilograms of sulfur dioxide per metric ton (kg/t) of sulfuric acid can be achieved, and sulfur trioxide levels of the order of 0.15 to 0.2 kg/t of sulfuric acid are attainable. Scrubbers are used to remove fluorides and acid from air emissions. The effluent from the scrubbers is normally recycled to the process.

If it is not possible to maintain an operating water balance in the phosphoric acid plant, treatment to precipitate fluorine, phosphorus, and heavy metals may be necessary. Lime can be used for treatment. Spent vanadium catalyst is returned to the supplier for recovery, or, if that cannot be done, is locked in a solidification matrix and disposed of in a secure landfill. Opportunities to use gypsum wastes as a soil conditioner (for alkali soil and soils that are deficient in sulfur) should be explored to minimize the volume of the gypsum stack.

## COKE MANUFACTURING

Coke and coke by-products, including coke oven gas, are produced by the pyrolysis (heating in the absence of air) of suitable grades of coal. The process also includes the processing of coke oven gas to remove tar, ammonia (usually recovered as ammonium sulfate), phenol, naphthalene, light oil, and sulfur before the gas is used as fuel for heating the ovens. This section provides an overview of the production of metallurgical coke and the associated by-products using intermittent horizontal retorts, as well as the pollution prevention practices.

In the coke-making process, bituminous coal is fed (usually after processing operations to control the size and quality of the feed) into a series of ovens, which are sealed and heated at high temperatures in the absence of oxygen, typically in cycles lasting 14 to 36 hours. Volatile compounds that are driven off the coal are collected and processed to recover combustible gases and other byproducts. The solid carbon remaining in the oven is coke.

The coke is taken to the quench tower, where it is cooled with a water spray or by circulating an inert gas (nitrogen), a process known as dry quenching. The coke is screened and sent to a blast furnace or to storage. Coke oven gas is cooled, and by-products are recovered. Flushing liquor, formed from the cooling of coke oven gas, and liquor from primary coolers contain tar and are sent to a tar decanter. Note that the coke oven gas has a heating value and can be used effectively in cogeneration-type projects.

An electrostatic precipitator is used to remove more tar from coke oven gas. The tar is then sent to storage. Ammonia liquor is also separated from the tar decanter and sent to wastewater treatment after ammonia recovery. Coke oven gas is further cooled in a final cooler. Naphthalene is removed in the separator on the final cooler. Light oil is then removed from the coke oven gas and is fractionated to recover benzene, toluene, and xylene. Some facilities may include an onsite tar distillation unit. The Claus process is normally used to recover sulfur from coke oven gas. During the coke quenching, handling, and screening operation, coke breeze is produced. It is either reused on site (e.g., in the sinter plant) or sold off site as a by-product.

The coke oven is a major source of fugitive air emissions. The coking process emits particulate matter (PM); volatile organic compounds (VOCs); polynuclear aromatic hydrocarbons (PAHs); methane, at approximately 100 grams per metric ton (g/t) of coke; ammonia; carbon monoxide; hydrogen sulfide (50-80 g/t of coke from pushing operations); hydrogen cyanide; and sulfur oxides, $SO_x$, (releasing 30% of sulfur in the feed). Significant amount of VOCs may also be released in by-product recovery operations. For every ton of coke produced, approximately 0.7 to 7.4 kilograms (kg) of PM, 2.9 kg of $SO_x$, (ranging from 0.2 to 6.5 kg), 1.4 kg of nitrogen oxides $NO_x$, 0.1 kg of ammonia, and 3 kg of VOCs (including 2 kg of benzene) may be released into the atmosphere if there is no vapor recovery system. Coal-handling operations may account for about 10% of the particulate load. Coal charging, coke pushing, and quenching are major sources of dust emissions.

Wastewater is generated at an average rate ranging from 0.3 to 4 cubic meters ($m^3$) per ton of coke processed. Major wastewater streams are generated from the cooling of the coke oven gas and the processing of ammonia, tar, naphthalene, phenol, and light oil. Process wastewater may contain 10 milligrams per liter (mg/l) of benzene, 1,000 mg/l of biochemical oxygen demand (BOD) (4 kg/t of coke), 1500 to 6000 mg/l of chemical oxygen demand (COD), 200 mg/l of total suspended solids (TSS), and 150 to 2,000 mg/l of phenols (0.3 to 12 kg/t of coke). Wastewaters also contain PAHs at significant concentrations (up to 30 mg/l), ammonia (0.1 to 2 kg nitrogen/t of coke), and cyanides (0.1-0.6 kg/t of coke). Coke production facilities generate process solid wastes other than coke breeze (which averages 1 kg/t of product).

Most of the solid wastes contain hazardous components such as benzene and PAHs. Waste streams of concern include residues from coal tar recovery (typically 0.1 kg/t of coke), the tar decanter (0.2 kg/t of coke), tar storage (0.4 kg/t of coke), light oil processing (0.2 kg/t of coke), wastewater treatment (0.1 kg/t of coke), naphthalene collection and recovery (0.02 kg/t of coke), tar distillation (0.01 kg/t of coke), and sludges from biological treatment of wastewater.

Pollution prevention in coke making is focused on reducing coke oven emissions and developing cokeless iron- and steelmaking techniques. Implementation of cleaner production processes and pollution prevention measures can yield both economic and environmental benefits. By way of some general guidelines, the generation rate for wastewater should be less than 0.3 $m^3$/t of coke. New coke plants should not generate more than 1 kg of process solid waste (excluding coke breeze and biosludges) per ton of coke.

Baghouses are preferred over venturi scrubbers for controlling particulate matter emissions from loading and pushing operations because of the higher removal efficiencies. ESPs are effective for final tar removal from coke oven gas. Stack air emissions should be monitored continuously for particulate matter. Alternatively, opacity measurements of stack gases could suffice. Fugitive emissions should be monitored annually for VOCs.

Wastewater treatment systems include screens and settling tanks to remove total suspended solids, oil, and tar; steam stripping to remove ammonia, hydrogen sulfide, and hydrogen cyanide; biological treatment; and final polishing with filters. Wastewater discharges should be monitored daily for flow rate and for all parameters, except for dibenz(*a,h*)anthracene and benzo(*a*)pyrene. The latter should be monitored at least on a monthly basis or when there are process changes. Frequent sampling may be required during startup and upset conditions.

All process hazardous wastes except for coke fines should be recycled to coke ovens. Wastewater treatment sludges should be dewatered. If toxic organics are detectable, dewatered sludges are to be charged to coke ovens or disposed in a secure landfill or an appropriate combustion unit.

Solid hazardous wastes containing toxic organics should be recycled to a coke oven or treated in a combustion unit, with residues disposed of in a secure landfill. In summary, the key production and control practices that will lead to compliance with emissions guidelines can be summarized as follows:

- Use cokeless iron- and steelmaking processes, such as the direct reduction process for ironmaking, to eliminate the need for coke manufacturing.
- Where feasible, use dry quenching instead of wet quenching.
- Use vapor-recovery systems in light oil processing, tar processing and storage, naphthalene processing, and phenol and ammonia recovery operations.
- Recover sulfur from coke oven gas.
- Segregate process and cooling water.
- Recycle process solid wastes to the coke oven.

## DYE MANUFACTURING

Dyes are soluble at some stage of the application process, whereas pigments, in general, retain essentially their particulate or crystalline form during application. A dye is used to impart color to materials of which it becomes an integral part. An aromatic ring structure coupled with a side chain is usually required for resonance and thus to impart color. Resonance structures cause displacement or appearance of absorption bands in the visible spectrum of light, and hence they are responsible for color. Correlation of chemical structure with color has been accomplished in the synthesis of dye using a chromogen-chromophore with auxochrome. Chromogen is the aromatic structure containing benzene, naphthalene, or anthracene rings. A chromophore group is a color giver or donor and is represented by the following radicals, which form a basis for the chemical classification of dyes when coupled with the chromogen: azo ($-N=N-$); carbonyl ($=C=O$); carbon ($=C=C=$); carbon-nitrogen ($>C=NH$ or $-CH=N-$); nitroso ($-NO$ or $N-OH$); nitro ($-NO2$ or $=NO-OH$); and sulfur ($>C=S$, and other carbon-sulfur groups). The chromogen-chromophore structure is often not sufficient to impart solubility and cause adherence of dye to fiber. The auxochrome or bonding affinity groups are amine, hydroxyl, carboxyl, and sulfonic radicals, or their derivatives. These auxochromes are important in the use classification of dyes. A listing of dyes by use classification comprises the following:

- *Acetate rayon dyes:* developed for cellulose acetate and some synthetic fibers
- *Acid dyes:* used for coloring animal fibers via acidified solution (containing sulfuric acid, acetic acid, sodium sulfate, and surfactants) in combination with amphoteric protein
- *Azoic dyes:* contain the azo group (and formic acid, caustic soda, metallic compounds, and sodium nitrate); especially for application to cotton
- *Basic dyes:* amino derivatives (and acetic acid and softening agents); used mainly for application on paper
- *Direct dyes:* azo dyes, and sodium salts, fixing agents, and metallic (chrome and copper) compounds; used generally on cotton-wool, or cotton-silk combinations
- *Mordant or chrome dyes:* metallic salt or lake formed directly on the fiber by the use of aluminum, chromium, or iron salts that cause precipitation in situ
- *Lake or pigment dyes:* form insoluble compounds with aluminum, barium, or chromium on molybdenum salts; the precipitates are ground to form pigments used in paint and inks
- *Sulfur or sulfide dyes:* contain sulfur or are precipitated from sodium sulfide bath; furnish dull shades with good fastness to light, washing, and acids but susceptible to chlorine and light
- *Vat dyes:* impregnated into fiber under reducing conditions and reoxidized to an insoluble color

Chemical classification is based on chromogen. For example, nitro dyes have the chromophore -$NO_2$. The *Color Index (C.I.),* published by the Society of Dyers and Colourists (United Kingdom) in cooperation with the American Association of Textile Chemists and Colorists (AATC), provides a detailed classification of commercial dyes and pigments by generic name and chemical constitution.

Dyes are synthesized in a reactor, then filtered, dried, and blended with other additives to produce the final product. The synthesis step involves reactions such as sulfonation, halogenation, amination, diazotization, and coupling, followed by separation processes that may include distillation, precipitation, and crystallization.

In general, organic compounds such as naphthalene are reacted with an acid or an alkali along with an intermediate (such as a nitrating or a sulfonating compound) and a solvent to form a dye mixture. The dye is then separated from the mixture and purified. On completion of the manufacture of actual color, finishing operations, including drying, grinding, and standardization, are performed; these are important for maintaining consistent product quality.

Major solid wastes of concern include filtration sludges, process and effluent treatment sludges, and container residues. Examples of wastes considered toxic include wastewater treatment sludges, spent acids, and process residues from the manufacture of chrome yellow and orange pigments, molybdate orange pigments, zinc yellow pigments, chrome and chrome oxide green pigments, iron blue pigments, and azo dyes.

Dedicated effort should be made to substitute degradable and less toxic ingredients for highly toxic and persistent ingredients in this industry sector. Recommended pollution prevention measures include the following:

- Avoid the manufacture of toxic azo dyes and provide alternative dyestuffs to users such as textile manufacturers.
- Meter and control the quantities of toxic ingredients to minimize wastage.
- Reuse by-products from the process as raw materials or as raw material substitutes in other processes.
- Use automated filling to minimize spillage.
- Use equipment washdown waters as makeup solutions for subsequent batches.
- Return toxic materials packaging to suppliers for reuse, where feasible.
- Find productive uses for off-specification products to avoid disposal problems.
- Use high-pressure hoses for equipment cleaning to reduce the amount of wastewater generated.
- Label and store toxic and hazardous materials in secure areas.

Contaminated solid wastes are generally incinerated, and the flue gases, when acidic wastes, are scrubbed. Contaminated solid wastes should be incinerated under controlled conditions to reduce toxic organics to nondetectable levels, in no case exceeding 0.05 mg/kg or the health-based level. Emissions levels for the design and operation of each project must be established based upon national and local emissions standards.

## PHARMACEUTICALS MANUFACTURING

The pharmaceutical industry includes the manufacture, extraction, processing, purification, and packaging of chemical materials to be used as medications for humans or animals. Pharmaceutical manufacturing is divided into two major stages: the production of the active ingredient or drug (primary processing, or manufacture) and secondary processing, the conversion of the active drugs into products suitable for administration. This section briefly deals with the synthesis of the active ingredients and their usage in drug formulations to deliver the prescribed dosage. Formulation is also referred to as galenical production. The main pharmaceutical groups manufactured include:

- Proprietary ethical products or prescription only medicines (POM), which are usually patented products
- General ethical products, which are basically standard prescription-only medicines made to a recognized formula that may be specified in standard industry reference books
- Over-the counter (OTC), or nonprescription, products

The products are available as tablets, capsules, liquids (in the form of solutions, suspensions, emulsions, gels, or injectables), creams (usually oil-in-water emulsions), ointments (usually water-in-oil emulsions), and aerosols, which contain inhalable products or products suitable for external use. Propellants used in aerosols include chlorofluorocarbons (CFCs), which are being phased out. Recently, butane has been used as a propellant in externally applied products. The major manufactured groups include:

- Antibiotics such as penicillin, streptomycin, tetracyclines, chloramphenicol, and antifungals
- Other synthetic drugs, including sulfa drugs, antituberculosis drugs, antileprotic drugs, analgesics, anesthetics, and antimalarials;
- Vitamins
- Synthetic hormones
- Glandular products drugs of vegetable origin, such as quinine, strychnine and brucine, emetine, and digitalis glycosides
- Vaccines and sera
- Other pharmaceutical chemicals such as calcium gluconate, ferrous salts, nikethamide, glycerophosphates, chloral hydrate, saccharin, antihistamines (including meclozine and buclozine), tranquilizers (including meprobamate and chloropromazine), antifilarials, diethyl carbamazepine citrate, and oral antidiabetics, including tolbutamide and chlorpropamide;
- Surgical sutures and dressings

  The principal manufacturing steps are as follows:

  (a) Preparation of process intermediates
  (b) Introduction of functional groups
  (c) Coupling and esterification
  (d) Separation processes such as washing and stripping
  (e) Purification of the final product

Additional product preparation steps include granulation; drying; tablet pressing, printing, and coating; filling; and packaging. Each of these steps may generate air emissions, liquid effluents, and solid wastes.

The manufacture of penicillin, for example, involves batch fermentation-using 100 to 200 $m^3$ batches-of maize steep liquor or a similar base, with organic precursors added to control the yield. Specific mold culture such as *Penicillium chrysogenum* for Type 11 is inoculated into the fermentation medium. Penicillin is separated from the fermentation broth by solvent extraction.

The product is further purified using acidic extraction. This is followed by treatment with a pyrogen-free distilled water solution containing the alkaline salt of the desired element. The purified aqueous concentrate is separated from the solvent in a supercentrifuge and pressurized through a biological filter to remove the final traces of bacteria and pyrogens.

The solution can be concentrated by freeze drying or vacuum spray drying. Oil-soluble procaine penicillin is made by reacting a penicillin concentrate (20-30%) with a 50% aqueous solution of procaine hydrochloride. Procaine penicillin crystallizes from this mixture.

In some countries, the manufacture of pharmaceuticals is controlled by Good Management Practices (GMP). Some countries require an environmental assessment (EA) report addressing the fate and toxicity of drugs and their metabolized by-products. The EA data relate to the parent drug, not to all metabolites, and include:
(a) Physical and chemical properties
(b) Biodegradability
(c) Photolysis propensity
(d) Aqueous toxicity to fish
(e) Prediction of existing or planned treatment plant to treat wastes and wastewaters
(f) Treatment sequences that are capable of treating wastes and wastewaters

Liquid effluents resulting from equipment cleaning after batch operation contain toxic organic residues. Their composition varies, depending on the product manufactured, the materials used in the process, and other process details. Cooling waters are normally recirculated. Some wastewaters may contain mercury, in a range of 0.1-4 milligrams per liter (mg/l), cadmium (10 to 600 mg/l), isomers of hexachlorocyclohexane, 1,2-dichloroethane, and solvents. Typical amounts released with the wastewater are 25 kilograms of biochemical oxygen demand (BOD) per metric ton of product (kg/t), or 2000 mg/l; 50 kg/t chemical oxygen demand (COD), or 4000 mg/l; 3 kg/t of suspended solids; and up to 0.8 kg/t of phenol.

The principal solid wastes of concern include process and effluent treatment sludges, spent catalysts, and container residues. Approximately 200 kg wastes per ton of product of waste are generated. Some solid wastes contain significant concentrations of spent solvents and other toxic organics. Every effort should be made to replace highly toxic and persistent ingredients with degradable and less toxic ones.

## PETROLEUM REFINING

Petroleum refining is one of the leading manufacturing industries in the United States in terms of its share of the total value of shipments of the U.S. economy. In relation to its economic importance, however, the industry is comprised of relatively few companies and facilities. The number of refineries operating in the United States can vary significantly depending on the information source. For example, in 1992, the Census Bureau counted 232 facilities and the Department of Energy reported 199 facilities.

In addition, EPA's Toxic Release Inventory (TRI) for 1993 identified 159 refineries. The differences lie in each organization's definition of a refinery. The Census Bureau's definition is based on the type of product that a facility produces and includes a number of very small operations producing a specific petroleum product, such as lubricating oils from other refined petroleum products. These small facilities often employ fewer than 10 people and account for only 1% to 2% of the petroleum refining industry's total value of shipments. In comparison to the typically much more complex, larger, and more numerous crude oil processing refineries, these facilities with their smaller and relatively simple operations do not warrant the same level of attention from an economic and environmental compliance standpoint, nor are the pollution prevention opportunities likely to be substantial, except on a collective basis. Refineries recognized by the Department of Energy tend to be only the larger facilities which process crude oil into refined petroleum products.

### INDUSTRY DESCRIPTION AND PRACTICES

This section describes the major industrial processes within the petroleum refining industry, including the materials and equipment used, and the processes employed. The section is necessary for an understanding of the industry, and for grasping the interrelationship between the industrial processes and pollutant outputs and pollution prevention opportunities. This section specifically contains a description of commonly used production processes, associated raw materials, the by-products produced or released, and the materials either recycled or transferred off-site. This discussion, coupled with schematic drawings of the identified processes, provides a description of where wastes may be produced in the process. This section also describes the potential fate (via air, water, and soil pathways) of these waste products.

Petroleum refining is the physical, thermal, and chemical separation of crude oil into its major distillation fractions which are then further processed through a series of separation and conversion steps into finished petroleum products. The primary products of the industry fall into three major categories: fuels (motor gasoline, diesel and distillate fuel oil, liquefied petroleum gas, jet fuel, residual fuel oil, kerosene, and coke); finished nonfuel products (solvents, lubricating oils, greases, petroleum wax, petroleum jelly, asphalt, and coke); and chemical industry feedstocks (naphtha, ethane, propane, butane, ethylene, propylene, butylenes, butadiene, benzene, toluene, and xylene). These petroleum products comprise about 40% of the total energy consumed in the United States and are used as primary input to a vast number of products, including: fertilizers, pesticides, paints, waxes, thinners, solvents, cleaning fluids, detergents, refrigerants, anti-freeze, resins, sealants, insulations, latex, rubber compounds, hard plastics, plastic sheeting, plastic foam and synthetic fibers. About 90% of the petroleum products used in the United States are fuels with motor gasoline accounting for about 43% of the total.

The Standard Industrial Classification (SIC) code established by the Bureau of Census to track the flow of goods and services within the economy is 29 for the Petroleum Refining and Related Industries. The petroleum refining industry is classified as SIC 2911, which includes the production of petroleum products through distillation and fractionation of crude oil, redistillation of unfinished petroleum derivatives, cracking, or other processes. The related industries under SIC 29 are 2951, Asphalt Paving Mixtures and Blocks; 2952, Asphalt Felts and Coatings; 2992, Lubricating Oils and Greases; and 2999, Petroleum and Coal Products, Not Elsewhere Classified. Certain products that are produced by the petroleum refining industry are also produced by other industries, including 2865, Cyclic Organic Crudes and Intermediates, and Organic Dyes and Pigments; 2869, Industrial Organic Chemicals; 2819, Industrial Inorganic Chemicals, Not Elsewhere Classified; 2821, Plastic Materials, Synthetic Resins, Nonvulcanizable Elastomers; 2873, Nitrogenous Fertilizers; 4613, Refined Petroleum Pipelines; and 5171, Petroleum Bulk Stations and Terminals. Most crude oil distillation capacity is owned by large, integrated companies with multiple high-capacity refining facilities. Small refineries with capacities below 50,000 barrels per day, however, make up about half of all facilities, but only 14% of the total crude distillation capacity.

The United States is a net importer of crude oil and petroleum products. In 1994, imports accounted for more than 50% of the crude oil used in the United States and about 10% of finished petroleum products. The imported share of crude oil is expected to increase as U.S. demand for petroleum products increases and the domestic production of crude oil declines. Imported finished petroleum products serve specific market niches arising from logistical considerations, regional shortages, and long-term trade relations between suppliers and refiners. Exports of refined petroleum products, which primarily consist of petroleum coke, residual fuel oil, and distillate fuel oil, account for about 4% of the U.S. refinery output. Exports of crude oil produced in the Unites States account for about one percent of the total U.S. crude oil produced and imported.

The petroleum refining industry in the United States has felt considerable economic pressures in the past two decades arising from a number of factors, including increased costs of labor; compliance with new safety and environmental regulations; and the elimination of government subsidies through the Crude Oil Entitlements Program which had encouraged smaller refineries to add capacity throughout the 1970s. A rationalization period began after crude oil pricing and entitlements were decontrolled in early 1981. The market determined that there was surplus capacity and the margins dropped to encourage the closure of the least efficient capacity. Reflecting these pressures, numerous facilities have closed in recent years. Between 1982 and 1994, the number of U.S. refineries as determined by the Department of Energy dropped from 301 to 176. Most of these closures have involved small facilities refining less than 50,000 barrels of crude oil per day. Some larger facilities, however, have also closed in response to economic pressures. Industry representatives cited complying with the increasing environmental regulations, particularly the requirements of the Clean Air Act Amendments of 1990, as the most important factor affecting petroleum refining in the 1990s. Despite the closing of refineries in recent years, total refinery output of finished products has remained relatively steady with slight increases in the past 2 to 3 years. Increases in refinery outputs are attributable to higher utilization rates of refinery capacity, and to incremental additions to the refining capacity at existing facilities as opposed to construction of new refineries.

Demand for refined petroleum products is expected to increase on the average by about 1.5% per year, which is slower than the expected growth of the economy. This slower rate of increase of demand will be due to increasing prices of petroleum products as a result of conservation, the development of substitutes for petroleum products, and rising costs of compliance with environmental and safety requirements.

Recent and future environmental and safety regulatory changes are expected to force the petroleum refining industry to make substantial investments in upgrading certain refinery processes to reduce emissions and alter product compositions. For example, industry estimates of the capital costs to comply with the 1990 Clean Air Act Amendments, which mandate specific product compositions, are about $35 to $40 billion. There is concern that in some cases it may be more economical for some refineries to close down partially or entirely rather than upgrade facilities to meet these standards. In fact, the U.S. Departments of Energy and Commerce expect refinery shutdowns to continue through the early part of the new decade; however, total crude oil distillation capacity is expected to remain relatively stable as a result of increased capacity and utilization rates at existing facilities. Increases in demand for finished petroleum products will be filled by increased imports. Pressure to meet the Clean Air Amendments is a major driving force for pollution prevention programs in this industry sector.

## PROCESSES AND OPERATIONS

Crude oil is a mixture of many different hydrocarbons and small amounts of impurities. The composition of crude oil can vary significantly depending on its source. Petroleum refineries are a complex system of multiple operations and the operations used at a given refinery depend upon the properties of the crude oil to be refined and the desired products. For these reasons, no two refineries are alike. Portions of the outputs from some processes are refed back into the same process, fed to new processes, fed back to a previous process, or blended with other outputs to form finished products. The major unit operations typically involved at petroleum refineries are described briefly below. In addition to those listed below, there are also many special-purpose processes that cannot be described here and which may play an important role in a facility's efforts to comply with pollutant discharge and product specification requirements.

Refining crude oil into useful petroleum products can be separated into two phases and a number of supporting operations. The first phase is desalting of crude oil and the subsequent distillation into its various components or "fractions." The second phase is made up of three different types of "downstream" processes: combining, breaking, and reshaping.

Downstream processes convert some of the distillation fractions into petroleum products (residual fuel oil, gasoline, kerosene, etc.) through any combination of different cracking, coking, reforming, and alkylation processes. Supporting operations may include wastewater treatment, sulfur recovery, additive production, heat exchanger cleaning, blowdown systems, blending of products, and storage of products.

### Crude Oil Distillation and Desalting

One of the most important operations in a refinery is the initial distillation of the crude oil into its various boiling point fractions. Distillation involves the heating, vaporization, fractionation, condensation, and cooling of feedstocks. This subsection discusses the atmospheric and vacuum distillation processes which when used in sequence result in lower costs and higher efficiencies. This subsection also discusses the important first step of desalting the crude oil prior to distillation.

*Desalting*. Before separation into fractions, crude oil usually must first be treated to remove corrosive salts. The desalting process also removes some of the metals and suspended solids which cause catalyst deactivation. Desalting involves the mixing of heated crude oil with water (about 3 to 10% of the crude oil volume) so that the salts are dissolved in the water. The water must then be separated from the crude oil in a separating vessel by adding demulsifier chemicals to assist in breaking the emulsion and/or, more commonly, by applying a high potential electric field across the settling vessel to coalesce the polar saltwater droplets. The desalting process creates an oily desalter sludge and a high temperature salt water waste stream which is typically added to other process wastewaters for treatment in the refinery wastewater treatment facilities. The water used in crude desalting is often untreated or partially treated water from other refining process water sources.

*Atmospheric Distillation*. The desalted crude oil is then heated in a heat exchanger and furnace to about 750°F and fed to a vertical distillation column at atmospheric pressure where most of the feed is vaporized and separated into its various fractions by condensing on 30 to 50 fractionation trays, each corresponding to a different condensation temperature. The lighter fractions condense and are collected toward the top of the column. Heavier fractions, which may not vaporize in the column, are further separated later by vacuum distillation. Within each atmospheric distillation tower, a number of side streams (at least four) of low-boiling-point components are removed from the tower from different trays. These low-boiling point mixtures are in equilibrium with heavier components which must be removed. The side streams are each sent to a different small stripping tower containing four to 10 trays with steam injected under the bottom tray. The steam strips the light-end components from the heavier components and both the steam and light-ends are fed back to the atmospheric distillation tower above the corresponding side stream draw tray. Fractions obtained from atmospheric distillation include naphtha, gasoline, kerosene, light fuel oil, diesel oils, gas oil, lube distillate, and heavy bottoms. Most of these can be sold as finished products, or blended with products from downstream processes. Another product produced in atmospheric distillation, as well as many other refinery processes, is the light, noncondensible refinery fuel gas (mainly methane and ethane). Typically this gas also contains hydrogen sulfide and ammonia gases. The mixture of these gases is known as "sour gas" or "acid gas." The sour gas is sent to the refinery sour gas treatment system which separates the fuel gas so that it can be used as fuel in the refinery heating furnaces. Air emissions during atmospheric distillation arise from the combustion of fuels in the furnaces to heat the crude oil, process vents and fugitive emissions. Oily sour water (condensed steam containing hydrogen sulfate and ammonia) and oil is also generated in the fractionators.

*Vacuum Distillation.* Heavier fractions from the atmospheric distillation unit that cannot be distilled without cracking under its pressure and temperature conditions are vacuum distilled. Vacuum distillation is simply the distillation of petroleum fractions at a very low pressure (0.2 to 0.7 psia) to increase volatilization and separation. In most systems, the vacuum inside the fractionator is maintained with steam ejectors and vacuum pumps, barometric condensers, or surface condensers. The injection of superheated steam at the base of the vacuum fractionator column further reduces the partial pressure of the hydrocarbons in the tower, facilitating vaporization and separation. The heavier fractions from the vacuum distillation column are processed downstream into more valuable products through either cracking or coking operations. A potential source of emissions from distillation of crude oil are the combustion of fuels in the furnace and some light gases leaving the top of the condensers on the vacuum distillation column. A certain amount of noncondensable light hydrocarbons and hydrogen sulfide pass through the condenser to a hot well, and then is discharged to the refinery sour fuel system or is vented to a process heater, flare, or another control device to destroy hydrogen sulfide. The quantity of these emissions depends on the size of the unit, the type of feedstock, and the cooling water temperature. If barometric condensers are used in vacuum distillation, significant amounts of oily wastewater can be generated. Vacuum pumps and surface condensers have largely replaced barometric condensers in many refineries to eliminate this oily wastewater stream. Oily sour water is also generated in the fractionators.

### Downstream Processing

Certain fractions from the distillation of crude oil are further refined in thermal cracking (visbreaking), coking, catalytic cracking, catalytic hydrocracking, hydrotreating, alkylation, isomerization, polymerization, catalytic reforming, solvent extraction, Merox, dewaxing, propane deasphalting and other operations. These downstream processes change the molecular structure of hydrocarbon molecules either by breaking them into smaller molecules, joining them to form larger molecules, or reshaping them into higher quality molecules. For many of the operations, a number of different techniques are used in the industry.

*Thermal Cracking/Visbreaking.* Thermal cracking, or visbreaking, uses heat and pressure to break large hydrocarbon molecules into smaller, lighter molecules. The process has been largely replaced by catalytic cracking and some refineries no longer employ thermal cracking. Both processes reduce the production of less valuable products such as heavy fuel oil and cutter stock and increase the feedstock to the catalytic cracker and gasoline yields. In thermal cracking, heavy gas oils and residue from the vacuum distillation process are typically the feed stocks. The feedstock is heated in a furnace or other thermal unit to up to 1000°F and then fed to a reaction chamber which is kept at a pressure of about 140 psig. Following the reactor step, the process stream is mixed with a cooler recycle stream, which stops the cracking reactions. The product is then fed to a flasher chamber, where pressure is reduced and lighter products vaporize and are drawn off. The lighter products are fed to a fractionating tower where the various fractions are separated. The "bottoms" consist of heavy residue, part of which is recycled to cool the process stream leaving the reaction chamber; the remaining bottoms are usually blended into residual fuel (refer to Fig. 1).

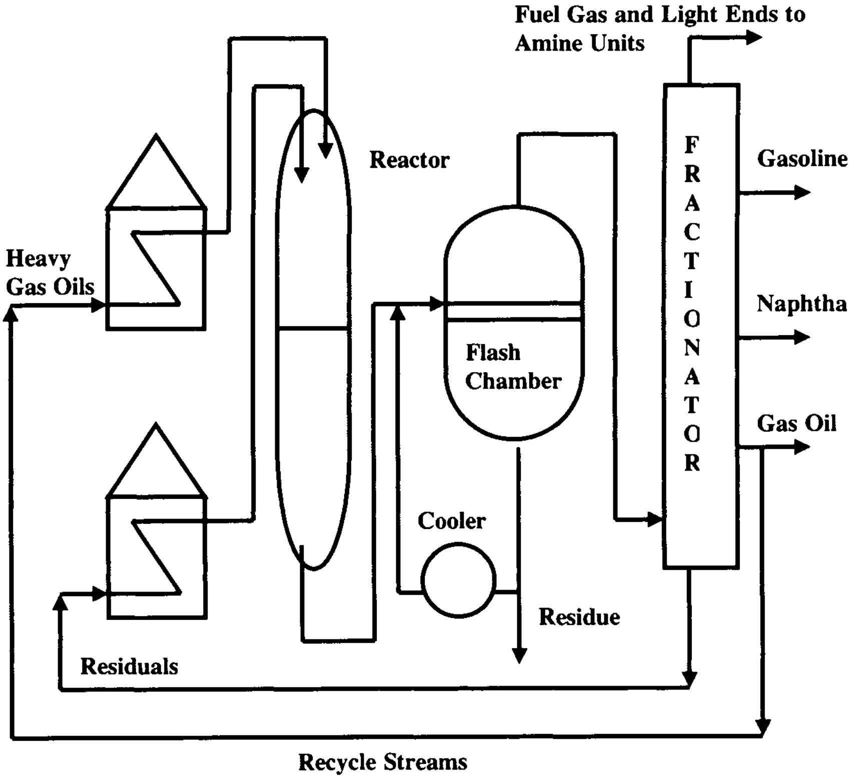

Figure 1. Flow diagram of thermal cracker unit.

Air emissions from thermal cracking include emissions from the combustion of fuels in the process heater, vents, and fugitive emissions." A sour water stream is generated in the fractionator.

*Coking*. Coking is a cracking process used primarily to reduce refinery production of low-value residual fuel oils to transportation fuels, such as gasoline and diesel. As part of the upgrading process, coking also produces petroleum coke, which is essentially solid carbon with varying amounts of impurities, and is used as a fuel for power plants if the sulfur content is low enough. Coke also has nonfuel applications as a raw material for many carbon and graphite products including anodes for the production of aluminum, and furnace electrodes for the production of elemental phosphorus, titanium dioxide, calcium carbide and silicon carbide. A number of different processes are used to produce coke; both *delayed coking* and *fluid coking* are the most widely used processes. Fluid coking produces a higher grade of coke. In delayed coking operations, the same basic process as thermal cracking is used except feed streams are allowed to react longer without being cooled. The delayed coking feed stream of residual oils from various upstream processes is first introduced to a fractionating tower where residual lighter materials are drawn off and the heavy ends are condensed. The heavy ends are removed and heated in a furnace to about 900 to 1000°F and then fed to an insulated vessel called a coke drum where the coke is formed. When the coke drum is filled with product, the feed is switched to an empty parallel drum. Hot vapors from the coke drums, containing cracked lighter hydrocarbon products, hydrogen sulfide, and ammonia, are fed back to the fractionator where they can be treated in the sour gas treatment system or drawn off as intermediate products.

Steam is then injected into the full coke drum to remove hydrocarbon vapors, water is injected to cool the coke, and the coke is removed. Typically, high-pressure water jets are used to cut the coke from the drum.

Air emissions from coking operations include the process heater flue gas emissions, fugitive emissions and emissions, that may arise from the removal of the coke from the coke drum. The injected steam is condensed and the remaining vapors are typically flared. Wastewater is generated from the coke removal and cooling operations and from the steam injection. In addition, the removal of coke from the drum can release particulate emissions and any remaining hydrocarbons to the atmosphere.

*Catalytic Cracking*. Catalytic cracking uses heat, pressure and a catalyst to break larger hydrocarbon molecules into smaller, lighter molecules. Catalytic cracking has largely replaced thermal cracking because it is able to produce more gasoline with a higher octane and less heavy fuel oils and light gases. Feedstocks are light and heavy oils from the crude oil distillation unit which are processed primarily into gasoline as well as some fuel oil and light gases. Most catalysts used in catalytic cracking consist of mixtures of crystalline synthetic silica-alumina, termed "zeolites," and amorphous synthetic silica-alumina. The catalytic cracking processes, as well as most other refinery catalytic processes, produce coke which collects on the catalyst surface and diminishes its catalytic properties. The catalyst, therefore, needs to be regenerated continuously or periodically essentially by burning the coke off the catalyst at high temperatures. The method and frequency in which catalysts are regenerated are a major factor in the design of catalytic cracking units. A number of different catalytic cracking designs are currently in use, including fixed-bed reactors, moving-bed reactors, fluidized-bed reactors, and once-through units. The fluidized- and moving-bed reactors are by far the most prevalent.

Fluidized-bed catalytic cracking units (FCCUs) are the most common catalytic cracking units. In the fluidized-bed process, oil and oil vapor preheated to 500 to 800°F is contacted with hot catalyst at about 1,300°F either in the reactor itself or in the feed line (called the 'riser') to the reactor. The catalyst is in a fine, granular form which, when mixed with the vapor, has many of the properties of a fluid. The fluidized catalyst and the reacted hydrocarbon vapor separate mechanically in the reactor and any oil remaining on the catalyst is removed by steam stripping. The cracked oil vapors are then fed to a fractionation tower where the various desired fractions are separated and collected. The catalyst flows into a separate vessel(s) for either single- or two-stage regeneration by burning off the coke deposits with air.

In the moving-bed process, oil is heated to up to 1300°F and is passed under pressure through the reactor where it comes into contact with a catalyst flow in the form of beads or pellets. The cracked products then flow to a fractionating tower where the various compounds are separated and collected. The catalyst is regenerated in a continuous process where deposits of coke on the catalyst are burned off. Some units also use steam to strip remaining hydrocarbons and oxygen from the catalyst before being fed back to the oil stream. In recent years moving-bed reactors have largely been replaced by fluidized-bed reactors.

Catalytic cracking is one of the most significant sources of air pollutants at refineries. Air emissions from catalytic cracking operations include: the process heater flue gas emissions, fugitive emissions, and emissions generated during regeneration of the catalyst. Relatively high concentrations of carbon monoxide can be produced during regeneration of the catalyst which is typically converted to carbon dioxide either in the regenerator or further downstream in a carbon monoxide waste heat boiler. In addition, a significant amount of fine catalyst dust is produced in FCCUs as a result of the constant movement of the catalyst grains against each other. Much of this dust, consisting primarily of alumina and relatively small amounts of nickel, is carried with the carbon monoxide stream to the carbon monoxide burner.

The catalyst dust is then separated from the resulting carbon dioxide stream via cyclones and/or electrostatic precipitators and is sent off-site for disposal or treatment. Generated wastewater is typically sour water from the fractionator containing some oil and phenols. Wastewater containing metal impurities from the feed oil can also be generated from the steam used to purge and regenerate catalysts.

*Catalytic Hydrocracking.* Catalytic hydrocracking normally utilizes a fixed-bed catalytic cracking reactor with cracking occurring under substantial pressure (1,200 to 2,000 psig) in the presence of hydrogen. Feedstocks to hydrocracking units are often those fractions that are the most difficult to crack and cannot be cracked effectively in catalytic cracking units. The feedstocks include middle distillates, cycle oils, residual fuel oils, and reduced crudes.

The hydrogen suppresses the formation of heavy residual material and increases the yield of gasoline by reacting with the cracked products. However, this process also breaks the heavy sulfur- and nitrogen-bearing hydrocarbons and releases these impurities to where they could potentially foul the catalyst. For this reason, the feedstock is often first hydrotreated to remove impurities before being sent to the catalytic hydrocracker. Sometimes hydrotreating is accomplished by using the first reactor of the hydrocracking process to remove impurities. Water also has a detrimental effect on some hydrocracking catalysts and must be removed before being fed to the reactor. The water is removed by passing the feed stream through a silica gel or molecular sieve dryer. Depending on the products desired and the size of the unit, catalytic hydrocracking is conducted in either single-stage or multi-stage reactor processes. Most catalysts consist of a crystalline mixture of silica-alumina with small amounts of rare earth metals. Hydrocracking feedstocks are usually first hydrotreated to remove the hydrogen sulfide and ammonia that will poison the catalyst. Sour gas and sour water streams are produced at the fractionator, however, if the hydrocracking feedstocks are first hydrotreated to remove impurities, both streams will contain relatively low levels of hydrogen sulfide and ammonia. Hydrocracking catalysts are typically regenerated off-site after 2 to 4 years of operation. Therefore, few or no emissions are generated from the regeneration processes. Air emissions arise from the process heater, vents, and fugitive emissions.

*Hydrotreating/Hydroprocessing.* Hydrotreating and hydroprocessing are similar processes used to remove impurities such as sulfur, nitrogen, oxygen, halides, and trace-metal impurities that may deactivate process catalysts. Hydrotreating also upgrades the quality of fractions by converting olefins and diolefins to paraffins for the purpose of reducing gum formation in fuels. Hydroprocessing, which typically uses residuals from the crude distillation units, also cracks these heavier molecules to lighter, more saleable products. Both hydrotreating and hydroprocessing units are usually placed upstream of those processes in which sulfur and nitrogen could have adverse effects on the catalyst, such as catalytic reforming and hydrocracking units. The processes utilize catalysts in the presence of substantial amounts of hydrogen under high pressure and temperature to react the feedstocks and impurities with hydrogen. The reactors are nearly all fixed-bed with catalyst replacement or regeneration done after months or years of operation often at an off-site facility. In addition to the treated products, the process produces a stream of light fuel gases, hydrogen sulfide, and ammonia. The treated product and hydrogen-rich gas are cooled after they leave the reactor before being separated. The hydrogen is recycled to the reactor. The off-gas stream may be very rich in hydrogen sulfide and light fuel gas. The fuel gas and hydrogen sulfide are typically sent to the sour gas treatment unit and sulfur recovery unit. Catalysts are typically cobalt or molybdenum oxides on alumina, but can also contain nickel and tungsten. Air emissions from hydrotreating may arise from process heater flue gas, vents, and fugitive emissions.

*Alkylation.* Alkylation is used to produce a high-octane gasoline blending stock from the isobutane formed primarily during catalytic cracking and coking operations, but also from catalytic reforming, crude distillation and natural gas processing. Alkylation joins an olefin and an isoparaffin compound using either a sulfuric acid or a hydrofluoric acid catalyst. The products are alkylates including propane and butane liquids. When the concentration of acid becomes less than 88%, some of the acid must be removed and replaced with stronger acid. In the hydrofluoric acid process, the slipstream of acid is redistilled.

Dissolved polymerization products are removed from the acid as a thick dark oil. The concentrated hydrofluoric acid is recycled and the net consumption is about 0.3 pounds per barrel of alkylates produced. Hydrofluoric acid alkylation units require special engineering design, operator training, and safety equipment precautions to protect operators from accidental contact with hydrofluoric acid, which is an extremely hazardous substance. In the sulfuric acid process, the sulfuric acid removed must be regenerated in a sulfuric acid plant which is generally not a part of the alkylation unit and may be located off-site. Spent sulfuric acid generation is substantial; typically in the range of 13 to 30 pounds per barrel of alkylate. Air emissions from the alkylation process may arise from process vents and fugitive emissions.

*Isomerization.* Isomerization is used to alter the arrangement of a molecule without adding or removing anything from the original molecule. Typically, paraffins (butane or pentane from the crude distillation unit) are converted to isoparaffins having a much higher octane. Isomerization reactions take place at temperatures in the range of 200 to 400°F in the presence of a catalyst that usually consists of platinum on a base material. Two types of catalysts are currently in use. One requires the continuous addition of small amounts of organic chlorides which are converted to hydrogen chloride in the reactor. In such a reactor, the feed must be free of oxygen sources including water to avoid deactivation and corrosion problems. The other type of catalyst uses a molecular sieve base and does not require a dry and oxygen free feed. Both types of isomerization catalysts require an atmosphere of hydrogen to minimize coke deposits; however, the consumption of hydrogen is negligible. Catalysts typically need to be replaced about every 2 to 3 years or longer. Platinum is then recovered from the used catalyst off-site. Light ends are stripped from the product stream leaving the reactor and are then sent to the sour-gas treatment unit. Some isomerization units utilize caustic treating of the light fuel gas stream to neutralize any entrained hydrochloric acid. This will result in a calcium chloride (or other salts) waste stream. Air emissions may arise from the process heater, vents, and fugitive emissions. Wastewater streams include caustic wash and sour water.

*Polymerization.* Polymerization is occasionally used to convert propene and butene to high-octane gasoline blending components. The process is similar to alkylation in its feed and products, but is often used as a less expensive alternative to alkylation. The reactions typically take place under high pressure in the presence of a phosphoric acid catalyst. The feed must be free of sulfur, which poisons the catalyst; basic materials, which neutralize the catalyst; and oxygen, which affects the reactions. The propene and butene feed is washed first with caustic to remove mercaptans (molecules containing sulfur), then with an amine solution to remove hydrogen sulfide, then with water to remove caustics and amines, and finally dried by passing through a silica gel or molecular sieve dryer. Air emissions of sulfur dioxide may arise during the caustic washing operation. Spent catalyst, which typically is not regenerated, is occasionally disposed as a solid waste. Wastewater streams will contain caustic wash and sour water with amines and mercaptans.

*Catalytic Reforming.* Catalytic reforming uses catalytic reactions to process primarily low-octane heavy straight run (from the crude distillation unit) gasolines and naphthas into high-octane aromatics (including benzene). There are four major types of reactions which occur during reforming processes: (1) dehydrogenation of naphthenes to aromatics; (2) dehydrocyclization of paraffins to aromatics; (3) isomerization; and (4) hydrocracking. The dehydrogenation reactions are very endothermic, requiring that the hydrocarbon stream be heated between each catalyst bed. All but the hydrocracking reaction release hydrogen which can be used in the hydrotreating or hydrocracking processes. Fixed-bed or moving-bed processes are utilized in a series of three to six reactors. Feedstocks to catalytic reforming processes are usually hydrotreated first to remove sulfur, nitrogen, and metallic contaminants. In continuous reforming processes, catalysts can be regenerated one reactor at a time, once or twice per day, without disrupting the operation of the unit. In semiregenerative units, regeneration of all reactors can be carried out simultaneously after 3 to 24 months of operation by first shutting down the process. Because the recent reformulated gasoline rules have limited the allowable amount of benzene in gasoline, catalytic reforming is being used less as an octane enhancer than in past years.

Air emissions from catalytic reforming arise from the process heater gas and fugitive emissions. The catalysts used in catalytic reforming processes are usually very expensive and extra precautions are taken to ensure that catalyst is not lost. When the catalyst has lost its activity and can no longer be regenerated, the catalyst is usually sent off-site for recovery of the metals. Subsequent air emissions from catalyst regeneration are, therefore, relatively low. Relatively small volumes of wastewater containing sulfides, ammonia, and mercaptans may be generated from the stripping tower used to remove light ends from the reactor effluent.

*Solvent Extraction.* Solvent extraction uses solvents to dissolve and remove aromatics from lube-oil feed stocks, improving viscosity, oxidation resistance, color and gum formation. A number of different solvents are used, with the two most common being furfural and phenol. Typically, feed lube stocks are contacted with the solvent in a packed tower or rotating disk contactor. Each solvent has a different solvent-to-oil ratio and recycle ratio within the tower. Solvents are recovered from the oil stream through distillation and steam stripping in a fractionator. The stream extracted from the solvent will likely contain high concentrations of hydrogen sulfide, aromatics, naphthenes and other hydrocarbons and is often fed to the hydrocracking unit. The water stream leaving the fractionator will likely contain some oil and solvents.

*Chemical Treating.* In petroleum refining, chemical treating is used to remove or change the undesirable properties associated with sulfur, nitrogen, or oxygen compound contaminates in petroleum products. Chemical treating is accomplished by either extraction or oxidation (also known as sweetening), depending upon the product. Extraction is used to remove sulfur from the very light petroleum fractions, such as propane/propylene (PP) and butane/butylene (BB). Sweetening, though, is more effective on gasoline and middle distillate products. A typical extraction process is "Merox" extraction. Merox extraction is used to remove mercaptans (organic sulfur compounds) from PP and BB streams. PP streams may undergo amine treating before the Merox extraction to remove excess $H_2S$ which tends to fractionate with PP and interferes with the Merox process. A caustic prewash of the PP and BB removes any remaining trace $H_2S$ prior to Merox extraction. The PP and BB streams are passed up through the trays of an extraction tower. Caustic solution flowing down the extraction tower absorbs mercaptan from the PP and BB streams. The rich caustic is then regenerated by oxidizing the mercaptans to disulfide in the presence of aqueous Merox catalyst and the lean caustic recirculated to the extraction tower. The disulfide is insoluble in the caustic and can be separated.

Oxidation or "sweetening" is used on gasoline and distillate fractions. A common oxidation process is also a Merox process that uses a solid catalyst bed. Air and a minimum amount of alkaline caustic ("mini-alky" operation) is injected into the hydrocarbon stream. As the hydrocarbon passes through the Merox catalyst bed, sulfur mercaptans are oxidized to disulfide. In the sweetening Merox process, the caustic is not regenerated. The disulfide can remain with the gasoline product, since it does not possess the objectionable odor properties of mercaptans; hence, the product has been "sweetened."

In the extraction process, a waste oily disulfide stream leaves the separator. Air emissions arise from fugitive hydrocarbons and the process vents on the separator which may contain disulfides.

*Dewaxing.* Dewaxing of lubricating oil base stocks is necessary to ensure that the oil will have the proper viscosity at lower ambient temperatures. Two types of dewaxing processes are used: selective hydrocracking and solvent dewaxing. In selective hydrocracking, one or two zeolite catalysts are used to selectively crack the wax paraffins. Solvent dewaxing is more prevalent. In solvent dewaxing, the oil feed is diluted with solvent to lower the viscosity, chilled until the wax is crystallized, and then filtered to remove the wax. Solvents used for the process include propane and mixtures of methyl ethyl ketone (MEK) with methyl isobutyl ketone (MIBK) or MEK with toluene. Solvent is recovered from the oil and wax through heating and two-stage flashing, followed by steam stripping. The solvent-recovery stage results in solvent-contaminated water which typically is sent to the wastewater treatment plant. The wax either is used as feed to the catalytic cracker or is deoiled and sold as industrial wax. Air emissions may arise from fugitive emissions of the solvents.

*Propane Deasphalting* Propane deasphalting produces lubricating oil base stocks by extracting asphaltenes and resins from the residuals of the vacuum distillation unit. Propane is usually used to remove asphaltenes because of its unique solvent properties. At lower temperatures (100 to 140°F), paraffins are very soluble in propane and at higher temperatures (about 200°F) all hydrocarbons are almost insoluble in propane. The propane deasphalting process is similar to solvent extraction in that a packed or baffled extraction tower or rotating disk contactor is used to mix the oil feedstocks with the solvent. In the tower method, four to eight volumes of propane are fed to the bottom of the tower for every volume of feed flowing down from the top of the tower. The oil, which is more soluble in the propane dissolves and flows to the top. The asphaltene and resins flow to the bottom of the tower where they are removed in a propane mix. Propane is recovered from the two streams through two-stage flash systems followed by steam stripping in which propane, is condensed and removed by cooling at high pressure in the first stage and at low pressure in the second stage. The asphalt recovered can be blended with other asphalts or heavy fuels, or can be used as feed to the coker. The propane recovery stage results in propane-contaminated water which typically is sent to the wastewater treatment plant. Air emissions may arise from fugitive propane emissions and process vents.

## Supporting Operations

Many important refinery operations are not directly involved in the production of hydrocarbon fuels but serve in a supporting role. Some of the major supporting processes are described below.

*Wastewater Treatment.* Relatively large volumes of water are used by the petroleum refining industry. Four types of wastewater are produced: surface water runoff, cooling water, process water, and sanitary wastewater. Surface water runoff is intermittent and will contain constituents from spills to the surface, leaks in equipment and any materials that may have collected in drains. Runoff surface water also includes water coming from crude and product storage tank roof drains.

A large portion of water used in petroleum refining is used for cooling. Cooling water typically does not come into direct contact with process oil streams and therefore contains less contaminants than process wastewater. Most cooling water is recycled over and over with a bleed or blowdown stream to the wastewater treatment unit to control the concentration of contaminants and the solids content in the water. Cooling towers within the recycle loop cool the water using ambient air. Some cooling water, termed "once through," is passed through a process unit once and is then discharged directly without treatment in the wastewater treatment plant. The water used for cooling often contains chemical additives such as chromates, phosphates, and antifouling biocides to prevent scaling of pipes and biological growth. It should be noted that many refineries in the United States no longer use chromates in cooling water as antifouling agents; however, this is not the case in other parts of the world. Although cooling water usually does not come into direct contact with oil process streams, it also may contain some oil contamination due to leaks in the process equipment.

Water used in processing operations also accounts for a significant portion of the total wastewater. Process wastewater arises from desalting crude oil, steam stripping operations, pump gland cooling, product fractionator reflux drum drains, and boiler blowdown. Because process water often comes into direct contact with oil, it is usually highly contaminated. Petroleum refineries typically utilize primary and secondary wastewater treatment technologies. Primary wastewater treatment consists of the separation of oil, water and solids in two stages. During the first stage, an API separator, a corrugated plate interceptor, or other separator design is used. Wastewater moves very slowly through the separator allowing free oil to float to the surface and be skimmed off, and solids to settle to the bottom and be scraped off to a sludge collecting hopper. The second stage utilizes physical or chemical methods to separate emulsified oils from the wastewater. Physical methods may include the use of a series of settling ponds with a long retention time, or the use of dissolved air flotation (DAF). In DAF, air is bubbled through the wastewater, and both oil and suspended solids are skimmed off the top. Chemicals, such as ferric hydroxide or aluminum hydroxide, can be used to coagulate impurities into a froth or sludge which can be more easily skimmed off the top. Some wastes associated with the primary treatment of wastewater at petroleum refineries may be considered hazardous and include API separator sludge, primary treatment sludge, sludges from other gravitational separation techniques, float from DAF units, and wastes from settling ponds.

After primary treatment, the wastewater can be discharged to a publicly owned treatment works or undergo secondary treatment before being discharged directly to surface waters under a National Pollution Discharge Elimination System (NPDES) permit. In secondary treatment, dissolved oil and other organic pollutants may be consumed biologically by microorganisms. Biological treatment may require the addition of oxygen through a number of different techniques, including activated sludge units, trickling filters, and rotating biological contactors. Secondary treatment generates biomass waste which is typically treated anaerobically and then dewatered.

Some refineries employ an additional stage of wastewater treatment called polishing to meet discharge limits. The polishing step can involve the use of activated carbon, anthracite coal, or sand to filter out any remaining impurities, such as biomass, silt, trace metals, and other inorganic chemicals, as well as any remaining organic chemicals.

Certain refinery wastewater streams are treated separately, prior to the wastewater treatment plant, to remove contaminants that would not easily be treated after mixing with other wastewater. One such waste stream is the sour water drained from distillation reflux drums. Sour water contains dissolved hydrogen sulfide and other organic sulfur compounds and ammonia which are stripped in a tower with gas or steam before being discharged to the wastewater treatment plant.

Wastewater treatment plants are also a significant source of refinery air emissions and solid wastes. Air releases arise from fugitive emissions from the numerous tanks, ponds and sewer system drains. Solid wastes are generated in the form of sludges from a number of the treatment units.

*Gas Treatment and Sulfur Recovery.* Sulfur is removed from a number of refinery process off-gas streams (sour gas) in order to meet the $SO_x$ emissions limits of the CAA and to recover saleable elemental sulfur. Process off-gas streams, or sour gas, from the coker, catalytic cracking unit, hydrotreating units and hydroprocessing units can contain high concentrations of hydrogen sulfide mixed with light refinery fuel gases. Before elemental sulfur can be recovered, the fuel gases (primarily methane and ethane) need to be separated from the hydrogen sulfide. This is typically accomplished by dissolving the hydrogen sulfide in a chemical solvent. Solvents most commonly used are amines, such as diethanolamine (DEA). Dry adsorbents such as molecular sieves, activated carbon, iron sponge and zinc oxide are also used. In the amine solvent processes, DEA solution or another amine solvent is pumped to an absorption tower where the gases are contacted and hydrogen sulfide is dissolved in the solution. The fuel gases are removed for use as fuel in process furnaces in other refinery operations. The amine-hydrogen sulfide solution is then heated and steam stripped to remove the hydrogen sulfide gas.

Current methods for removing sulfur from the hydrogen sulfide gas streams are typically a combination of two processes: the Claus Process followed by the Beaven process, the Scot process, or the Wellman-Land Process. The Claus process consists of partial combustion of the hydrogen sulfide-rich gas stream (with one-third the stoichiometric quantity of air) and then reacting the resulting sulfur dioxide and unburned hydrogen sulfide in the presence of a bauxite catalyst to produce elemental sulfur.

Since the Claus process by itself removes only about 90% of the hydrogen sulfide in the gas stream, the Beaven, SCOT, or Wellman-Land processes are often used to further recover sulfur. In the Beaven process, the hydrogen sulfide in the relatively low-concentration gas stream from the Claus process can be almost completely removed by absorption in a quinone solution.

The dissolved hydrogen sulfide is oxidized to form a mixture of elemental sulfur and hydro-quinone. The solution is injected with air or oxygen to oxidize the hydro-quinone back to quinone. The solution is then filtered or centrifuged to remove the sulfur and the quinone is then reused.

The Beaven process is also effective in removing small amounts of sulfur dioxide, carbonyl sulfide, and carbon disulfide that are not affected by the Claus process. These compounds are first converted to hydrogen sulfide at elevated temperatures in a cobalt molybdate catalyst prior to being fed to the Beaven unit. Air emissions from sulfur recovery units will consist of hydrogen sulfide, $SO_x$, and $NO_x$ in the process tail gas as well as fugitive emissions and releases from vents.

The SCOT process is also widely used for removing sulfur from the Claus tail gas. The sulfur compounds in the Claus tail gas are converted to hydrogen sulfide by heating and passing it through a cobalt-molybdenum catalyst with the addition of a reducing gas. The gas is then cooled and contacted with a solution of diisopropanolamine (DIPA) which removes all but trace amounts of hydrogen sulfide. The sulfide-rich DIPA is sent to a stripper where hydrogen sulfide gas is removed and sent to the Claus plant. The DIPA is returned to the absorption column.

*Additive Production.* A number of chemicals (mostly alcohols and ethers) are added to motor fuels to either improve performance or meet federal and state environmental requirements. Since the 1970s, alcohols (methanol and ethanol) and ethers have been added to gasoline to increase octane levels and reduce carbon monoxide generation in place of the lead additives which were being phased out as required by the 1970 Clean Air Act. In 1990, the more stringent Clean Air Act Amendments established minimum and maximum amounts of chemically combined oxygen in motor fuels as well as an upper limit on vapor pressure. As a result, alcohol additives have been increasingly supplemented or replaced with a number of different ethers which are better able to meet both the new oxygen requirements and the vapor pressure limits.

The most common ethers being used as additives are methyl tertiary butyl ether (MTBE), and tertiary amyl methyl ether (TAME). Many of the larger refineries manufacture their own supplies of MTBE and TAME by reacting isobutylene and/or isoamylene with methanol. Smaller refineries usually buy their supplies from chemical manufacturers or the larger refineries.

Isobutylene is obtained from a number of refinery sources, including the light naphtha from the FCCU and coking units, the by-product from steam cracking of naphtha or light hydrocarbons during the production of ethylene and propylene, catalytic dehydrogenation of isobutane, and conversion of tertiary butyl alcohol recovered as a by-product in the manufacture of propylene oxides. Several different processes are currently in use to produce MTBE and TAME from isobutylene and methanol. Most processes use a two-stage acidic ion-exchange resin catalyst. The reaction is exothermic and cooling to the proper reaction temperature is critical in obtaining the optimal conversion efficiency. The process usually produces an MTBE or TAME stream and a relatively small stream of unreacted hydrocarbons and methanol. The methanol is extracted in a water wash and the resulting methanol-water mixture is distilled to recover the methanol for recycling.

*Heat Exchanger Cleaning.* Heat exchangers are used abundantly throughout petroleum refineries to heat or cool petroleum process streams. The heat exchangers consist of bundles of pipes, tubes, plate coils, or steam coils enclosing heating or cooling water, steam, or oil to transfer heat indirectly to or from the oil process stream. The bundles are cleaned periodically to remove accumulations of scales, sludge and any oily residues.

Because chromium has almost been eliminated as a cooling water additive, wastes generated from the cleaning of heat exchanger bundles no longer account for a significant portion of the hazardous wastes generated at refining facilities. The sludge generated may contain lead or chromium, although some refineries which do not produce leaded gasoline and which use non-chrome corrosion inhibitors typically do not generate sludge that contains these constituents. Oily wastewater is also generated during heat exchanger cleaning.

*Blowdown System.* Most refinery process units and equipment are manifolded into a collection unit, called the blowdown system. Blowdown systems provide for the safe handling and disposal of liquid and gases that either are automatically vented from the process units through pressure relief valves, or that are manually drawn from units. Recirculated process streams and cooling water streams are often manually purged to prevent the continued buildup of contaminants in the stream. Part or all of the contents of equipment can also be purged to the blowdown system prior to shutdown before normal or emergency shutdowns.

Blowdown systems utilize a series of flash drums and condensers to separate the blowdown into its vapor and liquid components. The liquid is typically composed of mixtures of water and hydrocarbons containing sulfides, ammonia, and other contaminants, which are sent to the wastewater treatment plant. The gaseous component typically contains hydrocarbons, hydrogen sulfide, ammonia, mercaptans, solvents, and other constituents and either is discharged directly to the atmosphere or is combusted in a flare. The major air emissions from blowdown systems are hydrocarbons in the case of direct discharge to the atmosphere and sulfur oxides when flared.

*Blending.* Blending is the final operation in petroleum refining. It consists of mixing the products in various proportions to meet specifications such as vapor pressure, specific gravity, sulfur content, viscosity, octane number, initial boiling point, and pour point. Blending can be carried out inline or in batch blending tanks. Air emissions from blending are fugitive VOCs from blending tanks, valves, pumps and mixing operations.

*Storage Tanks.* Storage tanks are used throughout the refining process to store crude oil and intermediate process feeds for cooling and further processing. Finished petroleum products are also kept in storage tanks before transport off site. Storage tank bottoms are mixtures of iron rust from corrosion, sand, water, and emulsified oil and wax, which accumulate at the bottom of tanks. Liquid tank bottoms (primarily water and oil emulsions) are periodically drawn off to prevent their continued buildup.

Tank bottom liquids and sludge are also removed during periodic cleaning of tanks for inspection. Tank bottoms may contain amounts of tetraethyl or tetramethyl lead (although this is increasingly rare because of the phaseout of leaded products), other metals, and phenols. Solids generated from leaded gasoline storage tank bottoms are listed as a RCRA hazardous waste. Even if equipped with floating tops, storage tanks account for considerable VOC emissions at petroleum refineries. A study of petroleum refinery emissions found that the majority of tank losses occurred through tank seals on gasoline storage tanks.

*Cooling Towers.* Cooling towers cool heated water by circulating the water through a tower with a predetermined flow of ambient air pushed with large fans. A certain amount of water exits the system through evaporation, mist droplets and as bleed or blowdown to the wastewater treatment system. Therefore, makeup water in the range of about 5% of the circulation rate is required.

## MATERIAL BALANCE INFORMATION

Raw material input to petroleum refineries is primarily crude oil; however, petroleum refineries use and generate an enormous number of chemicals, many of which leave the facilities as discharges of air emissions, wastewater, or solid waste. Pollutants generated typically include VOCs, carbon monoxide (CO), sulfur oxides ($SO_x$), nitrogen oxides ($NO_x$), particulates, ammonia ($NH_3$) hydrogen sulfide ($H_2S$) metals, spent acids, and numerous toxic organic compounds.

When discussing material outputs of the petroleum refining industry, it is important to note the relationship between the outputs of the industry itself and the outputs resulting from the use of refinery products. Petroleum refineries play an important role in the U.S. economy, supplying approximately 40% of the total energy used in the United States and virtually all of the energy consumed in the transportation sector.

The pollutant outputs from the refining facilities, however, are modest in comparison to the pollutant outputs realized from the consumption of petroleum products by the transportation sector, electric utilities, chemical manufacturers, and other industrial and commercial users.

Air emissions from refineries include fugitive emissions of the volatile constituents in crude oil and its fractions, emissions from the burning of fuels in process heaters, and emissions from the various refinery processes themselves. Fugitive emissions occur throughout refineries and arise from the thousands of potential fugitive emission sources such as valves, pumps, tanks, pressure relief valves and flanges.

Although individual leaks are typically small, the sum of all fugitive leaks at a refinery can be one of its largest emission sources. Fugitive emissions can be reduced through a number of techniques, including improved leak resistant equipment, reducing the number of tanks and other potential sources and, perhaps the most effective method, an ongoing Leak Detection and Repair (LDAR) program.

The numerous process heaters used in refineries to heat process streams or to generate steam (boilers) for heating or steam stripping, can be potential sources of $SO_x$, $NO_x$, CO, particulate matter and hydrocarbons emissions. When operating properly and when burning cleaner fuels such as refinery fuel gas, fuel oil, or natural gas, these emissions are relatively low. If, however, combustion is not complete, or heaters are fired with refinery fuel pitch or residuals, emissions can be significant.

The majority of gas streams exiting each refinery process contain varying amounts of refinery fuel gas, hydrogen sulfide and ammonia. These streams are collected and sent to the gas treatment and sulfur recovery units to recover the refinery fuel gas and sulfur. Emissions from the sulfur recovery unit typically contain some $H_2S$, $SO_x$, and $NO_x$.

Other emissions sources from refinery processes arise from periodic regeneration of catalysts. These processes generate streams that may contain relatively high levels of carbon monoxide, particulates and VOCs. Before being discharged to the atmosphere, such off-gas streams may be treated first through a carbon monoxide boiler to burn carbon monoxide and any VOCs, and then through an electrostatic precipitator or cyclone separator to remove particulate matter.

Wastewaters consist of cooling water, process water, sanitary sewage water, and storm water. Wastewaters are treated in on-site wastewater treatment facilities and then discharged to POTWs or discharged to surfaces waters under NPDES permits. In addition, some facilities use underground injection of some wastewater streams.

Many refineries unintentionally release, or have unintentionally released in the past, liquid hydrocarbons to ground water and surface waters. At some refineries contaminated groundwater has migrated off-site and resulted in continuous "seeps" to surface waters. While the actual volume of hydrocarbons released in such a manner is relatively small, there is the potential to contaminate large volumes of groundwater and surface water, possibly posing a substantial risk to human health and the environment.

There are a variety of other wastes that are generated from many of the refining processes, and petroleum-handling operations, as well as wastewater treatment. Both hazardous and nonhazardous wastes are generated, treated, and disposed.

Residual refinery wastes are typically in the form of sludges, spent process catalysts, filter clay, and incinerator ash. Treatment of these wastes includes incineration, land treating off-site, landfilling onsite, landfilling off-site, chemical fixation, neutralization, and other treatment methods.

A significant portion of the nonpetroleum product outputs of refineries is transported off-site and sold as by-products. These outputs include sulfur, acetic acid, phosphoric acid, and recovered metals. Metals from catalysts and from the crude oil that have deposited on the catalyst during the production often are recovered by third-party recovery facilities.

Table 1 provides a summary of the typical material outputs from major petroleum refining operations. Where possible, typical quantities and concentrations of pollutants are reported. These should be considered very approximate figures since no two refinery operations are identical. However, they do provide a general idea of the quantities, flows, and levels of different types of priority pollutants handled by refinery operations.

Table 1. Material Outputs from Selected Petroleum Refining Processes

| **Air emissions** | **Process waste water** | **Residual wastes generated** |
|---|---|---|
| ***Process: Crude oil desalting*** | | |
| Heater stack gas (CO, $SO_x$, $NO_x$, hydrocarbons and particulates), fugitive emissions (hydrocarbons) | Flow=2.1 gal/bbl oil, $H_2S$, NH, phenol, high levels of SS, dissolved solids, high BOD, high temperature | Crude oil/desalter sludge (iron rust, clay, sand, water, emulsified oil and wax, metals) |
| ***Process: Atmospheric distillation and vacuum distillation*** | | |
| Heater stack gas (CO, $SO_x$, $NO_x$, hydrocarbons and PM), vents and fugitive emissions (hydrocarbons); steam ejector emissions (hydrocarbons), heater stack gas (CO, $SO_x$, $NO_x$, Hydrocarbons, and PM), vents and fugitive emissions (hydrocarbons) | Flow=26.0 Gal/Bbl Oil, $H_2S$ NH, suspended solids, chlorides, mercaptans, phenol, elevated pH | Typically, little or no residual waste generated |
| ***Process: Thermal Cracking/Visbreaking*** | | |
| Heater stack gas (CO, $SO_x$, $NO_x$, HCs and PM), vents, and fugitive emissions (HCs) | Flow=2.0 Gal/Bbl Oil, $H_2S$ NH, phenol, suspended solids, high pH, BOD, COD | Typically, little or no residual waste generated |
| ***Process: Coking*** | | |
| Heater stack gas (CO, $SO_x$, $NO_x$, hydrocarbons and PM), vents and fugitive emissions (HCs) and decoking emissions (HCs and PM) | Flow=1.0 Gal/Bbl<br>High pH, $H_2S$, $NH_3$, SS, COD | Coke dust (carbon particles and HCs) |
| ***Process: Catalytic cracking*** | | |

| **Air emissions** | **Process waste water** | **Residual wastes generated** |
|---|---|---|
| Heater stack gas (CO, $SO_x$, $NO_x$, HCs and PM), fugitive emissions (HCs) and catalyst regeneration (CO, $NO_x$, $SO_x$, and PM) | Flow=15.0 gal/bbl high levels of oil, SS, phenols, cyanides, $H_2S$, NH3, high pH, BOD, COD | Spent catalysts (metals from crude oil and hydrocarbons), spent catalyst fines from ESPs (aluminum silicate and metals) |
| ***Process: Catalytic Hydrocracking*** | | |
| Heater stack gas (CO, $SO_x$, $NO_x$, hydrocarbons and PM), fugitive emissions (hydrocarbons) and catalyst regeneration (CO, $NO_x$, $SO_x$, and catalyst dust) | Flow=2.0 Gal/Bbl High COD, SS, $H_2S$, relatively low levels of BOD | Spent catalysts fines (metals from crude oil, and hydrocarbons). |
| **Process: Hydrotreating/hydroprocessing** | | |
| Heater stack gas (CO, $SO_x$, $NO_x$, hydrocarbons and PM), vents and fugitive emissions (HCs) and catalyst regeneration (CO, $NO_x$, $SO_x$) | Flow=1.0 gal/bbl $H_2S$, NH, High pH, phenols, SS, BOD, COD | Spent catalyst fines (aluminum silicate and metals) |
| ***Process: Alkylation*** | | |
| Heater stack gas (CO, $SO_x$, $NO_x$, HCs and PM), vents and fugitive emissions (HCs) | Low pH, SS, dissolved solids, COD, $H_2S$, spent sulfuric acid | Neutralized alkylation sludge (sulfuric acid or calcium fluoride, HCs) |
| ***Process: Isomerization*** | | |
| Heater stack gas (CO, $SO_x$, $NO_x$, HCs and PM), HCl (potentially in light ends), vents and fugitive emissions (HCs) | Low pH, chloride salts, caustic wash, relatively low $H_2S$, and $NH_3$ | Calcium chloride sludge from neutralized HCl gas |
| ***Process: Polymerization*** | | |

| **Air emissions** | **Process waste water** | **Residual wastes generated** |
|---|---|---|
| $H_2S$, from caustic washing | $H_2S$, $NH_3$, caustic wash, mercaptans and ammonia, high pH | Spent catalyst containing phosphoric acid |
| ***Process: Catalytic Reforming*** | | |
| Heater stack gas (CO, $SO_x$, $NO_x$, HCs and PM), fugitive emissions (hydrocarbons) and catalyst regeneration (CO, $NO_x$, $SO_x$) | Flow=6.0 gal/bbl<br>High levels oil, SS, COD.<br>Relatively low $H_2S$ | Spent catalyst fines from electrostatic precipitators (alumina silicate and metals) |
| ***Process: Solvent Extraction*** | | |
| Fugitive solvents | Oil and solvents | Little or no residual wastes generated |
| ***Process: Dewaxing*** | | |
| Fugitive solvents, heaters | Oil and solvents | Little or no residual wastes generated |
| ***Process: Propane deasphalting*** | | |
| Heater stack gas (CO, $SO_x$, $NO_x$, HCs and PM), fugitive propane | Oil and propane | Little or no residual wastes generated |
| ***Process: Merox treating*** | | |
| Vents and fugitive emissions (HCs and disulfides) | Little or no wastewater generated | Spent Merox caustic solution, waste oil-disulfide mixture |
| ***Process: Wastewater treatment*** | | |
| Fugitive emissions ($H_2S$, $NH_3$, and HCs) | Not Applicable | API separator sludge (phenols, metals and oil), chemical precipitation sludge (chemical coagulants, oil), DAF floats, biological sludges (metals, oil, SS), spent lime |
| ***Process: Gas treatment and sulfur recovery*** | | |

| Air emissions | Process waste water | Residual wastes generated |
|---|---|---|
| $SO_x$, $NO_x$, and $H_2S$ from vent and tail gas emissions | $H_2S$, NH,, amines, Stretford solution | Spent catalyst |
| ***Process: Blending*** | | |
| Fugitive emissions (HCs). | Little or no wastewater generated. | Little or no residual waste generated. |
| ***Process: Heat exchanger cleaning*** | | |
| Periodic fugitive emissions (HCs.) | Oily wastewater generated | Heat exchanger sludge (oil, metals, and SS) |
| ***Process: Storage tanks*** | | |
| Fugitive emissions (hydrocarbons). | Water drained from tanks contaminated with tank product. | Tank bottom sludge (iron rust, clay, sand, water, emulsified oil and wax, metals). |
| ***Process: Blowdown and flaring operations*** | | |
| Combustion products (CO, $SO_x$, $NO_x$, and HCs) from flares, fugitive emissions | Little or no wastewater generated | Little or no residual waste generated |

*Sources:* Assessment of Atmospheric Emissions from Petroleum Refining, Radian Corp., 1980; Petroleum Refining Hazardous Waste Generation, U.S. EPA, Office of Solid Waste, 1994.

## POLLUTION PREVENTION PRACTICES AND OPPORTUNITIES

The Pollution Prevention Act of 1990 (PPA) requires facilities to report information about the management of TRI chemicals in waste and efforts made to eliminate or reduce those quantifies. These data have been collected annually in the TRI reporting Form R beginning with the 1991 reporting year. The following discussions are based on a review of data between the years 1992 and 1995 and is meant to provide a basic understanding of the quantities of waste handled by the industry, the methods typically used to manage this waste, and recent trends, practices, and opportunities for further pollution prevention. From the yearly data it is apparent that the portion of the wastes reported as recycled on-site has increased and the portions treated or managed through energy recovery on-site have decreased between 1992 and 1995. Table 2 shows that the petroleum refining industry managed about 1.6 billion pounds of production-related waste (total quantity of TRI chemicals in the waste from routine production operations) in 1993 (column B). Column C reveals that of this production-related waste, 30% was either transferred off-site or released to the environment. Column C is calculated by dividing the total TRI transfers and releases by the total quantity of production-related waste. In other words, about 70 percent of the industry's TRI wastes were managed on-site through recycling, energy recovery, or treatment as shown in columns E, F, and G, respectively. The majority of waste that is released or transferred off-site can be divided into portions that are recycled off-site, recovered for energy off-site, or treated off-site as shown in columns H, I, and J, respectively. The remaining portion of the production related wastes (4%), shown in column D, is either released to the environment through direct discharges to air, land, water, and underground injection, or it is disposed of off-site. In general, toxic chemical releases have been declining. Reported releases dropped by 42.7% between 1988 and 1993, with declining trends continued throughout the 1990s. Although on-site releases have decreased, the total amount of reported toxic waste has not declined because the amount of toxic chemicals transferred off-site has increased. Transfers have increased from 3.7 billion pounds in 1991 to 4.7 billion pounds in 1993. Better management practices have led to increases in off-site transfers of toxic chemicals for recycling. The amount of TRI chemicals generated by the petroleum refining industry provides a gross profile of the types and relative amounts of toxic chemical outputs from refining processes. Additional information, which can be related back to possible compliance requirements, is available from the distribution of chemical releases across specific media within the environment.

Table 2. Source Reduction and Recycling Activity for Petroleum Industry

| A | B | C | D | On-site | | | Off-site | | |
|---|---|---|---|---|---|---|---|---|---|
| Year | Quantity of production-related waste ($10^6$lbs.)[A] | % Released and transferred[b] | % Released and disposed off-site[c] | | | | | | |
| | | | | E | F | G | H | I | J |
| | | | | % recycled | % energy recovery | % treated | % recycled | % energy recovery | % treated |
| 1992 | 1476 | 24% | 3% | 10% | 37% | 22% | 27% | <1% | <1 % |
| 1993 | 1600 | 30% | 4% | 14% | 36% | 20% | 26% | <1% | <1 % |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1994 | 1867 | --- | 4% | 19% | 37% | 15% | 25% | <1% | <1 % |
| | | --- | 4% | 21% | 32% | 17% | 27% | <1% | |

[a]- *Within this industry sector, non-production related waste < 1 percent of production related wastes for 1993.*
[b] - *Total TRI transfers and releases as reported in Sections 5 and 6 of Form R as a percentage of production related wastes.*
[c] - *Percentage of production related waste released to the environment and transferred off-site for disposal.*

The TRI data requires filers to list releases to air, water, and land separately. The distribution across media can also be compared to the profile of other industry sectors.

The petroleum refining industry releases 75% of its total TRI poundage to the air, 24% to the water (including 20% to underground injection and 4 percent to surface waters), and 1% to the land. This release profile differs from other TRI industries which average approximately 59% to air, 30% to water, and 10% to land. Examining the petroleum refining industry's TRI reported toxic chemical releases highlights the likely origins of the large air releases for the industry.

According to TRI data, the petroleum refining industry releases (discharges to the air, water, or land without treatment) and transfers (shipped off-site) a total of 482 million pounds of pollutants per year, made up of 103 different chemicals. This represents about 11% of the total pounds of TRI chemicals released and transferred by all manufacturers in a year. In comparison, the chemical industry generates on the average 2.5 billion pounds per year, accounting for 33% of all releases and transfers.

Overall, the petroleum refining industry's releases declined between 1988 and 1993. Between 1991 and 1993 the decrease in releases was 6.7% compared to the average for all industries of 18%. In the same period, however, transfers were reported to increase 65%, which is higher than the average increase in transfers of 25% for all manufacturing industries.

A large portion of the increases were in the form of transfers to recycling. Spent sulfuric acid generated in the alkylation process makes up about half of all transfers of TRI listed chemicals off-site. At the facility level, the industry reported a level of pollution prevention activities of 42% of all refineries which is slightly higher than the overall average of about 35% of TRI reporting facilities.

Comparisons of the reported pounds released or transferred per facility demonstrate that the petroleum refining industry is far above average in its pollutant releases and transfers per facility when compared to other TRI industries. Of the twenty manufacturing SIC codes listed in the TRI database, the mean amount of pollutant release per facility (including petroleum refining) was approximately 120,000 pounds.

The TRI releases of the average petroleum refining facility (SIC 2911) were 404,000 pounds, making the industry 3.4 times higher in per facility releases than for other industries. For transfers, the mean of petroleum refining facilities was about 13 times as much that of all TRI manufacturing facilities (202,000 pounds transferred off-site per facility compared to 2,626,000 per refinery). These high releases and transfers per facility reflect the large volumes of material processed at a relatively small number of facilities.

Of the top 10 most frequently reported toxic chemicals on the TRI list, the prevalence of volatile chemicals explains the air intensive toxic chemical loading of the refining industry. Nine of the 10 most commonly reported toxic chemicals are highly volatile. Seven of the 10 are aromatic hydrocarbons (benzene, toluene, ethylbenzene, xylene, cyclohexane, 1,2,4-trimethylbenzene, and ethylbenzene).

Aromatic hydrocarbons are highly volatile compounds and make up a portion of both crude oil and many finished petroleum products. Ammonia, the ninth most commonly reported toxic chemical, is also released and transferred from petroleum refineries in large quantities. Ammonia may be found in high concentrations in process water streams from steam distillation processes and in refinery sour gas. The primary means of release to the environment is through underground injection of wastewater and emissions to air.

Gasoline blending additives (i.e., methanol, ethanol, and MTBE) and chemical feedstocks (propylene, ethylene, and naphthalene) are also commonly reported to TRI. Additives and chemical feedstocks are, for the most part, released as air emissions due to their high volatility. A significant portion of the remaining chemicals of the reported TRI toxic chemicals are metals compounds, which are typically transferred off-site for recovery or as a component of hazardous wastes.

Although it is not the most frequently reported toxic chemical released or transferred, sulfuric acid is generated in by far the largest quantities. Spent sulfuric acid is primarily generated during the alkylation process. The acid is typically transferred off-site for regeneration.

Table 3 provides a summary of the toxicity and fate information for the principal hazardous chemicals released by petroleum refinery operations. The table provides descriptions of the most common routes by which these pollutants enter the environment as a result of common refinery practices and operations.

Table 3. Toxicity and Environmental Fate Information.

| |
|---|
| **Ammonia CAS #7664-41-7** |
| **Sources.** Ammonia is formed from the nitrogen bearing components of crude oil and can be found throughout petroleum refineries in both the gaseous and aqueous forms. Gaseous ammonia often leaves distillation, cracking and treating processes mixed with the sour gas or acid gas along with refinery fuel gases and hydrogen sulfide. Aqueous ammonia is present in the sourwater generated in the vacuum distillation unit and steam strippers or fractionators. Some release sources include fugitive emissions, sour gas stripper, sulfur units, and wastewater discharges.<br>**Toxicity.** Anhydrous ammonia is irritating to the skin, eyes, nose, throat, and upper respiratory system. Ecologically, ammonia is a source of nitrogen (an essential element for aquatic plant growth) and may therefore contribute to eutrophication of standing or slow-moving surface water, particularly in nitrogen-limited waters such as the Chesapeake Bay. In addition, aqueous ammonia is moderately toxic to aquatic organisms.<br>**Carcinogenicity.** There is currently no evidence to suggest that this chemical is carcinogenic.<br>**Environmental Fate.** Ammonia combines with sulfate ions in the atmosphere and is washed out by rainfall, resulting in rapid return of ammonia to the soil and surface waters. Ammonia is a central compound in the environmental cycling of nitrogen. Ammonia in lakes, rivers, and streams is converted to nitrate.<br>**Physical Properties.** Ammonia is a corrosive and severely irritating gas with a pungent odor. |
| **Toluene CAS #108-88-3** |
| **Sources.** Toluene is a component of crude oil and is therefore present in many refining operations. Toluene is also produced during catalytic reforming and is sold as one of the large volume aromatics used as feedstocks in chemical manufacturing. Its volatile nature makes fugitive emissions its largest release source. Point air sources may arise during the process of separating toluene from other aromatics and from solvent dewaxing operations where toluene is often used as the solvent.<br>**Toxicity.** Inhalation or ingestion of toluene can cause headaches, confusion, weakness, and memory loss. Toluene may also affect the way the kidneys and liver function. Reactions of toluene in the atmosphere contribute to ozone formation. Ozone can affect the respiratory system, especially in sensitive individuals such as asthma or allergy sufferers. Unborn animals were harmed when high levels of toluene were inhaled by their mothers, although the same effects were not seen when the mothers were fed large quantities of toluene. Note that these results may reflect similar difficulties in humans.<br>**Carcinogenicity.** There is currently no evidence to suggest carcinogenicity. |

**Environmental Fate.** A portion of releases of toluene to land and water will evaporate. Toluene may also be degraded by microorganisms. Once volatilized, toluene in the lower atmosphere will react with other atmospheric components contributing to the formation of ground-level ozone and other air pollutants.

**Physical Properties.** Toluene is a volatile organic chemical.

### Xylenes (Mixed Isomers) CAS #1330-20-7

**Sources.** Xylene isomers are a component of crude oil and are therefore present in many refining operations. Xylenes are also produced during catalytic reforming and are sold as one of the large-volume aromatics used as feedstocks in chemical manufacturing. Xylenes volatile nature make fugitive emissions the largest release source. Point air sources may arise during the process of separating xylene from other aromatics.

**Toxicity.** Xylenes are rapidly absorbed into the body after inhalation, ingestion, or skin contact. Short-term exposure of humans to high levels of xylenes can cause irritation of the skin, eyes, nose, and throat, difficulty in breathing, impaired lung function, impaired memory, and possible changes in the liver and kidneys. Both short- and long-term exposure to high concentrations can cause effects such as headaches, dizziness, confusion, and lack of muscle coordination. Reactions of xylenes in the atmosphere contribute to the formation of ozone in the lower atmosphere. Ozone can affect the respiratory system, especially in sensitive individuals such as asthma or allergy sufferers.

**Carcinogenicity.** There is currently no evidence to suggest that this chemical is carcinogenic.

**Environmental Fate.** A portion of releases to land and water will quickly evaporate, although some degradation by microorganisms will occur. Xylenes are moderately mobile in soils and may leach into groundwater, where they may persist for many years. Xylenes are VOCs. As such, xylenes will react with other atmospheric components, contributing to the formation of ground-level ozone and other air pollutants.

### Methyl Ethyl Ketone CAS #78-93-3

**Sources.** Methyl ethyl ketone (MEK) is used in some refineries as a solvent in lube oil dewaxing. Its extremely volatile characteristic makes fugitive emissions its primary source of releases to the environment.

**Toxicity.** Breathing moderate amounts of methyl ethyl ketone (MEK) for short periods of time can cause adverse effects on the nervous system ranging from headaches, dizziness, nausea, and numbness in the fingers and toes to unconsciousness. Its vapors are irritating to the skin, eyes, nose, and throat and can damage the eyes. Repeated exposure to moderate to high amounts may cause liver and kidney effects.

**Carcinogenicity.** No agreement exists over the carcinogenicity of MEK. One source believes MEK is a possible carcinogen in humans based on limited animal evidence. Other sources believe that there is insufficient evidence to make any statements about possible carcinogenicity.

**Environmental Fate.** Most of the MEK released to the environment will end up in the atmosphere. MEK can contribute to the formation of air pollutants in the lower atmosphere. It can be degraded by microorganisms living in water and soil.

**Physical Properties.** Methyl ethyl ketone is a flammable liquid.

### Propylene CAS # 115-07-1

**Sources.** Propylene (propene) is one of the light ends formed during catalytic and thermal cracking and coking operations. It is usually collected and used as a feedstock to the alkylation unit. Propylene is volatile and soluble in water making releases to both air and water significant.

**Toxicity.** At low concentrations, inhalation of propylene causes mild intoxication, a tingling sensation, and an inability to concentrate. At higher concentrations, unconsciousness, vomiting, severe vertigo, reduced blood pressure, and disordered heart rhythms may occur. Skin or eye contact with propylene causes freezing burns. Reaction of propylene (see environmental fate) in the atmosphere contributes to the formation of ozone in the lower atmosphere. Ozone can affect the respiratory system, especially in sensitive individuals such as asthma or allergy sufferers. Ecologically, similar to ethylene, propylene has a stimulating effect on plant growth at low concentrations, but inhibits plant growth at high levels.

**Carcinogenicity.** There is currently no evidence to suggest that this chemical is carcinogenic.

**Environmental Fate.** Propylene is degraded principally by hydroxyl ions in the atmosphere. Propylene released to soil and water is removed primarily through volatilization. Hydrolysis, bioconcentration, and soil adsorption are not expected to be significant fate processes of propylene in soil or aquatic ecosystems. Propylene is readily biodegraded by microorganisms in surface water.

**Physical Properties.** Propylene is a volatile organic chemical.

### Benzene CAS # 71-43-2

**Sources.** Benzene is a component of crude oil. It is also produced during catalytic reforming and is sold as one of the large volume aromatics used as feedstocks in chemical manufacturing. Benzene's volatile nature makes fugitive emissions the largest release source.

**Toxicity.** Short-term inhalation of benzene affects the central nervous system and respiratory system. Chronic exposure causes bone marrow toxicity in animals and humans, causing suppression of the immune system and development of leukemia. Ingestion of benzene is rare. Reactions of benzene in the atmosphere contributes to the formation of ozone in the lower atmosphere (troposphere).

**Carcinogenicity.** Benzene is a known human carcinogen.

**Environmental Fate.** A portion of benzene releases to soil and surface waters evaporate rapidly. Benzene is highly mobile in the soil and may leach to groundwater. Once in groundwater, it is likely biodegraded by microorganisms only in the presence of oxygen. Benzene is not expected to significantly adsorb to sediments, bioconcentrate in aquatic organisms, or break down in water. Atmospheric benzene is broken down through reacting with chemical ions in the air; this process is greatly accelerated in the presence of other air pollutants such as nitrogen oxides or sulfur dioxide. Benzene is fairly soluble in water and is removed from the atmosphere in rain. As a volatile chemical, benzene in the lower atmosphere will react with other atmospheric components, contributing to the formation of ground-level ozone and other air pollutants, which can contribute to respiratory illnesses in both the general and highly susceptible populations, such as asthmatics and allergysufferers.

In addition to chemicals covered under TRI, many other chemicals are released. For example, the EPA Office of Air Quality Planning and Standards has compiled air pollutant emission factors for determining the total air emissions of priority pollutants (e.g., VOCs, $SO_x$, $NO_x$ CO, particulates, etc.) from many refinery sources. The EPA Office of Aerometric Information Retrieval System (AIRS) contains a wide range of information related to stationary sources of air pollution, including the emissions of a number of air pollutants which may be of concern within a particular industry. With the exception of volatile organic compounds (VOCs), there is little overlap with the TRI chemicals reported above.

Control technologies employed for the handling of air emissions normally include the capture and recycling or combustion of emissions from vents, product transfer points, storage tanks, and other handling equipment. Boilers, heaters, other combustion devices, cokers, and catalytic units may require particulate matter controls. Use of a carbon monoxide boiler is normally a standard practice in the fluidized catalytic cracking units. Catalytic cracking units should be provided with particular removal devices. Steam injection in flaring stacks can reduce particulate matter emissions.

Refinery wastewaters often require a combination of treatment methods to remove oil and contaminants before discharge. Separation of different streams, such as stormwater, cooling water, process water, sanitary, and sewage, is essential for minimizing treatment requirements. A typical system may include sour water stripper, gravity separation of oil and water, dissolved air flotation, biological treatment, and clarification. A final polishing step using filtration, activated carbon, or chemical treatment may also be required. Achievable pollutant loads per ton of crude processed include BOD, 6 g; COD, 50 g; suspended solids, 10 g; and oil and grease, 2 g.

Sludge treatment is usually performed using land application (bioremediation) or solvent extraction followed by combustion of the residue or by use for asphalt, where feasible. In some cases, the residue may require stabilization prior to disposal to reduce the leachability of toxic metals. Oil is recovered from slops using separation techniques such as gravity separators and centrifuges.

Implementation of pollution prevention measures can yield both economic and environmental benefits. However, a balance on energy usage and environmental impacts may have to be struck. New refineries should be designed to maximize energy conservation and reduce hydrocarbon losses. A good target for simple refineries (i.e., refineries with distillation, catalytic reforming, hydrotreating, and off-site facilities) is that the total quantity of oil consumed as fuel and lost in production operations should not exceed 3.5% of the throughput. For refineries with secondary conversion units (i.e., hydrocrackers or lubricating oil units), the target should be 5-6% (and, in some cases, up to 10%) of the throughput. Fugitive VOC emissions from the process units can be reduced to 0.05% of the throughput, with total VOC emissions of less than 1 kg per ton of crude (or 0.1% of throughput). Methods of estimating these figures include emissions monitoring, mass balance, and inventories of emissions sources. Design assumptions should be recorded to allow for subsequent computation and reduction of losses. Vapor recovery systems to control losses of VOCs from storage tanks and loading areas should achieve 90-100% recovery.

Plant operators should aim at using fuel with less than 0.5% sulfur (or an emissions level corresponding to 0.5% sulfur in fuel). High-sulfur fuels should be directed to units equipped with $SO_x$ controls. Fuel blending is another option. A sulfur recovery system that achieves at least 97% (but preferably over 99%) sulfur recovery should be used when the hydrogen sulfide concentration in tail gases exceeds 230 $mg/Nm^3$. The total release of sulfur dioxide should be below 0.5 kg per ton for a hydroskimming refinery and below 1 kg per ton for a conversion refinery. A wastewater generation rate of 0.4 $m^3/t$ of crude processed is achievable with good design and operation, and new refineries should achieve this target as a minimum. The generation rate of solid wastes and sludges should be less than 0.5% of the crude processed, with a target of 0.3%.

As already noted, petroleum refineries are complex plants, and the combination and sequence of processes is usually very specific to the characteristics of the raw materials (crude oil) and the products. Specific pollution prevention or source reduction measures can often be determined only by the technical staff of the specific refinery operation. However, there are a number of general areas where improvements are often possible, and site-specific waste reduction measures in these areas should be designed into the plant and targeted by management of operating plants. Areas where efforts should be concentrated are summarized in Table 4.

Although numerous cases have been documented where petroleum refineries have simultaneously reduced pollution outputs and operating costs through pollution prevention techniques, there are often barriers to their implementation.

The primary barrier to most pollution prevention projects is cost. Many pollution prevention options simply do not pay for themselves, or the economics often appear marginal. Corporate investments typically must earn an adequate return on invested capital for the shareholders and some pollution prevention options at some facilities may not meet the requirements set by company policies. Additionally, the equipment used in the petroleum refining industry are very capital intensive and have very long lifetimes. This reduces the incentive to make process modifications to (expensive) installed equipment that is still useful.

It should be emphasized however, that pollution prevention techniques are, nevertheless, often more cost-effective than pollution reduction through end-of-pipe treatment technologies. A case study based on the Amoco/EPA joint study claimed that the same pollution reduction currently realized through end-of-pipe regulatory requirements at the Amoco facility could be achieved at 15 percent the current costs using pollution prevention techniques. To better understand some of the broad areas of pollution prevention practices listed in Table 4, the following provides a summary of these widespread pollution prevention techniques found to be effective at petroleum refineries.

## Process and Equipment Modification Practices

**Place secondary seals on storage tanks.** One of the largest sources of fugitive emissions from refineries is storage tanks containing gasoline and other volatile products. These losses can be significantly reduced by installing secondary seals on storage tanks. An Amoco/EPA joint study estimated that VOC losses from storage tanks could be reduced 75 to 93%. Equipping an average tank with a secondary seal system was estimated to cost about $20,000.

Table 4. Recommended Pollution Prevention Practices

| **Area of opportunity** | **Recommended pollution prevention practice** |
|---|---|
| *Reduction of air emissions* | 1. Minimize losses from storage tanks and product transfer areas by methods such as vapor recovery systems and double seals.<br>2. Minimize $SO_x$ emissions either through desulfurization of fuels, to the extent feasible, or by directing the use of high-sulfur fuels to units equipped with $SO_x$ emissions controls.<br>3. Recover sulfur from tail gases in high-efficiency sulfur recovery units.<br>4. Recover nonsilica-based (i.e., metallic) catalysts and reduce particulate emissions.<br>5. Use low-$NO_x$ burners to reduce nitrogen oxide emissions.<br>6. Avoid and limit fugitive emissions by proper process design and maintenance.<br>7. Keep fuel usage to a minimum. |
| *Elimination or reduction of pollutants* | 8. Consider reformate and other octane boosters instead of tetraethyl lead and other organic lead compounds for octane boosting.<br>9. Use nonchrome-based inhibitors in cooling water, where inhibitors are needed.<br>10. Use long-life catalysts and regenerate to extend the catalysts' life cycle. |
| *Recycling and reuse* | 11. Recycle cooling water and, where cost-effective, treated wastewater.<br>12. Maximize recovery of oil from oily waste waters and sludges. Minimize losses of oil to the effluent system.<br>13. Recover and reuse phenols, caustics, and solvents from their spent solutions.<br>14. Return oily sludges to coking units or crude distillation units. |
| *Operating procedures* | 15. Segregate oily waste waters from stormwater systems.<br>16. Reduce oil losses during tank drainage carried out to remove water before product dispatch.<br>17. Optimize frequency of tank and equipment cleaning to avoid accumulating residue at the bottom of the tanks.<br>18. Prevent solids and oily wastes from entering the drainage system. |

| | |
|---|---|
| | 19. Institute dry sweeping instead of washdown to reduce wastewater volumes.<br>20. Establish and maintain an emergency preparedness and response plan and carry out frequent training.<br>21. Practice corrosion monitoring, prevention, and control in underground piping and tank bottoms.<br>22. Establish leak detection and repair programs. |

**Establish leak detection and repair program.** Fugitive emissions are one of the largest sources of refinery hydrocarbon emissions. A leak detection and repair (LDAR) program consists of using a portable VOC detecting instrument to detect leaks during regularly scheduled inspections of valves, flanges, and pump seals. Leaks are then repaired immediately or are scheduled for repair as quickly as possible. A LDAR program could reduce fugitive emissions 40 to 64%, depending on the frequency of inspections.

**Regenerate or eliminate filtration clay.** Clay from refinery filters must periodically be replaced. Spent clay often contains significant amounts of entrained hydrocarbons and, therefore, must be designated as hazardous waste. Back washing spent clay with water or steam can reduce the hydrocarbon content to levels so that it can be reused or handled as a nonhazardous waste. Another method used to regenerate clay is to wash the clay with naphtha, dry it by steam heating and then feed it to a burning kiln for regeneration. In some cases clay filtration can be replaced entirely with hydrotreating.

**Reduce the generation of tank bottoms.** Tank bottoms from crude oil storage tanks constitute a large percentage of refinery solid waste and pose a particularly difficult disposal problem because of the presence of heavy metals. Tank bottoms comprise of heavy hydrocarbons, solids, water, rust and scale. Minimization of tank bottoms is carried out most cost effectively through careful separation of the oil and water remaining in the tank bottom. Filters and centrifuges can also be used to recover the oil for recycling.

**Minimize solids leaving the desalter.** Solids entering the crude distillation unit are likely to eventually attract more oil and produce additional emulsions and sludges. The amount of solids removed from the desalting unit should, therefore, be maximized. A number of techniques can be used, such as using low-shear mixing devices to mix desalter wash water and crude oil; using lower pressure water in the desalter to avoid turbulence; and replacing the water jets used in some refineries with mud rakes which add less turbulence when removing settled solids.

**Minimize cooling-tower blowdown.** The dissolved solids concentration in the recirculating cooling water is controlled by purging or blowing down a portion of the cooling-water stream to the wastewater treatment system. Solids in the blowdown eventually create additional sludge in the wastewater treatment plant. However, the amount of cooling tower blowdown can be lowered by minimizing the dissolved solids content of the cooling water. A significant portion of the total dissolved solids in the cooling water can originate in the cooling water makeup stream in the form of naturally occurring calcium carbonates. Such solids can be controlled either by selecting a source of cooling tower makeup water with less dissolved solids or by removing the dissolved solids from the makeup water stream. Common treatment methods include cold lime softening, reverse osmosis, or electrodialysis.

**Install vapor recovery for barge loading.** Although barge loading is not a factor for all refineries, it is an important emissions source for many facilities. One of the largest sources of VOC emissions identified during the Amoco/EPA study was fugitive emissions from loading of tanker barges. It was estimated that these emissions could be reduced 98% by installing a marine vapor loss control system. Such systems could consist of vapor recovery or VOC destruction in a flare.

**Minimize FCCU decant oil sludge.** Decant oil sludge from the fluidized bed catalytic cracking unit (FCCU) can contain significant concentrations of catalyst fines. These fines often prevent the use of decant oil as a feedstock or require treatment which generates an oily catalyst sludge. Catalysts in the decant oil can be minimized by using a decant-oil catalyst removal system. One system incorporates high voltage electric fields to polarize and capture catalyst particles in the oil. The amount of catalyst fines reaching the decant oil can be minimized by installing high-efficiency cyclones in the reactor to shift catalyst fines losses from the decant oil to the regenerator where they can be collected in the electrostatic precipitator.

**Control of heat-exchanger cleaning solids.** In many refineries, using high pressure water to clean heat exchanger bundles generates and releases water and entrained solids to the refinery wastewater treatment system. Exchanger solids may then attract oil as they move through the sewer system and may also produce finer solids and stabilized emulsions that are more difficult to remove. Solids can be removed at the heat-exchanger cleaning pad by installing concrete overflow weirs around the surface drains or by covering drains with a screen. Other ways to reduce solids generation are by using antifoulants on the heat exchanger bundles to prevent scaling and by cleaning with reusable cleaning chemicals that also allow for the easy removal of oil.

**Control of surfactants in wastewater.** Surfactants entering the refinery wastewater streams will increase the amount of emulsions and sludges generated. Surfactants can enter the system from a number of sources, including washing unit pads with detergents; treating gasolines with an end point over 400°F; thereby producing spent caustics; cleaning tank truck tank interiors; and using soaps and cleaners for miscellaneous tasks. In addition, the overuse, and mixing of the organic polymers used to separate oil, water, and solids in the wastewater treatment plant can actually stabilize emulsions. The use of surfactants should be minimized by educating operators, by routing surfactant sources to a point downstream of the DAF unit and by using dry cleaning, high-pressure water, or steam to clean oil surfaces of oil and dirt.

**Thermal treatment of applicable sludges.** The toxicity and volume of some deoiled and dewatered sludges can be further reduced through thermal treatment. Thermal sludge treatment units use heat to vaporize the water and volatile components in the feed and leave behind a dry solid residue. The vapors are condensed for separation into the hydrocarbon and water components. Non-condensible vapors are either flared or sent to the refinery amine unit for treatment and use as refinery fuel gas.

**Eliminate use of open ponds.** Open ponds used to cool, settle out solids, and store process water can be a significant source of VOC emissions. Wastewater from coke cooling and coke VOC removal is occasionally cooled in open ponds where VOCs easily escape to the atmosphere. In many cases, open ponds can be replaced with closed storage tanks.

**Remove unnecessary storage tanks from service.** Since storage tanks are one of the largest sources of VOC emissions, a reduction in the number of these tanks can have a significant impact. The need for certain tanks can often be eliminated through improved production planning and more continuous operations. By minimizing the number of storage tanks, tank bottom solids and decanted wastewater may also be reduced.

**Replace old boilers.** Older refinery boilers can be a significant source of $SO_x$, $NO_x$, and particulate emissions. It is possible to replace a large number of old boilers with a single new cogeneration plant with emissions controls.

**Modify the FCCU to allow the use of catalyst fines.** Some FCCUs can be modified to recycle some of the catalyst fines generated.

**Reduce the use of 55-gallon drums.** Replacing 55-gallon drums with bulk storage can minimize the chances of leaks and spills.

**Install rupture disks and plugs.** Rupture disks on pressure-relief valves and plugs in open-ended valves can reduce fugitive emissions.

**Install high pressure power washer.** Chlorinated solvent vapor degreasers can be replaced with high-pressure power washers which do not generate spent solvent hazardous wastes.

**Refurbish or eliminate underground piping.** Underground piping can be a source of undetected releases to the soil and groundwater. Inspecting, repairing, or replacing underground piping with surface piping can reduce or eliminate these potential sources.

### Waste Segregation and Separation Practices

**Segregate process waste streams.** A significant portion of refinery waste arises from oily sludges found in combined process/storm sewers. Segregation of the relatively clean rainwater runoff from the process streams can reduce the quantity of oily sludges generated. Furthermore, there is a much higher potential for recovery of oil from smaller, more concentrated process streams.

**Control solids entering sewers.** Solids released to the wastewater sewer system can account for a large portion of a refinery's oily sludges. Solids entering the sewer system (primarily soil particles) become coated with oil and are deposited as oily sludges in the API oil/water separator. Because a typical sludge has a solids content of 5 to 30% by weight, preventing 1 lb of solids from entering the sewer system can eliminate 3 to 20 pounds of oily sludge. An Amoco/EPA study estimated that at the Yorktown facility 1000 tons of solids per year enter the refinery sewer system. Solids controls methods include using a street sweeper on paved areas, paving unpaved areas, planting ground cover on unpaved areas, relining sewers, cleaning solids from ditches and catch basins, and reducing heat-exchanger bundle cleaning solids by using antifoulants in cooling water.

**Improve recovery of oils from oily sludges.** Because oily sludges make up a large portion of refinery solid wastes, any improvement in the recovery of oil from the sludges can significantly reduce the volume of waste. There are a number of technologies currently in use to mechanically separate oil, water and solids, including belt filter presses, recessed chamber pressure filters, rotary vacuum filters, scroll centrifuges, disk centrifuges, shakers, thermal driers, and centrifuge-drier combinations.

**Identify benzene sources and install upstream water treatment.** Benzene in wastewater can often be treated more easily and effectively at the point, where it is generated rather than at the wastewater treatment plant after it is mixed with other wastewater.

### Recycling Practices

**Recycle and regenerate spent caustics.** Caustics used to absorb and remove hydrogen sulfide and phenol contaminants from intermediate and final product streams can often be recycled. Spent caustics may be saleable to chemical recovery companies if concentrations of phenol or hydrogen sulfide are high enough. Process changes in the refinery may be needed to raise the concentration of phenols in the caustic to make recovery of the contaminants economical. Caustics containing phenols can also be recycled on-site by reducing the pH of the caustic until the phenols become insoluble thereby allowing physical separation. The caustic can then be treated along with the refinery wastewaters.

**Use oily sludges as feedstock.** Many oily sludges can be sent to a coking unit or the crude distillation unit where they become part of the refinery products. Sludge sent to the coker can be injected into the coke drum with the quench water, injected directly into the delayed coker, or injected into the coker blowdown contactor used in separating the quenching products. Use of sludge as a feedstock has increased significantly in recent years and is currently carried out by most refineries. The quantity of sludge that can be sent to the coker is restricted by coke quality specifications which may limit the amount of sludge solids in the coke. Coking operations can be upgraded, however, to increase the amount of sludge that they can handle.

**Control and reuse FCCU and coke fines.** Significant quantities of catalyst fines are often present around the FCCU catalyst hoppers and reactor and regeneration vessels. Coke fines are often present around the coker unit and coke storage areas. The fines can be collected and recycled before being washed to the sewers or migrating off-site via the wind. Collection techniques include dry sweeping the catalyst and coke fines and sending the solids to be recycled or disposed of as nonhazardous waste. Coke fines can also be recycled for fuel use. Another collection technique involves the use of vacuum ducts in dusty areas (and vacuum hoses for manual collection) which run to a small baghouse.

**Recycle lab samples.** Lab samples can be recycled to the oil recovery system.

### Training and Supervision

**Train personnel to reduce solids in sewers.** A facility training program which emphasizes the importance of keeping solids out of the sewer systems will help reduce that portion of wastewater treatment plant sludge arising from the everyday activities of refinery personnel.

**Train personnel to prevent soil contamination.** Contaminated soil can be reduced by educating personnel on how to avoid leaks and spills.

### Material Substitution

**Use nonhazardous degreasers.** Spent conventional degreaser solvents can be reduced or eliminated through substitution with less toxic and/or biodegradable products.

**Eliminate chromates as an anti-corrosive.** Chromate-containing wastes can be reduced or eliminated in cooling tower and heat exchanger sludges by replacing chromates with less toxic alternatives such as phosphates.

**Use high-quality catalysts.** By using catalysts of a higher quality, process efficiencies can be increased while the required frequency of catalyst replacement can be reduced.

**Replace ceramic catalyst support with activated alumina supports.** Activated alumina supports can be recycled with spent alumina catalyst.

# ALUMINUM MANUFACTURING

## INDUSTRY DESCRIPTION AND PRACTICES

The United States' aluminum industry annually produces about $39.1 billion in products and exports. U.S. companies are the largest single producer of primary aluminum. The U.S. industry operates more than 300 plants in 35 states, produces more than 23 billion pounds of metal annually, and employs more than 145,000 people with an annual payroll of about $5 billion.

Aluminum is the second most abundant metallic element in the earth's crust after silicon. It weighs about one-third as much as steel or copper; is malleable, ductile, and easily machined and cast; and has excellent corrosion resistance and durability. Measured in either quantity or value, aluminum's use exceeds that of any other metal except iron, and it is critical to many segments of the world economy. Some of the many uses for aluminum are in transportation (automobiles, airplanes, trucks, railcars, marine vessels, etc.), packaging (cans, foil, etc.), construction (windows, doors, siding, etc.), consumer durables (appliances, cooking utensils, etc.), electrical transmission lines, and machinery.

Aluminum recovery from scrap (recycling) has become an important component of the aluminum industry. A common practice since the early 1900s, aluminum recycling is not new. It was, however, a low-profile activity until the late 1960s when recycling of aluminum beverage cans finally vaulted recycling into the public consciousness. Sources for recycled aluminum includes automobiles, windows and doors, appliances, and other products.

The top markets for the industry are transportation, beverage cans and other packaging, and building construction. In the 1990s transportation first emerged as the largest market for aluminum, at about one-quarter of the market, with passenger cars accounting for the vast majority of the growth. That trend has continued each subsequent year. Automotive and light truck applications accounted for almost 5.2 billion pounds of aluminum in 2000, or about one-fifth of industry shipments. In 2000, transportation accounted for 32.5% of all U.S. shipments. That same year aluminum passed plastic--with average content of 257 lb per vehicle--to become the third most-used material in automobiles. Automakers are increasingly choosing aluminum to improve fuel economy, reduce emissions, and enhance vehicle performance.

Containers and packaging rank second to transportation with 20.4% of the market, thanks to shipments of 4,,992 million pounds in products such as beverage cans, food containers, and household and institutional foil. Product producers and consumers are increasingly using foil because it has numerous applications.

Largely because of products in the residential, industrial, commercial, farm, and highway sectors, the 1999 building and construction market accounted for 3,237 millions of pounds of net shipments, good for 13.1% of total shipments and the third largest domestic market for aluminum.

## MANUFACTURING

Aluminum originates as an oxide called alumina. Deposits of bauxite ore are mined and refined into alumina--one of the feedstocks for aluminum metal. Then alumina and electricity are combined in a cell with a molten electrolyte called cryolite. Direct-current electricity is passed from a consumable carbon anode into the cryolite, splitting the aluminum oxide into molten aluminum metal and carbon dioxide. The molten aluminum collects at the bottom of the cell and is periodically "tapped" into a crucible and cast into ingots. While continual progress has been made over the more than 110-year history of aluminum processing to reduce the amount of electricity used, there are currently no viable alternatives to the electrometallurgical process. Between materials recovery and ongoing innovative research and development efforts, the aluminum industry is constantly searching for areas where energy and costs can be reduced. In the past two decades, the energy efficiency of the production of metal has improved by about 20%.

## PRODUCTS

The U.S. aluminum supply comprises three basic sources:

- **Primary** (domestic production from ore material)
- **Imports** (of primary and secondary ingot and mill products) and
- **Recycled** (metal recovered from scrap, also known as secondary recovery)

In 2000, the nation's total aluminum supply was 10.69 million metric tons, a decrease of 4.1% from 1999. Since 1990 the nation's total supply has expanded at an average rate of 3.4% annually. In 2000, primary production increased to 34.3% of total supply, and imports rose to 33.5%, while secondary recovery accounted for 32.2%.

Fabricated products include the following:

- **Castings.** The automotive industry is the largest market for aluminum castings and cast products make up more than half of the aluminum used in cars. Cast aluminum transmission housings and pistons have been virtually universal in cars and trucks throughout the world for years.
- **Extrusions.** To many designers and materials specifiers, extruded aluminum is the material of choice for countless applications. Experts chose aluminum profiles because extrusion offers so many design options: various alloys can be readily formed into complex shapes; extrusion tooling is inexpensive; lead times for custom shapes or prototypes are relatively brief; many different finishes are available; and the life cycle value of the product remains high because of aluminum's recyclability.
- **Mill products.**

## ENERGY USE

The aluminum industry is a major user of electricity, spending more than $2 billion per year on energy. Since the electrolytic process is the only commercially proven method of producing aluminum, the industry has on its own pursued opportunities to reduce its use of electricity. In the past 50 years, the average amount of electricity needed to make a pound of aluminum has been slashed from 12 kilowatt hours to about 7 kilowatt hours.

## RECYCLING

Total aluminum industry supply in 2001 was 10.69 million metric tons, 33% of which was recycled aluminum. Of the 101 billion aluminum cans shipped in 2000, 62.1% (63 billion) were recycled. Almost 90% of automotive aluminum is reclaimed and recycled. Recycling of aluminum saves energy and removes some 95% of emissions association with making new aluminum from ore. Recycling is also a critical component of the industry, both from its contributions to the environment and because of the favorable economic impact on production. This dual benefit is probably the reason aluminum beverage cans now account for virtually all of the beverage can market, and most of the total single-serve beverage market. The contribution of recycling has had a positive impact on the industry with energy savings brought about with the increased proportion of recycled metal as a resource. For instance, the energy used to produce aluminum is saved for future reuse through recycling. Recycling saves almost 95% of the energy needed to produce aluminum from its original source, bauxite ore. As of 2000, over one-third of the total U.S. aluminum supply is provided through recycling. Aluminum is the most commonly recycled postconsumer metal in the world.

The production of aluminum begins with the mining and beneficiation of bauxite. At the mine (usually of the surface type), bauxite ore is removed to a crusher. The crushed ore is then screened and stockpiled, ready for delivery to an alumina plant. In some cases, ore is upgraded by beneficiation (washing, size classification, and separation of liquids and solids) to remove unwanted materials such as clay and silica.

At the alumina plant, the bauxite ore is further crushed to the correct particle size for efficient extraction of the alumina through digestion by hot sodium hydroxide liquor. After removal of "red mud" (the insoluble part of the bauxite) and fine solids from the process liquor, aluminum trihydrate crystals are precipitated and calcined in rotary kilns or fluidized bed calciners to produce alumina ($Al_2O_3$). Some alumina processes include a liquor purification step.

Primary aluminum is produced by the electrolytic reduction of the alumina. The alumina is dissolved in a molten bath of fluoride compounds (the electrolyte), and an electric current is passed through the bath, causing the alumina to dissociate to form liquid aluminum and oxygen. The oxygen reacts with carbon in the electrode to produce carbon dioxide and carbon monoxide. Molten aluminum collects in the bottom of the individual cells or pots and is removed under vacuum into tapping crucibles. There are two prominent technologies for aluminum smelting: prebake and Soderberg. The following discussions focus on the prebake technology, with its associated reduced air emissions and energy efficiencies.

Raw materials for secondary aluminum production are scrap, chips, and dross. Pretreatment of scrap by shredding, sieving, magnetic separation, drying, and so on is designed to remove undesirable substances that affect both aluminum quality and air emissions. The prevailing process for secondary aluminum production is smelting in rotary kilns under a salt cover. Salt slag can be processed and reutilized. Other processes (smelting in induction furnaces and hearth furnaces) need no or substantially less salt and are associated with lower energy demand, but they are only suitable for high-grade scrap.

Depending on the desired application, additional refining may be necessary. For demagging (removal of magnesium from the melt), hazardous substances such as chlorine and hexachloroethane are often used, which may produce dioxins and dibenzofurans. Other, less hazardous methods, such as adding chlorine salts, are available. Because it is difficult to remove alloying elements such as copper and zinc from an aluminum melt, separate collection and separate reutilization of different grades of aluminum scrap are necessary. Note that secondary aluminum production uses substantially less energy than primary production (less than 10-20 gigajoules per metric ton (GJ/t) of aluminum produced, compared with 164 GJ/t for primary production).

## POLLUTION PREVENTION PRACTICES AND OPPORTUNITIES

At the bauxite production facilities, dust is emitted to the atmosphere from dryers and materials-handling equipment, through vehicular movement, and from blasting. Although the dust is not hazardous, it can be a nuisance if containment systems are not in place, especially on the dryers and handling equipment. Other air emissions could include $NO_x$, $SO_x$, and other products of combustion from the bauxite dryers. Ore washing and beneficiation yield process wastewaters containing suspended solids. Runoff from precipitation may also contain suspended solids. At the alumina plant, air emissions can include bauxite dust from handling and processing, limestone dust from limestone handling, burnt lime dust from conveyors and bins, alumina dust from materials handling, red mud dust and sodium salts from red mud stacks (impoundments), caustic aerosols from cooling towers, and products of combustion such as sulfur dioxide and nitrogen oxides from boilers, calciners, various mobile equipment, and kilns. The calciners may also emit alumina dust and the kilns, burnt lime dust.

Although alumina plants do not normally discharge effluents, heavy rainfalls can result in surface runoff that exceeds what the plant can use in the process. The excess may require treatment.

The main solid waste from the alumina plant is red mud (as much as 2 tons of mud per ton of alumina produced), which contains oxides of alumina, silicon, iron, titanium, sodium, calcium, and other elements. The pH is typically between 10 and 12. Disposal is to an impoundment.

Hazardous wastes from the alumina plant include spent sulfuric acid from descaling in tanks and pipes. Salt cake may be produced from liquor purification if this is practiced.

In the aluminum smelter, air emissions include alumina dust from handling facilities; coke dust from coke handling; gaseous and particulate fluorides; sulfur and carbon dioxides and various dusts from the electrolytic reduction cells; gaseous and particulate fluorides; sulfur dioxide; tar vapor and carbon particulates from the baking furnace; coke dust, tars, and polynuclear aromatic hydrocarbons (PAHs) from the green carbon and anode-forming plant; carbon dust from the rodding room; and fluxing emissions and carbon oxides from smelting, anode production, casting, and finishing operations. The electrolytic reduction cells (pot line) are the major source of the air emissions, with the gaseous and particulate fluorides being of prime concern. The anode effect associated with electrolysis also results in emissions of carbon tetrafluoride ($CF_4$) and carbon hexafluoride ($C_2F_6$), which are greenhouse gases of concern because of their potential for global warming. Emissions numbers that have been reported for uncontrolled gases from smelters are 20 to 80 kg/t for particulates, 6 to 12 kg/t for hydrogen fluoride, and 6-10 kg/t for fluoride particulates. Corresponding concentrations are 200 to 800 mg/m$^3$; 60 to 120 mg/m$^3$; and 60 to 100 mg/m$^3$. An aluminum smelter produces 40 to 60 kg of mixed solid wastes per ton of product, with spent cathodes (spent pot and cell linings) being the major fraction. The linings consist of 50% refractory material and 50% carbon. Over the useful life of the linings, the carbon becomes impregnated with aluminum and silicon oxides (averaging 16% of the carbon lining), fluorides (34% of the lining), and cyanide compounds (about 400 parts per million). Contaminant levels in the refractory portion of linings that have failed are generally low. Other by-products for disposal include skim, dross, fluxing slags, and road sweepings.

Atmospheric emissions from secondary aluminum melting include hydrogen chloride and fluorine compounds. Demagging may lead to emissions of chlorine, hexachloroethane, chlorinated benzenes, and dioxins and furans. Chlorinated compounds may also result from the melting of aluminum scrap that is coated with plastic. Salt slag processing emits hydrogen and methane. Solid wastes from the production of secondary aluminum include particulates, pot lining refractory material, and salt slag. Particulate emissions containing heavy metals are also associated with secondary aluminum production.

Pollution prevention is always preferred to the use of end-of-pipe pollution-control facilities. Therefore every attempt should be made to incorporate cleaner production processes and facilities to limit, at source, the quantity of pollutants generated.

In the bauxite mine, where beneficiation and ore washing are practiced, a tailings slurry of 79% solids is produced for disposal. The preferred technology is to concentrate these tailings and dispose of them in the mined-out area. A concentration of 25 to 30% can be achieved through gravity settling in a tailings pond. The tailings can be further concentrated, using a thickener, to 30-50%, yielding a substantially volume-reduced slurry.

The alumina plant discharges red mud in a slurry of 25 to 30% solids, and this also presents an opportunity to reduce disposal volumes. Modern technology, in the form of high-efficiency deep thickeners, and large-diameter conventional thickeners, can produce a mud of 50-60% solids concentration. The lime used in the process forms insoluble solids that leave the plant along with the red mud. These lime-based solids can be minimized by recycling the lime used as a filtering aid to digestion to displace the fresh lime that is normally added at this point. Also, effluent volume from the alumina plant can be minimized or eliminated by good design and operating practices: reducing the water added to the process, segregating condensates and recycling to the process, and using rainwater in the process. Using the prebake technology rather than the Soderberg technology for aluminum smelting is a significant pollution prevention measure. In the smelter, computer controls and point feeding of aluminum oxide to the centerline of the cell help reduce emissions, including emissions of organic fluorides such as $CF_4$, which can be held at less than 0.1 kg/t aluminum. Energy consumption is typically 14 megawatt hours per ton (MWh/t) of aluminum, with prebake technology. Soderberg technology uses 17.5 MWh/t. Gas collection efficiencies for the prebake process is better than for the Soderberg process: 98% versus 90%. Dry scrubber systems using aluminum oxide as the adsorbent for the cell gas permit the recycling of fluorides. The use of low-sulfur tars for baking anodes helps control $SO_2$ emissions. Spent pot linings are removed after they fail, typically because of cracking or heaving of the lining. The age of the pot linings can vary from 3 to 10 years. By improving the life of the lining through better construction and operating techniques, discharge of pollutants can be reduced. Note that part of the pot-lining carbon can be recycled when the pots are relined. Emissions of organic compounds from secondary aluminum production can be reduced by thoroughly removing coatings, paint, oils, greases, and the like from raw feed materials before they enter the melt process. European experience has shown that red mud produced at the alumina plant can be reduced from 2 t/t alumina to about 1 t/t alumina through implementation of good industrial practices.

At bauxite facilities, the major sources of dust emissions are the dryers, and emissions are controlled with electrostatic precipitators (ESPs) or baghouses. Removal efficiencies of 99% are achievable. Dust from conveyors and material transfer points is controlled by hoods and enclosures. Dust from truck movement can be minimized by treating road surfaces and by ensuring that vehicles do not drop material as they travel. Dusting from stockpiled material can be minimized by the use of water sprays or by enclosure in a building.

At the alumina plant, pollution control for the various production and service areas is implemented as follows:

- *Bauxite and limestone handling and storage:* Dust emissions are controlled by baghouses.
- *Lime kilns*: Dust emissions are controlled by baghouse systems. Kiln fuels can be selected to reduce $SO_x$ emissions; however, this is not normally a problem, since most of the sulfur dioxide that is formed is absorbed in the kiln.
- *Calciners:* Alumina dust losses are controlled by ESPs; $SO_2$ and $NO_x$ emissions are reduced to acceptable levels by contact with the alumina.
- *Red mud disposal*: The mud impoundment area must be lined with impervious clay prior to use to prevent leakage. Water spraying of the mud stack may be required to prevent fine dust from being blown off the stack. Longer term treatment of the mud may include reclamation of the mud, neutralization, covering with topsoil, and planting with vegetation.

In the smelter, primary emissions from the reduction cells are controlled by collection and treatment using dry sorbent injection; fabric filters or ESPs are used for controlling particulate matter. Primary emissions make up 97.5% of total cell emissions; the balance consists of secondary emissions that escape into the potroom and leave the building through roof ventilators. Wet scrubbing of the primary emissions can also be used, but large volumes of toxic waste liquors will need to be treated or disposed of. Secondary emissions result from the periodic replacement of anodes and other operations; the fumes escape when the cell hood panels have been temporarily removed. While wet scrubbing can be used to control the release of secondary fumes, the high-volume, low-concentration gases offer low scrubbing efficiencies, have high capital and operating costs, and produce large volumes of liquid effluents for treatment. Wet scrubbing is seldom used for secondary fume control in the prebake process.

When anodes are baked on-site, the dry scrubbing system using aluminum oxide as the adsorbent is used. It has the advantage of being free of waste products, and all enriched alumina and absorbed material are recycled directly to the reduction cells. Dry scrubbing may be combined with incineration for controlling emissions of tar and volatile organic compounds (VOCs) and to recover energy. Wet scrubbing can also be used but is not recommended, since a liquid effluent, high in fluorides and hydrocarbons, will require treatment and disposal.

Dry scrubber systems applied to the pot fumes and to the anode baking furnace result in the capture of 97% of all fluorides from the process.

The aluminum smelter solid wastes, in the form of spent pot lining, are disposed of in engineered landfills that feature clay or synthetic lining of disposal pits, provision of soil layers for covering and sealing, and control and treatment of any leachate. Treatment processes are available to reduce hazards associated with spent pot lining prior to disposal of the lining in a landfill. Other solid wastes such as bath skimmings are sold for recycling, while spalled refractories and other chemically stable materials are disposed of in landfill sites.

Modern smelters using good industrial practices are able to achieve the following in terms of pollutant loads (all values are expressed on an annualized basis): hydrogen fluoride, 0.2-0.4 kg/t; total fluoride, 0.3-0.6 kg/t; particulates, 1 kg/t; sulfur dioxide, 1 kg/t; and nitrogen oxides, 0.5 kg/t. $CF_4$ emissions should be less than 0.1 kg/t.

For secondary aluminum production, the principal treatment technology downstream of the melting furnace is dry sorbent injection using lime, followed by fabric filters. Waste gases from salt slag processing should be filtered as well. Waste gases from aluminum scrap pretreatment that contain organic compounds of concern may be treated by postcombustion practices.

Air emissions should be monitored regularly for particulate matter and fluorides. Hydrocarbon emissions should be monitored annually on the anode plant and baking furnaces. Liquid effluents should be monitored weekly for pH, total suspended solids, fluoride, and aluminum and at least monthly for other parameters. Monitoring data should be analyzed and reviewed at regular intervals and compared with the operating standards so that any necessary corrective actions can be taken.

## IRON AND STEEL

### INDUSTRY DESCRIPTION AND PRACTICES

Steel is an alloy of iron usually containing less than 1% carbon. The process of steel production requires several sequential steps. The two types of steelmaking technology in use today are the basic oxygen furnace (BOF) and the electric arc furnace (EAF). Although these two technologies use different input materials, the output for both furnace types is molten steel which is subsequently formed into steel mill products. The BOF input materials are molten iron, scrap, and oxygen. In the EAF, electricity and scrap are the input materials used. BOFs are typically used for high tonnage production of carbon steels, while EAFs are used to produce carbon steels and low tonnage alloy and specialty steels. The processes leading up to steelmaking in a BOF are very different than the steps preceding steelmaking in an EAF; the steps after each of these processes producing molten steel are the same.

Steel manufacturing may be defined as the chemical reduction of iron ore, using an integrated steel manufacturing process or a direct reduction process. In the conventional integrated steel manufacturing process, the iron from the blast furnace is converted to steel in a BOF. As noted, it can also be made in an electric arc furnace (EAF) from scrap steel and, in some cases, from direct reduced iron. An emerging technology, direct steel manufacturing, produces steel directly from iron ore. In the BOF process, coke making and iron making precede steelmaking; these steps are not necessary with an EAF. Pig iron is manufactured from sintered, pelletized, or lump iron ores using coke and limestone in a blast furnace. It is then fed to a BOF in molten form along with scrap metal, fluxes, alloys, and high-purity oxygen to manufacture steel. In some integrated steel mills, sintering (heating without melting) is used to agglomerate fines and so recycle iron-rich material such as mill scale.

When making steel using a BOF, coke-making and iron-making precede steelmaking; these steps are not needed for steelmaking with an EAF. Coke, which is the fuel and carbon source, is produced by heating coal in the absence of oxygen at high temperatures in coke ovens. Hence, merchant coke plants are needed to support industry based on this technology. Pig iron is then produced by heating the coke, iron ore, and limestone in a blast furnace. In the BOF, molten iron from the blast furnace is combined with flux and scrap steel where high-purity oxygen is injected. This process, with coke-making, iron-making, steelmaking, and subsequent forming and finishing operations is referred to as fully integrated production. Alternatively, in an EAF, the input material is primarily scrap steel, which is melted and refined by passing an electric current from the electrodes through the scrap. The molten steel from either process is formed into ingots or slabs that are rolled into finished products. Rolling operations may require reheating, rolling, cleaning, and coating the steel. Descriptions of both steelmaking processes follow.

### Basic Oxygen Furnace Technology

The process of making steel in a BOF is preceded by coke-making and ironmaking operations. In coke-making, coke is produced from coal. In ironmaking, molten iron is produced from iron ore and coke. Each of these processes and the subsequent steelmaking process in the BOF are briefly described below.

Coke-making. Coal processing typically involves producing coke, coke gas and by-product chemicals from compounds released from the coal during the coke-making process. Coke is carbon-rich and is used as a carbon source and fuel to heat and melt iron ore in ironmaking. The coke-making process starts with bituminous pulverized coal charge which is fed into the coke oven through ports in the top of the oven. After charging, the oven ports are sealed and the coal is heated at high temperatures (1600 to 2300° F) in the absence of oxygen. Coke manufacturing is done in a batch mode where each cycle lasts for 14 to 36 hours. A coke oven battery comprises a series of 10 to 100 individual ovens, side-by-side, with a heating flue between each oven pair. Volatile compounds are driven from the coal, collected from each oven, and processed for recovery of combustible gases and other coal by-products. The solid carbon remaining in the oven is the coke. The necessary heat for distillation is supplied by external combustion of fuels (e.g., recovered coke oven gas, blast furnace gas) through flues located between ovens.

At the end of the heating cycle, the coke is pushed from the oven into a rail quench car. The quench car takes it to the quench tower, where the hot coke is cooled with a water spray. The coke is then screened and sent to the blast furnace or to storage. In the by-products recovery process, volatile components of the coke oven gas stream are recovered including the coke oven gas itself (which is used as a fuel for the coke oven), naphthalene, ammonium compounds, crude light oils, sulfur compounds, and coke breeze (coke fines).

During the coke quenching, handling, and screening operation, coke breeze is produced. Typically, the coke breeze is reused in other manufacturing processes on-site (e.g., sintering) or sold off-site as a by-product.

Coke-making is perhaps the major environmental concern in this industry. Both air emissions and quench water are the key problems. As a result, many steelmakers have turned in recent years to pulverized coal injection, which substitutes coal for coke in the blast furnace. The use of pulverized coal injection can replace roughly 25-40% of the coke in the blast furnace thereby reducing the amount of coke needed and the associated emissions. It is also common practice to inject other fuels, such as natural gas, oil, and tar/pitch to replace a portion of the coke.

Quench water from coke-making is also an area of significant environmental concern. In Europe, many plants have implemented technology to shift from water quenching to dry quenching which eliminates suspected carcinogenic PM and VOCs. However, major construction changes are required for such a solution and considering the high capital costs of coke batteries, combined with the depressed state of the steel industry and increased regulations for coke-making, it is unlikely that new facilities will be constructed. Instead, many countries with steelmaking industries are experiencing increases in the amount of coke imported.

Iron ore, coke, and limestone are fed into the top of the blast furnace. Heated air is forced into the bottom of the furnace through a bustle pipe and tuyeres (orifices) located around the circumference of the furnace. The carbon monoxide from the burning of the coke reduces iron ore to iron.

The acid part of the ores reacts with the limestone to create a slag which is drawn periodically from the furnace. This slag contains unwanted impurities in the ore. Among the most common impurities is sulfur from the fuels. When the furnace is tapped, iron is removed through one set of runners and molten slag via another. The molten iron is tapped into refractory-lined cars for transport to the steelmaking furnaces. Residuals from the process are mainly sulfur dioxide or hydrogen sulfide, which are driven off from the hot slag. The slag is the largest by-product generated from the ironmaking process and is reused extensively in the construction industry.

Blast furnace flue gas is cleaned and used to generate steam to preheat the air coming into the furnace, or it may be used to supply heat to other plant processes. The cleaning of the gas may generate air pollution control dust in removing coarse particulates (which may be reused in the sintering plant or landfilled), and water treatment plant sludge in removing fine particulates by venturi scrubbers. Sintering (briefly described earlier) is the process that agglomerates fines (including iron ore fines, dusts, coke breeze, water treatment plant sludge, coke breeze, and flux) into a porous mass for charging to the blast furnace. By means of the sintering operations, a mill can recycle iron-rich material, such as mill scale and processed slag. Not all mills have sintering capabilities. The input materials are mixed together, placed on a slow- moving grate or rotating/tilting mixer, and ignited. Windboxes under the grate draw air through the materials to deepen the combustion throughout the traveling length of the grate. The coke breeze provides the carbon source for sustaining the controlled combustion. In the process, the fine materials are fused into the sinter agglomerates, which can be reintroduced into the blast furnace along with ore. Air pollution control equipment removes the particulate matter generated during the thermal fusing process. For wet scrubbers, water treatment plant sludge is generally land disposed waste. If electrostatic precipitators or baghouses are used as the air pollution control equipment, the dry particulate matter that is captured are typically recycled as sinter feedstock, or is landfilled as solid waste.

Steelmaking. Molten iron from the blast furnace, flux, alloy materials, and scrap are placed in the BOF, melted and refined by injecting high-purity oxygen. A chemical reaction occurs, where the oxygen reacts with carbon and silicon generating the heat necessary to melt the scrap and oxidize the impurities. The operation is performed as a batch process with a cycle time of about 45 min. Slag is produced from impurities removed by the combination of the fluxes with the injected oxygen. Various alloys are added to produce different grades of steel. The molten steel is typically cast into slabs, beams, or billets.

Waste products from the basic oxygen steelmaking process include slag, carbon monoxide, and oxides of iron emitted as dust. Also, when the hot iron is poured into ladles or the furnace, iron oxide fumes are released and some of the carbon in the iron is precipitated as graphite (called kish). The BOF slag can be processed to recover the high-metallic portions for use in sintering or blast furnaces, but its applications as a saleable construction material are more limited than those of the blast furnace slag. Basic oxygen furnaces are equipped with air pollution control systems for containing, cooling, and cleaning the volumes of hot gases and sub-micron fumes that are released during the process. Water is used to quench or cool the gases and fumes to temperatures at which they can be effectively treated by the gas cleaning equipment. The resulting waste streams from the pollution control operations include dust and water treatment plant sludge. About 1000 gallons of water per ton of steel is typically used in a wet scrubber in order to effectively remove air pollutants. The primary pollutants captured from the off-gases are TSS and metals such as zinc and lead.

### Electric Arc Furnace Technology

In the steelmaking process that uses an electric arc furnace (EAF), the primary raw material is scrap metal. The scrap metal is melted and refined using electrical energy. During melting, oxidation of phosphorus, silicon, manganese, carbon, and other materials occurs and a slag containing some of these oxidation products forms on top of the molten metal. Oxygen is used to decarburize the molten steel and to provide thermal energy. This is a batch process with a cycle time of about 2 to 3 hours. Since scrap metal is used instead of molten iron, there are no coke-making or ironmaking operations associated with steel production that uses an EAF.

This technology results in the production of metal dusts, slag, and gaseous products. Particulate matter and gases evolve together during the steelmaking process and are conveyed into a gas cleaning system. Emissions are cleaned using a wet or dry system. The particulate matter that is removed as emissions in the dry system is referred to as EAF dust, or EAF sludge if it is from a wet system. This waste is a listed hazardous waste under the RCRA. The composition of EAF dust can vary greatly depending on the scrap composition and furnace additives. The primary component is iron or iron oxides, and it may also contain flux (lime and/or fluorspar), zinc, chromium and nickel oxides (when stainless steel is being produced) and other metals associated with the scrap. The two primary hazardous constituents of EAF emission dust are lead and cadmium. Roughly 20 pounds of dust per ton of steel is expected, but as much as 40 pounds of dust per ton of steel may be generated, depending on production practices. Oils are burned off "charges" of oil-bearing scrap in the furnace. Small but not insignificant amounts of nitrogen oxides and ozone are generated during the melting process. The furnace is extensively cooled by water; however, this water is recycled through cooling towers.

### Forming and Finishing Operations

**Steel Forming**. Whether the molten steel is produced using a BOF or an EAF, to convert it into a product, it must be solidified into a suitable shape and finished. The traditional forming method is called ingot teeming, and involves pouring the metal into ingot molds, then allowing the steel to cool and solidify. The alternative method of forming steel is called continuous casting. This process bypasses several steps of the conventional ingot teeming process by casting steel directly into semifinished shapes. Molten steel is poured into a reservoir from which it is released into the molds of the casting machine. The metal is cooled as it descends through the molds, and before emerging, a hardened outer shell is formed. As the semifinished shapes proceed on the runout table, the center also solidifies, allowing the cast shape to be cut into lengths. Process contact water cools the continuously cast steel and is collected in settling basins along with oil, grease, and mill scale generated in the casting process. The scale settles out and is removed and recycled for sintering operations, if the mill has a sinter plant. Waste treatment plant sludge is also generated during the operation. The steel is further processed to produce slabs, strips, bars, or plates through various forming steps. The most common hot forming operation is hot rolling, where heated steel is passed between two rolls revolving in opposite directions. Hot rolling units may have as many as 13 stands, each producing an incremental reduction in thickness. The final shape and characteristics of a hot formed piece depend on the rolling temperature, the roll profile, and the cooling process after rolling. Wastes generated from hot rolling include waste treatment plant sludge and scale.

In subsequent cold forming, the cross-sectional area of unheated steel is progressively reduced in thickness as the steel passes through a series of rolling stands. Generally, wires, tubes, sheet and strip steel products are produced by cold-rolling operations. Cold forming is used to obtain improved mechanical properties, better machinability, special size accuracy, and the production of thinner gages than hot rolling can accomplish economically. During cold rolling, the steel becomes hard and brittle. To make the steel more ductile, it is heated in an annealing furnace. Process contact water is used as a coolant for rolling mills to keep the surface of the steel clean between roller passes. Cold rolling operations also produce a waste treatment plant sludge, primarily due to the lubricants applied during rolling. Grindings from resurfacing of the worn rolls and disposal of used rolls can be a significant contributor to the wastestream.

**Finishing Stages.** One of the most important aspects of a finished product is the surface quality. To prevent corrosion, a protective coating is usually applied to the steel product. Prior to coating, the surface of the steel must be cleaned so the coating will adhere to the steel. Mill scale, rust, oxides, oil, grease, and soil are chemically removed from the surface of steel using solvent cleaners, pressurized water or air blasting, cleaning with abrasives, alkaline agents or acid pickling. In the pickling process, the steel surface is chemically cleaned of scale, rust, and other materials. Inorganic acids such as hydrochloric or sulfuric acid are most commonly used for pickling. Stainless steels are pickled with hydrochloric, nitric, and hydrofluoric acids. Spent pickle liquor is a hazardous waste, if it contains considerable residual acidity and high concentrations of dissolved iron salts. Pickling prior to coating may use a mildly acidic bath which is not necessarily hazardous. Steel generally passes from the pickling bath through a series of rinses. Alkaline cleaners may also be used to remove mineral oils and animal fats and oils from the steel surface prior to cold rolling. Common alkaline cleaning agents include: caustic soda, soda ash, alkaline silicates, and phosphates. Steel products are often given a coating to inhibit oxidation and extend the life of the product. Coated products can also be painted to further inhibit corrosion. Common coating processes include: galvanizing (zinc coating), tin coating, chromium coating, aluminizing, and terne coating (lead and tin). Metallic coating application processes include hot dipping, metal spraying, metal cladding (to produce bimetal products), and electroplating. Galvanizing is a common coating process where a thin layer of zinc is deposited on the steel surface.

## MATERIAL BALANCE INFORMATION

There are a large number of outputs that are produced as a result of the manufacturing of coke, iron, and steel, the forming of metals into basic shapes, and the cleaning and scaling of metal surfaces. Many of these outputs, categorized by process are listed in Table 5.

Table 5. Inputs and Outputs from Steelmaking Processes

| Inputs | Outputs |
|---|---|
| **Coke-Making** | |
| Coal, heat, quench water. | Process residues from coke by-product recovery. |
| | Coke oven gas by-products such as coal tar, light oil, ammonia liquor, and the remainder of the gas stream is used as fuel. Coal tar is typically refined to produce commercial and industrial products including pitch, creosote oil, refined tar, naphthalene, and bitumen. |

| Inputs | Outputs |
|---|---|
| | Charging emissions (fine particles of coke generated during oven pushing, conveyor transport, loading and unloading of coke that are captured by pollution control equipment. Approximately 1 lb per ton of coke produced is captured and generally land disposed). |
| | Ammonia, phenol, cyanide, and hydrogen sulfide. |
| | Lime sludge, generated from the ammonia still. |
| | Decanter tank tar sludge. |
| | Benzene releases in coke by-product recovery operations. |
| | Naphthalene residues, generated in the final cooling tower. |
| | Tar residues. |
| | Sulfur compounds, emitted from the stacks of the coke ovens. |
| | Wastewater from cleaning and cooling (contains zinc, ammonia still lime, or decanter tank tar, tar distillation residues). |
| | Coke oven gas condensate from piping and distribution system. |
| **Ironmaking** | |
| Iron ore (primarily in the form of taconite pellets), coke, sinter, coal, limestone, heated air. | Slag, which is either sold as a by-product, primarily for use in the construction industry, or landfilled. |
| | Residual sulfur dioxide or hydrogen sulfide. |
| | Particulates captured in the gas, including the air pollution control dust or waste treatment plant sludge. |
| | Iron is the predominant metal found in the process wastewater. |
| | Blast-furnace gas (CO). |

| Inputs | Outputs |
|---|---|
| **Steelmaking** | |
| In the steelmaking process that uses a basic oxygen furnace (BOF), inputs include molten iron, metal scrap, and high-purity oxygen.<br>In the steelmaking process that uses an electric arc furnace (EAF), the primary inputs are scrap metal, electric energy and graphite electrodes.<br>For both processes, fluxes and alloys are added, and may include: fluorspar, dolomite, and alloying agents such as aluminum, manganese. | Basic oxygen furnace emission control dust and sludge, a metals bearing waste. |
| | Electric arc furnace emission control dust and sludge; generally, 20 pounds of dust per ton of steel is expected, but as much as 40 pounds of dust per ton of steel may be generated depending on the scrap that is used. |
| | Metal dusts (consisting of iron particulate, zinc, and other metals associated with the scrap and flux (lime and/or fluorspar) not associated with the EAF). |
| | Slag. |
| | Carbon monoxide. |
| | $NO_x$ and ozone, which are generated during the melting process. |

| Inputs | Outputs |
|---|---|
| **Forming, cleaning, and descaling** | |
| Carbon steel is pickled with hydrochloric acid; stainless steels are pickled with hydrochloric, nitric and hydrofluoric acids. | Wastewater sludge from rolling, cooling, descaling, and rinsing operations which may contain cadmium, chromium, and lead. |
| Various organic chemicals are used in the pickling process. | Oils and greases from hot and cold rolling. |
| Alkaline cleaners are used to remove mineral oils and animal fats and oils from the steel surface. Common alkaline cleaning agents include caustic soda, soda ash, alkaline silicates, phosphates. | Spent pickle liquor. |
| | Spent pickle liquor rinse water sludge from cleaning operations. |
| | Wastewater from the rinse baths. Rinse water from coating processes may contain zinc, lead, cadmium, or chromium. |
| | Grindings from roll refinishing may be RCRA characteristic waste from chromium. |
| | Zinc dross. |

Sintering operations can emit significant dust levels of about 20 kilograms per metric ton (kg/t) of steel. Pelletizing operations can emit dust levels of about 15 kg/t of steel. Air emissions from pig iron manufacturing in a blast furnace include PM, ranging from less than 10 kg/t of steel manufactured to 40 kg/t; sulfur oxides ($SO_x$) mostly from sintering or pelletizing operations (1.5 kg/t of steel); nitrogen oxides ($NO_x$) mainly from sintering and heating (1.2 kg/t of steel); hydrocarbons; carbon monoxide; in some cases dioxins (mostly from sintering operations); and hydrogen fluoride.

Air emissions from steel manufacturing using the BOF may include PM (ranging from less than 15 kg/t to 30 kg/t of steel). For closed systems, emissions come from the desulfurization step between the blast furnace and the BOF; the particulate matter emissions are about 10 kg/t of steel.

In the conventional process without recirculation, wastewaters, including those from cooling operations, are generated at an average rate of 80 $m^3$/t of steel manufactured. Major pollutants present in untreated wastewaters generated from pig iron manufacture include total organic carbon (typically 100-200 mg/l); total suspended solids (7000 mg/l, 137 kg/t); dissolved solids; cyanide (15 mg/l); fluoride (1000 mg/l); chemical oxygen demand, or COD (500 mg/l); and zinc (35 mg/l).

Major pollutants in wastewaters generated from steel manufacturing using the BOF include total suspended solids (up to 4000 mg/l, 1030 kg/t), lead (8 mg/l), chromium (5 mg/l), cadmium (0.4 mg/l), zinc (14 mg/l), fluoride (20 mg/l), and oil and grease. Mill scale may amount to 33 kg/t. The process generates effluents with high temperatures.

Process solid waste from the conventional process, including furnace slag and collected dust, is generated at an average rate ranging from 300 kg/t of steel manufactured to 500 kg/t, of which 30 kg may be considered hazardous depending on the concentration of heavy metals present. Approximately 65% of BOF slag from steel manufacturing can be recycled in various industries such as building materials and, in some cases, mineral wool.

## FATE OF SELECTED CHEMICALS

Table 6 provides a synopsis of current scientific toxicity and fate information for the top chemicals (by weight) that steel facilities self-report as being released based upon the TRI (Toxic Release Inventory) in the United States. The descriptions provided in Table 2 are taken directly from 1993 *Toxics Release Inventory Public Data Release* (EPA, 1994), and the Hazardous Substances Data Bank (HSDB), assessed via TOXNET. TOXNET is a computer system run by the National Library of Medicine. It includes a number of toxicological databases managed by EPA, the National Cancer Institute, and the National Institute for Occupational Safety and Health. HSDB contains chemical-specific information on manufacturing and use, chemical and physical properties, safety and handling, toxicity and biomedical effects, pharmacology, environmental fate and exposure potential, exposure standards and regulations, monitoring and analysis methods, and additional references. The information contained in Table 6 is based upon exposure assumptions that have been conducted using standard scientific procedures. The effects listed must be taken in context of these exposure assumptions, which are more fully explained within the full chemical profiles in HSDB.

Table 6. Toxicity and Environmental Fate Information

**Ammonia CAS #7664-41-7**

**Sources.** In coke-making, ammonia is produced by the decomposition of the nitrogen-containing compounds which takes place during the secondary thermal reaction (at temperatures greater than 700°C (1296°F)). The ammonia formed during coking exists in both the water and gas that form part of the volatile products. Recovery can be accomplished by several different processes where the by-product ammonium sulfate is formed by the reaction between the ammonia and sulfuric acid.

**Toxicity.** Anhydrous ammonia is irritating to the skin, eyes, nose,- throat, and upper respiratory system. Ecologically, ammonia is a source of nitrogen (an essential element for aquatic plant growth) and may contribute to eutrophication of standing or slow-moving surface water, particularly in nitrogen-limited waters. In addition, aqueous ammonia is moderately toxic to aquatic organisms.

**Carcinogenicity.** There is currently no evidence to suggest that this chemical is carcinogenic.

**Environmental Fate.** Ammonia combines with sulfate ions in the atmosphere and is washed out by rainfall, resulting in rapid return of ammonia to the soil and surface waters. Ammonia is a central compound in the environmental cycling of nitrogen. Ammonia in lakes, rivers, and streams is converted to nitrate.

**Physical Properties.** Ammonia is a corrosive and severely irritating gas with a pungent odor.

**Hydrochloric Acid CAS #7647-01-1**

**Sources.** During hot rolling, a hard black iron oxide is formed on the surface of the steel. This "scale" is removed chemically in the pickling process, which commonly uses hydrochloric acid.

**Toxicity.** HCl is primarily a concern in its aerosol form. Acid aerosols have been implicated in causing and exacerbating a variety of respiratory ailments. Dermal exposure and ingestion of highly concentrated HCl can result in corrosivity. Ecologically, accidental releases of solution forms of HCl may adversely affect aquatic life by including a transient lowering of the pH (i.e., increasing the acidity) of surface waters.

**Carcinogenicity.** There is currently no evidence to suggest carcinogenicity.

**Environmental Fate.** Releases to surface waters and soils will be neutralized to an extent due to the buffering capacities of both systems. The extent of these reactions will depend on the characteristics of the specific environment.

**Physical Properties.** Concentrated hydrochloric acid is highly corrosive.

### Manganese and Manganese Compounds CAS #7439-96-5; 20-12-2

**Sources.** Manganese is found in the iron charge and is used as an addition agent added to alloy steel to obtain desired properties in the final product. In carbon steel, Mg is used to combine with sulfur to improve steel ductility. An alloy steel with Mg is used for applications involving relatively small sections which are subject to severe service conditions, or in larger sections where the weight saving derived from the higher strength of the alloy steels is needed.

**Toxicity**. There is currently no evidence that human exposure to Mg at levels commonly observed in ambient atmosphere results in adverse health effects. Recent EPA review of the fuel additive MMT (methylcyclopentadienyl magnesium tricarbonyl) concluded that use of MMT in gasoline could lead to ambient exposures to Mg at a level sufficient to result in adverse neurological effects. Chronic Mg poisoning bears some similarity to chronic lead poisoning. Both occur via inhalation of dust or fumes, and primarily involve the central nervous system. Early symptoms include languor, speech disturbances, sleepiness, and cramping and weakness in legs. A stolid mask-like appearance of face, emotional disturbances such as absolute detachment broken by uncontrollable laughter, euphoria, and a spastic gait with a tendency to fall while walking are seen in more advanced cases. Chronic Mg poisoning is reversible if treated early and exposure is stopped. Populations at greatest risk of Mg toxicity are the very young and those with iron deficiencies. Ecologically, although Mg is an essential nutrient for both plants and animals, in excessive concentrations it inhibits plant growth.

**Carcinogenicity.** There is currently no evidence to suggest that this chemical is carcinogenic.

**Environmental Fate.** Mg is an essential nutrient for plants and animals. It accumulates in the top layers of soil or surface water sediments and cycles between the soil and living organisms. It occurs mainly as a solid under environmental conditions, though may also be transported in the atmosphere as a vapor or dust.

### 1,1,1-Trichloroethane CAS #71-55-6

**Sources.** Used for surface cleaning of steel prior to coating.

**Toxicity.** Repeated contact with skin may cause serious skin cracking and infection. Vapors cause a slight smarting of the eyes or respiratory system if present in high concentrations. Exposure to high concentrations of TCE causes reversible mild liver and kidney dysfunction, central nervous system depression, gait disturbances, stupor, coma, respiratory depression, and even death. Exposure to lower concentrations of TCE leads to light-headedness, throat irritation, headache, disequilibrium, impaired coordination, drowsiness, convulsions, and mild changes in perception.

**Carcinogenicity.** There is currently no evidence to suggest that this chemical is carcinogenic.

**Environmental Fate.** Releases of TCE to surface water or land will almost entirely volatilize. Releases to air may be transported long distances and may partially return to earth in rain. In the lower atmosphere, TCE degrades very slowly by photooxidation and slowly diffuses to the upper atmosphere where photodegradation is rapid. Any TCE that does not evaporate from soils leaches to groundwater. Degradation in soils and water is a very slow process. TCE does not hydrolyze in water, nor does it significantly bioconcentrate in aquatic organisms.

### Zinc and Zinc Compounds CAS #7440-66-6; 20-19-9

**Sources.** To protect steel from rusting, it is coated with a material that will protect it from moisture and air. In the galvanizing process, steel is coated with zinc.

**Toxicity.** Zinc is a nutritional trace element; toxicity from ingestion is low. Severe exposure to zinc might give rise to gastritis with vomiting due to swallowing of zinc dusts. Short-term exposure to very high levels of zinc is linked to lethargy, dizziness, nausea, fever, diarrhea, and reversible pancreatic and neurological damage. Long-term zinc poisoning causes irritability, muscular stiffness and pain, loss of appetite, and nausea. Zinc chloride fumes cause injury to mucous membranes and to the skin. Ingestion of soluble zinc salts may cause nausea, vomiting, and purging.

**Carcinogenicity.** There is currently no evidence to suggest that this chemical is carcinogenic.

**Environmental Fate.** Significant zinc contamination of soil is only seen in the vicinity of industrial point sources. Zinc is a relatively stable soft metal, though it burns in air (pyrophoric). Zinc bioconcentrates in aquatic organisms.

The toxic chemical release data obtained from TRI provides detailed information on the majority of facilities in the iron and steel industry in the United States. It also allows for a comparison across years and industry sectors. Reported chemicals are limited, however, to the 316 reported chemicals. Most of the hydrocarbon emissions from iron and steel facilities are not captured by TRI. The EPA Office of Air Quality Planning and Standards has compiled air pollutant emission factors for determining the total air emissions of priority pollutants (e.g., total hydrocarbons, $SO_x$, $NO_x$, CO, particulates, etc.) from many iron and steel manufacturing sources. The Aerometric Information Retrieval System (AIRS) contains a wide range of information related to stationary sources of air pollution, including the emissions of a number of air pollutants which may be of concern within a particular industry. With the exception of VOCs, there is little overlap with the TRI chemicals reported above. By way of comparison to other industry sectors, the steel industry in the United States emits about 1.5 million short tons/year of carbon monoxide, which is more than twice as much as the next largest releasing industry, pulp and paper. The iron and steel industry also ranks as one of the top five releasers for $NO_2$, $PM_{10}$, and $SO_2$. Carbon monoxide releases occur during ironmaking (in the burning of coke, CO produced reduces iron oxide ore), and during steelmaking (in either the basic oxygen furnace or the electric arc furnace). Nitrogen dioxide is generated during steelmaking. Particulate matter may be emitted from the coke-making (particularly in quenching operations), ironmaking or the basic oxygen furnace (as oxides of iron that are emitted as submicron dust) or electric arc furnace (as metal dust containing iron particulate, zinc, and other materials associated with the scrap). Sulfur dioxide can be released in ironmaking or sintering.

## POLLUTION PREVENTION PRACTICES AND OPPORTUNITIES

Most of the pollution prevention practices have concentrated on reducing coke-making emissions, electric arc furnace (EAF) dust, and spent acids used in finishing operations. Because of the complexity, size, and age of the equipment used, projects that have the highest pollution prevention potential often require major capital investments, which make many pollution prevention projects difficult to justify. Despite this, the industry must seek ways to become more cost-competitive, which requires investing in more cost-effective, less polluting technologies. Table 7 provides a summary of P2 practices and opportunities. To supplement this list, the following discussions should be considered.

With regard to coke-making, this process is seen by industry experts as one of the steel industry's areas of greatest environmental concern, with coke oven air emissions and quenching wastewater as the major problems. In response to expanding regulatory constraints in the United Sates, including the Clean Air Act National Emission Standards for coke ovens, U.S. steelmakers are turning to new technologies to decrease the sources of pollution from, and their reliance on, coke. Pollution prevention in coke-making has focused on two areas: reducing coke oven emissions and developing cokeless ironmaking techniques. Although these processes have not yet been widely demonstrated on a commercial scale, they may provide important benefits, especially for the integrated segment of the industry, by potentially lowering air emissions and wastewater discharges. Several technologies are available or are under development to reduce the emissions from coke ovens. Typically, these technologies reduce the quantity of coke needed by changing the method by which coke is added to the blast furnace or by substituting a portion of the coke with other fuels.

The reduction in the amount of coke produced proportionally reduces the coking emissions. Some of the most prevalent or promising coke-reduction technologies are listed in Table 7.

Cokeless technologies (refer to Table 7 for examples) substitute coal for coke in the blast furnace, hence eliminating the need for coke-making. Such technologies have enormous potential to reduce pollution generated during the steelmaking process. The drawbacks with these technologies are that (1) the capital investment required for retrofits is very significant, and (2) some countries whose economies are dependent upon the steel industry need to undergo significant industry rationalization and restructuring in order to justify investments into these technologies. For example, Russia and Ukraine, which have significant steel production and export capabilities, heavily depend on a labor-intensive coking industry. The elimination of the coking industry in these countries would likely result in significant social implications.

Table 7. Recommended Pollution Prevention Practices

| **Area of opportunity** | **Recommended pollution prevention practice** |
|---|---|
| *Eliminating coke with coke-less technologies* | 1. *The Japanese Direct Iron Ore Smelting (DIOS) process.* This process produces molten iron directly with coal and sinter feed ore. A 500 ton per day pilot plant was started up in October, 1993 and the designed production rates were attained as a short-term average. Data generated are being used to determine economic feasibility on a commercial scale. |

| Area of opportunity | Recommended pollution prevention practice |
|---|---|
| | 2. *HIsmelt process.* A plant using the HIsmelt process for molten iron production, developed by HIsmelt Corporation of Australia, was started up in late 1993. The process, using ore fines and coal, has achieved a production rate of 8 tons per hour using ore directly in the smelter. Developers anticipate reaching the production goal of 14 tons per hour. The data generated are being used to determine economic feasibility on commercial scale. If commercial feasibility is realized, Midrex is expected to become the U.S. engineering licensee of the HIsmelt process.<br>3. *Corex process.* The Corex or Cipcor process has integral coal desulfurizing, is amenable to a variety of coal types, and generates electrical power in excess of that required by an iron and steel mill which can be sold to local power grids. A Corex plant is in operation in South Africa, and other plants are expected to be operational in South Korea and India. |
| *Reducing coke oven emissions with other technologies* | 4. *Pulverized coal injection.* This technology substitutes pulverized coal for a portion of the coke in the blast furnace. Use of pulverized coal injection can replace about 25 to 40% of coke in the blast furnace, substantially reducing emissions associated with coke-making operations. This reduction ultimately depends on the fuel injection rate applied to the blast furnaces which will, in turn be dictated by the aging of existing coking facilities, fuel costs, oxygen availability, capital requirements for fuel injection, and available hot blast temperature.<br>5. *Nonrecovery coke battery.* As opposed to the by-product recovery coke plant, the nonrecovery coke battery is designed to allow combustion of the gases from the coking process, thus consuming the by-products that are typically recovered. The process results in lower air emissions and substantial reductions in coking process wastewater discharges.<br>6. *The Davy Still Auto-process.* In this precombustion cleaning process for coke ovens, coke oven battery process water is utilized to strip ammonia and hydrogen sulfide from coke oven emissions. |

| Area of opportunity | Recommended pollution prevention practice |
|---|---|
| | 7. *Alternative fuels*. Steel producers can inject other fuels, such as natural gas, oil, and tar/pitch, instead of coke into the blast furnace, but these fuels can only replace coke in limited amounts. |
| *Reducing wastewater* | 8. In Europe, some plants have implemented technology to shift from water quenching to dry quenching in order to reduce energy costs. However, major construction changes are required for such a solution. |
| *Recycling of coke by-products* | 9. Improvements in the in-process recycling of tar decanter sludge are common practice. Sludge can either be injected into the ovens to contribute to coke yield, or converted into a fuel that is suitable for the blast furnace. |
| *Electric arc furnace dust* | 10. EAF dust is a hazardous waste because of its high concentrations of lead and cadmium. With 550,000 tons of EAF dust generated annually in the United States, there is great potential to reduce the volume of this hazardous waste. U.S. steel companies typically pay a disposal fee of $150 to $200 per ton of dust. With an average zinc concentration of 19%, much of the EAF dust is sent off-site for zinc recovery. Most of the EAF dust recovery options are only economically viable for dust with a zinc content of at least 15 to 20 percent. Facilities that manufacture specialty steels such as stainless steel with a lower zinc content, still have opportunities to recover chromium and nickel from the EAF dust. In-process recycling of EAF dust involves pelletizing and then reusing the pellets in the furnace; however, recycling of EAF dust on-site has not proven to be technically or economically competitive for all mills. Improvements in technologies have made off-site recovery a cost-effective alternative to thermal treatment or secure landfill disposal. |
| *Pig iron manufacturing* | 11. Improve blast furnace efficiency by using coal and other fuels (such as oil or gas) for heating instead of coke, thereby minimizing air emissions.<br>12. Recover the thermal energy in the gas from the blast furnace before using it as a fuel.<br>13. Increase fuel efficiency and reduce emissions by improving blast furnace charge distribution.<br>14. Recover energy from sinter coolers and exhaust gases. |

| Area of opportunity | Recommended pollution prevention practice |
|---|---|
| | 15. Use dry $SO_x$ removal systems such as caron absorption for sinter plants or lime spraying in flue gases.<br>16. Recycle iron-rich materials such as iron ore fines, pollution control dust, and scale in a sinter plant.<br>17. Use low- $NO_x$ burners to reduce $NO_x$ emissions from burning fuel in ancillary operations.<br>18. Improve productivity by screening the charge and using better taphole practices.<br>19. Reduce dust emissions at furnaces by covering iron runners when tapping the blast furnace and by using nitrogen blankets during tapping.<br>20. Use pneumatic transport, enclosed conveyor belts, or self-closing conveyor belts, as well as wind barriers and other dust suppression measures, to reduce the formation of fugitive dust. |
| *Steel manufacturing* | 21. Use dry dust collection and removal systems to avoid the generation of wastewater. Recycle collected dust.<br>22. Use BOF gas as fuel.<br>23. Use enclosures for BOF.<br>24. Use a continuous process for casting steel to reduce energy consumption. |
| *Finishing stages* | 25. *Pickling acids* - In finishing, pickling acids are recognized as an area where pollution prevention efforts can have a significant impact in reducing the environmental impact of the steel mill. The pickling process removes scale and cleans the surface of raw steel by dipping it into a tank of hydrochloric or sulfuric acid. If not recovered, the spent acid may be transported to deep injection wells for disposal, but as those wells continue to close, alternative disposal costs are rising. |

| **Area of opportunity** | **Recommended pollution prevention practice** |
|---|---|
| | 26. *Pickling acids* - Large-scale steel manufacturers recover HCl in their finishing operations, however the techniques used are not suitable for small- to medium-sized steel plants. Currently, a recovery technique for smaller steel manufacturers and galvanizing plants is in pilot-scale testing. The system removes iron chloride (a saleable product) from the HCl, reconcentrates the acid for reuse, and recondenses the water to be reused as a rinse water in the pickling process. Because the only by-product of the hydrochloric acid recovery process is a non-hazardous, marketable metal chloride, this technology generates no hazardous wastes. The manufacturer projects industry-wide HCl waste reduction of 42,000 tons/year by 2010. This technology is less expensive than transporting and disposing waste acid, plus it eliminates the associated long-term liability. The total savings for a small- to medium-sized galvanizer is projected to be $260,000 each year.<br>27. *Pickling acids* - To reduce spent pickling liquor and simultaneously reduce fluoride in the plant effluent, one facility modified their existing treatment process to recover the fluoride ion from rinse water and spent pickling acid raw water waste streams. The fluoride is recovered as calcium fluoride (fluorspar), an input product for steelmaking. The melt shop in the same plant had been purchasing 930 tons of fluorspar annually for use as a furnace flux material in the EAF at a cost of $100 per ton. The recovered calcium fluoride is expected to be a better grade than the purchased fluorspar, which would reduce the amount of flux used by approximately 10%. Not only would the generation rate of sludge from spent pickling liquor treatment be reduced (resulting in a savings in off-site sludge disposal costs), but a savings in chemical purchases would be captured. |
| *Process modifications* | 28. Replacing single-pass wastewater systems with closed-loop systems to minimize chemical use in wastewater treatment and to reduce water use. |

| Area of opportunity | Recommended pollution prevention practice |
|---|---|
| | 29. Continuous casting, now used for about 90% of crude steel cast in the United States offers great improvements in process efficiency when compared to the traditional ingot teeming method. This increased efficiency also results in a considerable savings in energy and some reduction in the volume of mill wastewater. |
| *Materials substitution* | 30. Use scrap steel with low lead and cadmium content as a raw material, if possible.<br>31. Eliminate the generation of reactive desulfurization slag generated in foundry work by replacing calcium carbide with a less hazardous material. |
| *Recycling miscellaneous materials* | 32. Recycle or reuse oils and greases.<br>33. Recover acids by removing dissolved iron salts from spent acids.<br>34. Use thermal decomposition for acid recovery from spent pickle liquor.<br>35. Use a bipolar membrane/electrodialytic process to separate acid from metal by-products in spent $NO_3$-HF pickle liquor.<br>36. Recover sulfuric acid using low temperature separation of acid and metal crystals.<br>37. Use blast-furnace slag in construction materials. Slag containing free lime can be used in ironmaking. |

# LEAD AND ZINC SMELTING

## INDUSTRY DESCRIPTION AND PRACTICES

Lead and zinc can be produced pyrometallurgically or hydrometallurgically, depending on the type of ore used as a charge. In the pyrometallurgical process, ore concentrate containing lead, zinc, or both is fed, in some cases after sintering, into a primary smelter. Lead concentrations can be 50 to 70%, and the sulfur content of sulfidic ores is in the range of 15 to 20%. Zinc concentration is in the range of 40 to 60%, with sulfur content in sulfidic ores in the range of 26 to 34%. Ores with a mixture of lead and zinc concentrate usually have lower respective metal concentrations. During sintering, a blast of hot air or oxygen is used to oxidize the sulfur present in the feed to sulfur dioxide. Blast furnaces are used in conventional processes for reduction and refining of lead compounds to produce lead. Modem direct smelting processes include QSL, Kivcet, AUSMELT, and TBRC.

## Primary Lead Processing

The conventional pyrometallurgical primary lead production process consists of four steps: sintering, smelting, drossing, and refining. A feedstock made up mainly of lead concentrate is fed into a sintering machine. Other raw materials may be added, including iron, silica, limestone flux, coke, soda, ash, pyrite, zinc, caustic, and particulates gathered from pollution-control devices. The sintering feed, along with coke, is fed into a blast furnace for reducing, where the carbon also acts as a fuel and smelts the lead-containing materials. The molten lead flows to the bottom of the furnace, where four layers form: "speiss" (the lightest material, basically arsenic and antimony), “matte" (copper sulfide and other metal sulfides), blast furnace slag (primarily silicates), and lead bullion (98% by weight). All layers are then drained off. The speiss and matte are sold to copper smelters for recovery of copper and precious metals. The blast furnace slag, which contains zinc, iron, silica, and lime, is stored in piles and is partially recycled. Sulfur oxide emissions are generated in blast furnaces from small quantities of residual lead sulfide and lead sulfates in the sinter feed.

Rough lead bullion from the blast furnace usually requires preliminary treatment in kettles before undergoing refining operations. During drossing, the bullion is agitated in a drossing kettle and cooled to just above its freezing point, 370 to 425°C (700 to 800°F). A dross composed of lead oxide, along with copper, antimony, and other elements, floats to the top and solidifies above the molten lead. The dross is removed and is fed into a dross furnace for recovery of the nonlead mineral values.

The lead bullion is refined using pyrometallurgical methods to remove any remaining nonlead materials (e.g., gold, silver, bismuth, zinc, and metal oxides such as oxides of antimony, arsenic, tin, and copper). The lead is refined in a cast-iron kettle in five stages. First, antimony, tin, and arsenic are removed. Next, gold and silver are removed by adding zinc. The lead is then refined by vacuum removal of zinc. Refining continues with the addition of calcium and magnesium, which combine with bismuth to form an insoluble compound that is skimmed from the kettle. In the final step, caustic soda, nitrates, or both may be added to remove any remaining traces of metal impurities. The refined lead will have a purity of 99.90 to 99.99%. It may be mixed with other metals to form alloys, or it may be directly cast into shapes.

## Secondary Lead Processing

The secondary production of lead begins with the recovery of old scrap from worn-out, damaged, or obsolete products and with new scrap. The chief source of old scrap is lead-acid batteries; other sources include cable coverings, pipe, sheet, and other lead-bearing metals. Solder, a tin-based alloy, may be recovered from the processing of circuit boards for use as lead charge.

Prior to smelting, batteries are usually broken up and sorted into their constituent products. Fractions of cleaned plastic (such as polypropylene) case are recycled into battery cases or other products. The dilute sulfuric acid is either neutralized for disposal or recycled to the local acid market. One of the three main smelting processes is then used to reduce the lead fractions and produce lead bullion.

Most domestic battery scrap is processed in blast furnaces, rotary furnaces, or reverberatory furnaces. A reverberatory furnace is more suitable for processing fine particles and may be operated in conjunction with a blast furnace.

Blast furnaces produce hard lead from charges containing siliceous slag from previous runs (about 4.5% of the charge), scrap iron (about 4.5%), limestone (about 3%), and coke (about 5.5%). The remaining 82.5% of the charge is made up of oxides, pot furnace refining drosses, and reverberatory slag. The proportions of rerun slags, limestone, and coke vary but can run as high as 8% for slags, 10% for limestone, and 8% for coke. The processing capacity of the blast furnace ranges from 20 to 80 metric tons per day (tpd).

Newer secondary recovery plants use lead paste desulfurization to reduce sulfur dioxide emissions and generation of waste sludge during smelting. Battery paste containing lead sulfate and lead oxide is desulfurized with soda ash, yielding market-grade sodium sulfate as a by-product. The desulfurized paste is processed in a reverberatory furnace, and the lead carbonate product may then be treated in a short rotary furnace. The battery grids and posts are processed separately in a rotary smelter.

## Zinc Manufacturing

In the most common hydrometallurgical process for zinc manufacturing, the ore is leached with sulfuric acid to extract the lead/zinc. These processes can operate at atmospheric pressure or as pressure leach circuits. Lead/zinc is recovered from solution by electrowinning, a process similar to electrolytic refining. The process most commonly used for low-grade deposits is heap leaching. Imperial smelting is also used for zinc ores.

## POLLUTION PREVENTION PRACTICES AND OPPORTUNITIES

The principal air pollutants emitted from the processes are particulate matter and sulfur dioxide. Fugitive emissions occur at furnace openings and from launders, casting molds, and ladles carrying molten materials, which release sulfur dioxide and volatile substances into the working environment. Additional fugitive particulate emissions occur from materials handling and transport of ores and concentrates. Some vapors are produced in hydrometallurgy and in various refining processes.

The principal constituents of the particulate matter are lead/zinc and iron oxides, but oxides of metals such as arsenic, antimony, cadmium, copper, and mercury are also present, along with metallic sulfates. Dust from raw materials handling contains metals, mainly in sulfidic form, although chlorides, fluorides, and metals in other chemical forms may be present. Off-gases contain fine dust particles and volatile impurities such as arsenic, fluorine, and mercury.

Air emissions for processes with few controls may be of the order of 30 kilograms lead or zinc per metric ton (kg/t) of lead or zinc produced. The presence of metals in vapor form is dependent on temperature. Leaching processes will generate acid vapors, while refining processes result in products of incomplete combustion (PICs). Emissions of arsine, chlorine, and hydrogen chloride vapors and acid mists are associated with electrorefining.

Wastewaters are generated by wet air scrubbers and cooling water. Scrubber effluents may contain lead/zinc, arsenic, and other metals. In the electrolytic refining process, by-products such as gold and silver are collected as slimes and are subsequently recovered. Sources of wastewater include spent electrolytic baths, slimes recovery, spent acid from hydrometallurgy processes, cooling water, air scrubbers, washdowns, and stormwater. Pollutants include dissolved and suspended solids, metals, and oil and grease.

The larger proportion of the solid waste is discarded slag from the smelter. Discarded slag may contain 0.5-0.7% lead/zinc and is frequently used as fill or for sandblasting. Slags with higher lead/zinc content, say 15% zinc, can be sent for metals recovery. Leaching processes produce residues, while effluent treatment results in sludges that require appropriate disposal. The smelting process typically produces less than 3 tons of solid waste per ton of lead/zinc produced.

The most effective pollution prevention option is to choose a process that entails lower energy usage and lower emissions. Modern flash-smelting processes save energy, compared with the conventional sintering and blast furnace process. Process gas streams containing over 5% sulfur dioxide are usually used to manufacture sulfuric acid. The smelting furnace will generate gas streams with $SO_2$ concentrations ranging from 0.5% to 10%, depending on the method used. It is important, therefore, to select a process that uses oxygen-enriched air or pure oxygen. The aim is to save energy and raise the $SO_2$ content of the process gas stream by reducing the total volume of the stream, thus permitting efficient fixation of sulfur dioxide. Processes should be operated to maximize the concentration of the sulfur dioxide. An added benefit is the reduction (or elimination) of nitrogen oxides $NO_x$. Table 8 provides a list of pollution prevention practices and opportunities. Regarding standard treatment technologies, ESPs and baghouses are used for product recovery and for the control of particulate emissions. Dust that is captured but not recycled will need to be disposed of in a secure landfill or in another acceptable manner.

Table 8. Summary of Pollution Prevention Practices

| |
|---|
| Use doghouse enclosures where appropriate; use hoods to collect fugitive emissions. |
| Mix strong acidic gases with weak ones to facilitate production of sulfuric acid from sulfur oxides, thereby avoiding the release of weak acidic gases. |
| Maximize the recovery of sulfur by operating the furnaces to increase the $SO_x$ content of the flue gas and by providing efficient sulfur conversion. Use a double-contact, double-absorption process. |
| Desulfurize paste with caustic soda or soda ash to reduce $SO_2$ emissions. |
| Use energy-efficient measures such as waste heat recovery from process gases to reduce fuel usage and associated emissions. |
| Recover acid, plastics, and other materials when handling battery scrap in secondary lead production. |
| Recycle condensates, rainwater, and excess process water for washing, for dust control, for gas scrubbing, and for other process applications where water quality is not of particular concern. |
| Give preference to natural gas over heavy fuel oil for use as fuel and to coke with lower sulfur content. |
| Use low-$NO_x$ burners. |

| |
|---|
| Use suspension or fluidized bed roasters, where appropriate, to achieve high $SO_2$ concentrations when roasting zinc sulfides. |
| Recover and reuse iron-bearing residues from zinc production for use in the steel or construction industries. |
| Give preference to fabric filters over wet scrubbers or wet electrostatic precipitators (ESPs) for dust control. |
| Good housekeeping practices are key to minimizing losses and preventing fugitive emissions. Losses and emissions are minimized by enclosed buildings, covered conveyors and transfer points, and dust collection equipment. Yards should be paved and runoff water routed to settling ponds. |

Arsenic trioxide or pentoxide is in vapor form because of the high gas temperatures and must be condensed by gas cooling so that it can be removed in fabric filters. Collection and treatment of vent gases by alkali scrubbing may be required when sulfur dioxide is not being recovered in an acid plant.

Effluent treatment of process bleed streams, filter backwash waters, boiler blowdown, and other streams is required to reduce suspended and dissolved solids and heavy metals and to adjust pH. Residues that result from treatment are recycled to other industries such as the construction industry, sent to settling ponds (provided that groundwater and surface water contamination is not a concern), or disposed of in a secure landfill.

Slag should be either landfilled or granulated and sold for use in building materials.

## NICKEL ORE PROCESSING AND REFINING

### INDUSTRY DESCRIPTION AND PRACTICES

Primary nickel is produced from two very different ores, lateritic and sulfidic. Lateritic ores are normally found in tropical climates where weathering, with time, extracts and deposits the ore in layers at varying depths below the surface. Lateritic ores are excavated using large earth-moving equipment and are screened to remove boulders. Sulfidic ores, often found in conjunction with copper-bearing ores, are mined from underground. Following is a description of the processing steps used for the two types of ores.

### Lateritic Ore Processing

Lateritic ores have a high percentage of free and combined moisture, which must be removed. Drying removes free moisture; chemically bound water is removed by a reduction furnace, which also reduces the nickel oxide. Lateritic ores have no significant fuel value, and an electric furnace is needed to obtain the high temperatures required to accommodate the high magnesia content of the ore. Some laterite smelters add sulfur to the furnace to produce a matte for processing. Most laterite nickel processers run the furnaces so as to reduce the iron content sufficiently to produce ferronickel products. Hydrometallurgical processes based on ammonia or sulfuric acid leach are also used. Ammonia leach is usually applied to the ore after the reduction roast step.

### Sulfidic Ore Processing

Flash smelting is the most common process, but electric smelting is used for more complex raw materials when increased flexibility is needed. Both processes use dried concentrates. Electric smelting requires a roasting step before smelting to reduce sulfur content and volatiles. Older nickel-smelting processes, such as blast or reverberatory furnaces, are no longer acceptable because of low energy efficiencies and environmental concerns.

In flash smelting, dry sulfide ore containing less than 1% moisture is fed to the furnace along with preheated air, oxygen-enriched air (30-40% oxygen), or pure oxygen. Iron and sulfur are oxidized. The heat that results from exothermic reactions is adequate to smelt concentrate, producing a liquid matte (up to 45% nickel) and a fluid slag. Furnace matte still contains iron and sulfur, and these are oxidized in the converting step to sulfur dioxide and iron oxide by injecting air or oxygen into the molten bath. Oxides form a slag, which is skimmed off. Slags are processed in an electric furnace prior to discard to recover nickel. Process gases are cooled, and particulates are then removed by gas-cleaning devices.

### Nickel Refining

Various processes are used to refine nickel matte. Fluid-bed roasting and chlorine-hydrogen reduction produce high-grade nickel oxides (more than 95% nickel). Vapor processes such as the carbonyl process can be used to produce high-purity nickel pellets. In this process, copper and precious metals remain as a pyrophoric residue that requires separate treatment. Use of electrical cells equipped with inert cathodes is the most common technology for nickel refining.

Electrowinning, in which nickel is removed from solution in cells equipped with inert anodes, is the more common refining process. Sulfuric acid solutions or, less commonly, chloride electrolytes are used.

## POLLUTION PREVENTION PRACTICES AND OPPORTUNITIES

Sulfur dioxide is a major air pollutant emitted in the roasting, smelting, and converting of sulfide ores. (Nickel sulfide concentrates contain 6-20% nickel and up to 30% sulfur.) $SO_2$ releases can be as high as 4 metric tons (t) of sulfur dioxide per metric ton of nickel produced, before controls. Reverberatory furnaces and electric furnaces produce $SO_2$ concentrations of 0.5 to 2.0%, while flash furnaces produce $SO_2$ concentrations of over 10% - a distinct advantage for the conversion of the sulfur dioxide to sulfuric acid. Particulate emission loads for various process steps include 2.0 to 5.0 kilograms per metric ton (kg/t) for the multiple hearth roaster; 0.5 to 2.0 kg/t for the fluid bed roaster; 0.2 to 1.0 kg/t for the electric furnace; 1.0 to 2.0 kg/t for the Pierce-Smith converter; and 0.4 kg/t for the dryer upstream of the flash furnace. Ammonia and hydrogen sulfide are pollutants associated with the ammonia leach process; hydrogen sulfide emissions are associated with acid leaching processes. Highly toxic nickel carbonyl is a contaminant of concern in the carbonyl refining process. Various process offgases contain fine dust particles and volatilized impurities. Fugitive emissions occur at furnace openings, launders, casting molds, and ladles that carry molten product. The transport and handling of ores and concentrates produce windborne dust.

Pyrometallurgical processes for processing sulfidic ores are generally dry, and effluents are of minor importance, although wet ESPs are often used for gas treatment, and the resulting wastewater could have high metal concentrations. Process bleed streams may contain antimony, arsenic, or mercury. Large quantities of water are used for slag granulation, but most of this water should be recycled.

The smelter contributes a slag that is a dense silicate. Sludges that require disposal will result when neutralized process effluents produce a precipitate.

Pollution prevention is always preferred to the use of end-of-pipe pollution control facilities. Therefore, every attempt should be made to incorporate cleaner production processes and facilities to limit, at source, the quantity of pollutants generated. The choice of flash smelting over older technologies is the most significant means of reducing pollution at source. Sulfur dioxide emissions can be controlled by:

- Recovery as sulfuric acid
- Recovery as liquid sulfur dioxide (absorption of clean dry off-gas in water or chemical absorption by ammonium bisulfite or dimethyl aniline)
- Recovery as elemental sulfur, using reductants, such as hydrocarbons, carbon, or hydrogen sulfide

Toxic nickel carbonyl gas is normally not emitted from the refining process because it is broken down in decomposer towers. However, very strict precautions throughout the refining process are required to prevent the escape of the nickel carbonyl into the workplace. Continuous monitoring for the gas, with automatic isolation of any area of the plant where the gas is detected, is required. Impervious clothing is used to protect workers against contact of liquid nickel carbonyl with skin.

Preventive measures for reducing emissions of particulate matter include encapsulation of furnaces and conveyors to avoid fugitive emissions. Covered storage of raw materials should be considered.

Wet scrubbing should be avoided, and cooling waters should be recirculated. Stormwaters should be collected and used in the process. Process water used to transport granulated slag should be recycled. To the extent possible, all process effluents should be returned to the process.

The discharge of particulate matter emitted during drying, screening, roasting, smelting, and converting is controlled by using cyclones followed by wet scrubbers, ESPs, or bag filters. Fabric filters may require reduction of gas temperatures by, for example, dilution with low-temperature gases from hoods used for fugitive dust control. Preference should be given to the use of fabric filters over wet scrubbers.

Liquid effluents are used to slurry tailings to the tailings ponds, which act as a reservoir for the storage and recycle of plant process water. However, there may be a need to treat bleed streams of some process effluents to prevent a buildup of various impurities. Solid wastes from nickel sulfide ores often contain other metals such as copper and precious metals, and consideration should be given to further processing for their recovery. Slag can be used as construction material after nickel recovery, as appropriate (e.g., return of converter slag to the furnace). Sanitary sewage effluents require treatment in a separate facility or discharge to a municipal sewer.

# COPPER SMELTING

## INDUSTRY DESCRIPTION AND PRACTICES

Copper can be produced either pyrometallurgically or hydrometallurgically. The hydrometallurgical route is used only for a very limited amount of the world's copper production and is normally only considered in connection with *in situ* leaching of copper ores. From an environmental point of view, this is a questionable production route. Several different processes can be used for copper production. The traditional process is based on roasting, smelting in reverbatory furnaces (or electric furnaces for more complex ores), producing matte (copper-iron sulfide), and converting for production of blister copper, which is further refined to cathode copper. This route for production of cathode copper requires large amounts of energy per ton of copper: 30 to 40 million British thermal units (Btu) per ton cathode copper. It also produces furnace gases with low sulfur dioxide concentrations from which the production of sulfuric acid or other products is less efficient. The sulfur dioxide concentration in the exhaust gas from a reverbatory furnace is about 0.5-1.5%; that from an electric furnace is about 2 - 4%. So-called flash smelting techniques have therefore been developed that utilize the energy released during oxidation of the sulfur in the ore. The flash techniques reduce the energy demand to about 20 million Btu/ton of produced cathode copper. The $SO_2$ concentration in the off-gases from flash furnaces is also higher, over 30%, and is less expensive to convert to sulfuric acid. The INCO process results in 80% sulfur dioxide in the off-gas. Flash processes have been in use since the early 1950s.

In addition to the above processes, there are a number of newer processes such as Noranda, Mitsubishi, and Contop, which replace roasting, smelting, and converting, or processes such as ISA-SMELT and KIVCET, which replace roasting and smelting. For converting, the Pierce-Smith and Hoboken converters are the most common processes.

The matte from the furnace is charged to converters, where the molten material is oxidized in the presence of air to remove the iron and sulfur impurities (as converter slag) and to form blister copper. Blister copper is further refined as either fire-refined copper or anode copper (99.5% pure copper), which is used in subsequent electrolytic refining. In fire refining, molten blister copper is placed in a fire-refining furnace, a flux may be added, and air is blown through the molten mixture to remove residual sulfur. Air blowing results in residual oxygen, which is removed by the addition of natural gas, propane, ammonia, or wood. The fire-refined copper is then cast into anodes for further refining by electrolytic processes or is cast into shapes for sale.

In the most common hydrometallurgical process, the ore is leached with ammonia or sulfuric acid to extract the copper. These processes can operate at atmospheric pressure or as pressure leach circuits. Copper is recovered from solution by electrowinning, a process similar to electrolytic refining. The process is most commonly used for leaching low-grade deposits *in situ* or as heaps.

Recovery of copper metal and alloys from copper-bearing scrap metal and smelting residues requires preparation of the scrap (e.g., removal of insulation) prior to feeding into the primary process. Electric arc furnaces using scrap as feed are also common.

## POLLUTION PREVENTION PRACTICES AND OPPORTUNITIES

The principal air pollutants emitted from the processes are sulfur dioxide and particulate matter. The amount of sulfur dioxide released depends on the characteristics of the ore-complex ores which may contain lead, zinc, nickel, and other metals, and on whether facilities are in place for capturing and converting the sulfur dioxide. $SO_2$ emissions may range from less than 4 kilograms per metric ton (kg/t) of copper to 2000 kg/t of copper. Particulate emissions can range from 0.1 kg/t of copper to as high as 20 kg/t of copper. Fugitive emissions occur at furnace openings and from launders, casting molds, and ladles carrying molten materials. Additional fugitive particulate emissions occur from materials handling and transport of ores and concentrates. Some vapors, such as arsine, are produced in hydrometallurgy and various refining processes. Dioxins can be formed from plastic and other organic material when scrap is melted. The principal constituents of the particulate matter are copper and iron oxides. Other copper and iron compounds, as well as sulfides, sulfates, oxides, chlorides, and fluorides of arsenic, antimony, cadmium, lead, mercury, and zinc, may also be present. Mercury can also be present in metallic form. At higher temperatures, mercury and arsenic could be present in vapor form. Leaching processes will generate acid vapors, while fire-refining processes result in copper and $SO_2$ emissions. Emissions of arsine, hydrogen vapors, and acid mists are associated with electrorefining. Wastewater from primary copper production contains dissolved and suspended solids that may include concentrations of copper, lead, cadmium, zinc, arsenic, and mercury and residues from mold release agents (lime or aluminum oxides). Fluoride may also be present, and the effluent may have a low pH. Normally there is no liquid effluent from the smelter other than cooling water; wastewaters do originate in scrubbers (if used), wet electrostatic precipitators, cooling of copper cathodes, and so on. In the electrolytic refining process, by-products such as gold and silver are collected as slimes that are subsequently recovered. Sources of wastewater include spent electrolytic baths, slimes recovery, spent acid from hydrometallurgy processes, cooling water, air scrubbers, washdowns, stormwater, and sludges from wastewater treatment processes that require reuse/recovery or appropriate disposal. The main portion of the solid waste is discarded slag from the smelter. Discard slag may contain 0.5-0.7% copper and is frequently used as construction material or for sandblasting. Leaching processes produce residues, while effluent treatment results in sludges, which can be sent for metals recovery. The smelting process typically produces less than 3 tons of solid waste per ton of copper produced.

Process-gas streams containing sulfur dioxide are processed to produce sulfuric acid, liquid sulfur dioxide, or sulfur. The smelting furnace will generate process gas streams with $SO_2$ concentrations ranging from 0.5% to 80%, depending on the process used. It is important, therefore, that a process be selected that uses oxygen-enriched air (or pure oxygen) to raise the $SO_2$ content of the process gas stream and reduce the total volume of the stream, thus permitting efficient fixation of sulfur dioxide. Processes should be operated to maximize the concentration of the sulfur dioxide. An added benefit is the reduction of $NO_x$. Some pollution prevention practices for this industry include the following:

- Closed-loop electrolysis plants will contribute to prevention of pollution.
- Furnaces should be enclosed to reduce fugitive emissions, and dust from dust control equipment should be returned to the process.
- Energy efficiency measures (such as waste heat recovery from process gases) should be applied to reduce fuel usage and associated emissions.
- Recycling should be practiced for cooling water, condensates, rainwater, and excess process water used for washing, dust control, gas scrubbing, and other process applications where water quality is not a concern.
- Good housekeeping practices are key to minimizing losses and preventing fugitive emissions. Such losses and emissions are minimized by enclosed buildings, covered or enclosed conveyors and transfer points, and dust collection equipment. Yards should be paved and runoff water routed to settling ponds. Regular sweeping of yards and indoor storage or coverage of concentrates and other raw materials also reduces materials losses and emissions.

Pollution control technologies acceptable for this industry are as follows. Fabric filters are used to control particulate emissions. Dust that is captured but not recycled will need to be disposed of in a secure landfill or other acceptable manner. Vapors of arsenic and mercury present at high gas temperatures are condensed by gas cooling and removed. Additional scrubbing may be required. Effluent treatment by precipitation, filtration, and so on, of process bleed streams, filter backwash waters, boiler blowdown, and other streams may be required to reduce suspended and dissolved solids and heavy metals. Residues that result from treatment are sent for metals recovery or to sedimentation basins. Stormwaters should be treated for suspended solids and heavy metals reduction. Slag should be landfilled or granulated and sold. Modern plants using good industrial practices should set as targets total dust releases of 0.5 to 1.0 kg/t of copper and $SO_2$ discharges of 25 kg/t of copper. A double-contact, double-absorption plant should emit no more than 0.2 kg of sulfur dioxide per ton of sulfuric acid produced (based on a conversion efficiency of 99.7%).

## A SHORT REVIEW

Industry practices are shifting away from end-of-pipe treatment technologies toward pollution prevention. The transition in general is slow, because many companies face large-scale investments in more environmentally friendly technologies. Large infrastructure investments into green technologies which reduce pollution and forms of waste at the source generally are taking years of planning and implementation and are often implemented over several stages. Because these investments are not examined in terms of the four tiers of environmental costs, more conservative and lengthy transitions to greener technologies are taking place.

In the chapter to follow, the methodology behind waste minimization and pollution prevention programs is explained in greater detail. The principles of life-cycle costing and their application to assessing P2 technologies are described.

# Chapter 8

# ESTABLISHING P2 AND WASTE MINIMIZATION PROGRAMS

## INTRODUCTION

The first overall objective of any pollution management strategy is to bring a facility into compliance with environmental regulations. Simply stated, there are only two choices any company faces:

- Comply with environmental regulations and remain in business, or
- Don't comply, and face heavy fines, penalties, costly interruptions, or in the extreme, go out of business.

When a company approaches this objective with strategies based largely on end-of-pipe treatment technologies, it is addressing only the legal requirements for staying in business, and not growth. By repeatedly trying to meet more stringent effluent emission standards through the use of more advanced controls, a company is always on the defensive, i.e., playing catch-up with compliance requirements.

P2 and waste minimization strategies achieve the same end results as the application of control technologies (i.e., they help meet a compliance requirement), but they are more cost effective. The reason for this is that P2/waste minimization strategies reduce Tier 1 and 2 costs through savings not achievable through control technologies, which are simply add-on process components that impose additional demands on energy, materials, and labor. The savings can be applied toward reinvesting into modernization and improvements to operations, or in financing the implementation of an EMS (environmental management system). This enables a company to grow its operations.

P2 strategies also reduce or eliminate costs associated with future liabilities (Tier 3) and less tangible costs (Tier 4). In the ideal case, prevention eliminates waste and pollution altogether. Hence, issues such as third-party damages or joint and several liabilities for off-site damages are no longer a concern. When P2 strategies are employed, the owners/operators of facilities can exceed compliance requirements, because in the ideal case zero waste and pollution is the ultimate goal. Another way of looking at this is that when an organization focuses on continual reductions of waste and pollution, operating costs are steadily reduced over time, and profitability is maximized.

A P2 program consists of a systematic approach to identifying more cost-effective strategies and technologies for waste handling, then implementing those strategies and tracking their environmental and economic performances for the purposes of establishing new targets and goals, starting with the highest environmental priorities first, and then iteratively repeating the process for and applying lessons learned to successive pollution problems throughout the entire operation. Through the application of this iterative process, incremental savings are achieved with each new P2 activity. The savings are cumulative and hence, over time, represent significant capital returns that can be reinvested into a company's operations. Successive rounds of continual P2 improvements are what constitute the basis for an EMS.

## P2 DRIVERS

An overwhelming number of success stories illustrate the benefits of pollution prevention strategies. Many examples for a variety of industry categories are summarized in earlier publications devoted to this subject (Cheremisinoff, N. P., *Handbook of Pollution Prevention Practices*, 2001, and Cheremisinoff, N. P. and A. Bendavid-Val, *Green Profits: The Manager's Handbook for ISO 14001 and Pollution Prevention*, 2001). These case studies show distinct financial advantages to companies not only by identifying reductions in pollution and the costs associated with pollution management, but also through reduced raw material consumption, energy savings, reductions in treatment and disposal of wastes, and reductions in labor associated with environmental management. Many P2 and waste minimization strategies, such as substituting toxic materials with safer alternatives, do not require process changes, and as such are simple and cost very little to implement. The areas in which P2 has proven effective include the elimination and reduction of impacts from:

- Treatment, disposal, and associated labor costs
- Wildlife and habitat damage
- Property devaluation
- Remediation costs
- Civil and criminal fines
- Permitting fees
- Insurance costs
- Process outages and disruptions

There are case studies that testify to the fact that P2 benefits result in:

- **Enhanced public image**: consumers more favorably view businesses that adopt and practice P2 strategies, and the marketing of these practices can assist in increasing a company's profits.
- **Increased productivity and efficiency**: P2 assessments have proven helpful in identifying opportunities that decrease raw materials use, eliminate unnecessary operations, increase throughput, reduce off-spec product generation, and improve yields.
- **Reduced regulatory burden**: improving environmental performance and achieving performance goals that exceed compliance have been demonstrated in many P2 programs, which in turn reduce the costs of compliance,
- **Decreased liability**: handling hazardous and toxic materials brings along with it high liabilities should an accident such as a fire or explosion, or a major spill occur.
- **Improved environmental health and safety**: P2 practices can be applied to all forms of pollution media. Reductions in pollution minimize worker exposure and conserve resources and landfill space.

## DEVELOPING A P2 PROGRAM

The basic scheme for a P2 program involves the following:

1. Identifying and understanding the company's baseline costs for pollution and waste management. This includes an understanding of the total costs and the individual components contributing to overall costs for managing each environmental aspect.

2. Prioritizing environmental aspects of the company's operations. With infinite resources, all environmental aspects in even the largest companies can be addressed simultaneously. But no corporation has this luxury, and furthermore, there are other program priorities that compete for fixed budgets. In this regard, a P2 investment should be able to compete for budget approval just like any other capital project.

3. Working with the highest priority issues first, a company applies engineering and management expertise and tools to identify alternative approaches to pollution management within the hierarchy of environmental strategies.

4. With alternative strategies and technologies identified, a company performs an investment analysis to determine the financial attractiveness of the P2

investment alternatives. Those alternatives that are more financially attractive than the baseline strategies and technologies used become the recommendations for senior management to endorse and implement.

5. The entire process is then repeated within the company to address additional environmental aspects and also, as appropriate, rolled out to other parts of the company or other environmental and waste priorities in a process of continual improvement.

These five program elements have been organized by the authors into a three-phase plan that is referred to as the *P2 assessment.*

The P2 assessment is a systematic approach to evaluating alternative strategies that not only reduce pollution and wastes compared to baseline conditions or status quo, but are more cost effective than current technologies and strategies and/or reduce a company's risk in managing wastes. The assessment can be implemented by applying three phases sequentially:

- Preassessment
- Auditing
- Life-cycle costing analysis

## METHODOLOGY FOR P2 AUDITS

The following describes a step-by-step approach for carrying out the pollution prevention/waste minimization audit. It is designed to be generic and to apply to a broad spectrum of industries. The approach consists of three phases that are implemented in succession:

1. A preassessment phase for assessment preparation
2. A data collection phase to derive a material balance
3. A synthesis phase where the findings from material balances are translated into a waste reduction action plan

### Phase 1: The Preassessment

*Step 1: Assessment Focus and Preparation.* A thorough preparation for a pollution prevention audit is a prerequisite for an efficient and cost-effective study. Of particular importance is to gain support for the assessment from top-level management, and for the implementation of results; otherwise there will be no real action on recommendations. The pollution prevention auditing team should be identified. The number of people required on a team will depend on the size and complexity of the processes to be investigated. A pollution prevention audit of a small factory may be undertaken by one person with contributions from the employees. A more complicated process may require at least three to four people: technical staff, production employees, and an environmental specialist. Involving personnel from each stage of the manufacturing operations will increase employee awareness of waste reduction and promote input and support for the program.

The audit may require external resources, such as laboratory and possibly equipment for sampling and flow measurement. You should attempt to identify external resource requirements at the outset. Analytical services and equipment may not be available to a small factory. If this is the case, investigate the possibility of forming a pollution prevention association with other factories or industries; under this umbrella the external resource costs can be shared.

It is important to select the focus of your assessment at the preparation stage. You may wish the audit to cover a complete process or you may want to concentrate on a selection of unit operations within a process. The focus will depend on the objectives of the assessment. You may wish to look at waste minimization as a whole or you may wish to concentrate on particular wastes: for example, raw material losses, wastes that cause processing problems, wastes considered to be hazardous or for which regulations exist, and/or wastes for which disposal costs are high. A good starting point for designing a pollution prevention assessment is to determine the major problems/wastes associated with your particular process or industrial sector.

All existing documentation and information regarding the process, the plant or the regional industrial sector should be collated and reviewed as a preliminary step. Regional or plant surveys may have been undertaken; these could yield useful information indicating the areas for concern and will also show gaps where no data are available. The following prompts give some guidelines on useful documentation.

Is a site plan available?

- Are any process flow diagrams available?
- Have the process wastes ever been monitored -- do you have access to the records?
- Do you have a map of the surrounding area - indicating watercourses, hydrology, and human settlements?
- Are there any other factories/plants in the area which may have similar processes?
- What are the obvious wastes associated with your process?
- Where is water used in greatest volume?

- Do you use chemicals that have special instructions for their use and handling?
- Do you have waste treatment and disposal costs -- what are they?
- Where are your discharge points for liquid, solid, and gaseous emissions?

The plant employees should be informed that the assessment will be taking place, and they should be encouraged to take part. The support of the staff is imperative for this type of interactive study. It is important to undertake the assessment during normal working hours so that the employees and operators can be consulted, the equipment can be observed in operation, and, most importantly, wastes can be quantified.

*Step 2: Listing Unit Operations.* Your process will comprise a number of unit operations. A unit operation may be defined as an area of the process or a piece of equipment where materials are input, a function occurs and materials are output, possibly in a different form, state, or composition. For example, a process may comprise the following unit operations: raw material storage, surface treatment, rinsing, painting, drying, product storage, and waste treatment.

Any initial site survey should include a walk around the entire manufacturing plant in order to gain a sound understanding of all the processing operations and their interrelationships. This will help the assessment team decide how to describe a process in terms of unit operations. During this initial overview, it is useful to record visual observations and discussions and to make sketches of process layout, drainage systems, vents, plumbing and other material transfer areas. These help to ensure that important factors are not overlooked.

The assessment team should consult the production staff regarding normal operating conditions. The production or plant staff are likely to know about waste discharge points, and unplanned waste generating operations such as spills and washouts, and they can give the assessors a good indication of actual operating procedures. Investigations may reveal that night-shift procedures are different from day-shift procedures; also, a plant may disclose that actual material-handling practices are different from those set out in written procedures. A long-standing employee could give some insight into recurring process problems. In the absence of any historical monitoring this information can be very useful. Such employee participation must, however, be a nonblaming process; otherwise it will not be as useful as it could be. During the initial survey, note imminent problems that need to be addressed before the assessment is complete.

The audit team needs to understand the function and process variables associated with each unit operation. Similarly, all the available information on the unit operations and the process in general should be collated, possibly in separate files. It is useful to tabulate this information. Identification of materials handling operations (manual, automatic, bulk, drums, etc.) covering raw materials, transfer practices and products is also an important aspect which could usefully be included in the above tabulation as a prelude to development of a materials balance (Phase 2).

*Step 3: Constructing Process Flow Diagrams.* By connecting the individual unit operations in the form of a block diagram you can prepare a process flow diagram. Intermittent operations such as cleaning, make-up or tank dumping may be distinguished by using broken lines to link the boxes. For complex processes prepare a general flow diagram illustrating the main process areas and, on separate sheets of paper, prepare detailed flow diagrams for each main processing area.

Now decide on the level of detail that you require to achieve your objectives. It is important to realize that the less detailed or larger scale the assessment becomes, the more information is likely to be lost or masked by oversimplification. Establishing the correct level of detail and focusing in on specific areas is very important at an early stage. Pay particular attention to correcting any obvious waste arising which can be reduced or prevented easily, before proceeding to the development of a material balance (Phase 2).

If simple changes are made at this early stage, the resultant benefits will help enlist the participation and stimulate the enthusiasm of employees for the total pollution prevention assessment/reduction program.

### Phase 1. Summary

At the end of the P2 audit preassessment stage the team should be organized and be aware of the objectives of the pollution prevention assessment. Plant personnel should have been informed of the audit's purpose in order to maximize cooperation between all parties concerned. Any required financial resources should have been secured and external facilities checked out for availability and capability. The team should be aware of the overall history and local surroundings of the plant. The scope and focus of the audit should have been established, and a rough timetable worked out to fit in with production patterns. The audit team should be familiar with the layout of the processes within the plant and should have listed the unit operations associated with each process. Sources of wastes and their causes should also have been identified. It should be possible to draw process flow diagrams highlighting those areas to be covered in the pollution prevention assessment. Any very obvious waste saving measures which can be introduced easily should be implemented immediately. The findings of the Phase 1 investigations could usefully be presented to the management in the form of a brief preassessment report in order to reaffirm their commitment into the next phase.

### Phase 2: Material Balances: Process Inputs and Outputs

A material balance is defined as a precise account of the inputs and outputs of an operation. This phase describes a procedure for the collection and arrangement of input and output data. The procedure can be applied to derive the material balance of a plant, a process, or a unit operation. Note that infrequent outputs (e.g., the occasional dumping of an electroplating bath) may be as significant as continuous daily discharges and should therefore be accounted for in the material balance.

*Step 4: Determining Inputs.* Inputs to a process or a unit operation may include raw materials, chemicals, water, air, and power. The inputs to the process and to each unit operation need to be quantified. As a first step toward quantifying raw material usage, examine purchasing records. This rapidly gives us an idea of the sort of quantities involved. In many situations the unit operations where raw material losses are greatest are raw material storage and transfer. Look at these operations in conjunction with the purchasing records to determine the actual net input to the process.

Make notes regarding raw material storage and handling practices. Consider evaporation losses, spillages, leaks from underground storage tanks, vapor losses through storage tank pressure-relief vents, and contamination of raw materials. Often these can be rectified very simply. Record raw material purchases and storage and handling losses in a table in order to derive the net input to the process. Once the net input of raw materials to the process has been determined we can proceed with quantifying the raw material input to each unit operation. If accurate information about raw material consumption rates for individual unit operations is not available then we will need to take measurements to determine average figures. Measurements should be taken for an appropriate length of time. For example, if a batch takes 1 week to run, then measurements should be taken over a period of at least 3 weeks; these figures can be extrapolated for monthly, quarterly, or annual figures. Note that some quantification is possible by observation and some simple accounting procedures.

For solid raw materials, ask the warehouse operator how many sacks are stored at the beginning of the week or prior to using then in a unit operation; then ask him or her again at the end of the week or unit operation. Weigh a selection of sacks to check compliance with specifications.

For liquid raw materials such as water or solvents, check storage tank capacities and ask operators when a tank was last filled. Tank volumes can be estimated from the tank diameter and tank depth if automatic gauging is not used. Monitor the tank levels and the number of tankers arriving on site. While investigating the inputs, talking to staff, and observing the unit operations in action, the auditing team should be thinking about how to improve the efficiency of the unit operations.

The audit relies on information gathered in the field - by interviewing operators and various shop personnel. These interviews help the team to identify possible ways to save raw materials, reduce pollution, and conserve energy. These discussions should not be extemporaneous, but rather thought out in advance, and initially formulated during the walkthrough. It is advisable to have a list of questions and a checklist of issues for such meetings. Table 1 provides a sample list of questions which the reader can expand on and modify to make them more specific to the plant assessment.

The energy input to a unit operation should also be considered at this stage. Energy use and the potential for savings deserves a full assessment in its own right. For our discussions, we will focus on energy only as it relates to evaluating a P2 opportunity. In other words, our primary focus is on waste and pollution reduction opportunities; however, these could reduce energy costs as well. If energy usage is a particularly prominent factor, then you should recommend that a separate energy audit be undertaken.

Energy audits can focus on several opportunities within a process. The most obvious ones tend to be ways to reduce energy through improved operating efficiencies, by minimizing heat losses, changing fixed motors to variable speed drives, and incorporating automation techniques and tools that shut down or idle machinery during turnaround periods to name a few. There may also be opportunities where solid wastes have a heating value. These materials could be gasified or burned to generate low- to medium-Btu fuel gases that could be applied to CHP (combined heat and power) applications. In some situations it is feasible to convert the thermal energy into electrical and even generate a revenue stream by selling the electricity into a local grid.

Table 1. Sample Questions for Identifying Raw Materials Savings Opportunities

| | Lead Question | Follow-on Question |
|---|---|---|
| 1 | *Is the size of the raw material inventory appropriate to ensure that material-handling losses can be minimized?* | *How often is inventory checked?* |
| 2 | *Could transfer distances between storage and process or between unit operations be reduced to minimize potential wastage?* | *Are bins and silos a source of product losses?* |
| 3 | *Do the same tanks store different raw materials depending on the batch product?* | *Is there a risk of cross contamination?* |
| 4 | *Are sacks of materials emptied or is some material wasted?* | |
| 5 | *Are viscous raw material used on site?* | *Is it possible to reduce residual wastage in drums?* |
| 6 | *Is the raw material storage area secure?* | *Could a building be locked at night, or could an area be fenced off to restrict access?* |
| 7 | *How could the raw materials be protected from direct sunlight or from heavy downpours?* | |
| 8 | *Is dust from stockpiles a problem?* | |
| 9 | *Is the equipment used to pump or transfer materials working efficiently?* | *Is it maintained regularly?* |
| 10 | *Could spillages be avoided?* | *Is there a formal spill handling procedure?* |
| 11 | *Is the process adequately manned?* | *What is the experience level of operators?* |
| 12 | *How could the input of raw materials be monitored?* | |
| 13 | *Are there any obvious equipment items in need of repair?* | *Is there a regularly scheduled maintenance program? Describe.* |
| 14 | *Are pipelines self-draining?* | *Where does the residue go?* |
| 15 | *Is vacuum pump water recirculated?* | |

The input data collected for the material balance can be recorded on the process flow diagram or in tabular form on a spreadsheet.

Water is frequently used in the production process, for cooling, gas scrubbing, washouts, product rinsing, and steam cleaning. This water usage needs to be quantified as an input. Some unit operations may receive recycled wastes from other unit operations. These also represent an input. Steps 5 and 6 describe how these two factors should be included in the audit.

*Step 5: Recording Water Usage.* The use of water, other than for a process reaction, is a factor that should be covered in all pollution prevention assessments. The use of water to wash, rinse and cool is often overlooked, although it represents an area where waste reductions can frequently be achieved simply and cheaply.

Consider these general points about the site water supply before assessing the water usage for individual units.

- Identify the water sources within the plant operations.
- Is water extracted directly from a borehole, river or reservoir; is water stored on site in tanks or in a lagoon?
- What is the storage capacity for water on site?
- How is water transferred -- by pump, by gravity, manually?
- Is rainfall a significant factor on site?

For each unit operation consider the following,

- What is water used for in each operation - cooling, gas scrubbing, washing, product rinsing, dampening stockpiles, general maintenance, safety quench, etc.?
- How often does each action place?
- How much water is used for each action?

It is unlikely that the answers to these questions will be readily available -- you may need to undertake a monitoring program to assess the use of water in each unit operation. Again, the measurements must cover a sufficient period of time to ensure that all actions are monitored. Pay particular attention to intermittent actions such as steam cleaning and tank washout - water use is often indiscriminate during these operations. Find out when these actions will be undertaken so that detailed measurements can be made. Record water usage information in a tabular form -- ensure that the units used to describe intermittent actions indicate a time period. Make sure that all measurements used for recording data in Table 7 are standard (e.g., m3/day or m3/yr, etc.). Using less water can be a cost-saving exercise. In many older plant operations water conservation programs are often overlooked. Even something as straightforward as a valve maintenance program can result in significant reductions in water consumption. Consider the following points while investigating water use:

- Tighter control of water use can reduce the volume of wastewater requiring treatment and result in cost savings - in the extreme, it can sometimes reduce volumes and increase concentrations to the point of providing economic material recovery in place of costly wastewater treatment.
- Attention to good housekeeping practices often reduces water usage and, in turn, the amount of wastewater passing to drains.
- The cost of storing wastewater for subsequent reuse may be far less than the treatment and disposal costs.
- Counter-current rinsing and rinse water reuse are useful tips for reducing water usage.

*Step 6: Measuring Current Levels of Waste Reuse/Recycling.* Some wastes lend themselves to direct reuse in production and may be transferred from one unit to another; others require some modifications before they are suitable for reuse in a process. These reused waste streams should be quantified. If reused wastes are not properly documented double-counting may occur in the material balance particularly at the process or complete plant level; that is, a waste will be quantified as an output from one process and as an input to another. The reuse or recycling of wastes can reduce the amount of fresh water and raw materials required for a process. While looking at the inputs to unit operations think about the opportunities for reusing and recycling outputs from other operations.

*Steps 4, 5, and 6 Summary.* By the end of Step 6 you should have quantified all your process inputs. The net input of raw materials and water to the process should be established having taken into account any losses incurred at the storage and transfer stages. Any reused or recycled inputs should be documented. All notes regarding raw material handling, process layout, water losses, obvious areas where problems exist should all be documented for consideration in Phase 3.

*Step 7: Quantifying Process Outputs.* To calculate the second half of the material balance, the outputs from unit operations and the process as a whole need to be quantified. Outputs include primary product, by-products, wastewater, gaseous wastes (emissions to atmosphere), liquid and solid wastes which need to be stored and/or sent off-site for disposal, and reusable or recyclable wastes.

The assessment of the amount of primary product or useful product is a key factor in process or unit operation efficiency. If the product is sent off-site for sale, then the amount produced is likely to be documented in company records. However, if the product is an intermediate to be input to another process or unit operation, then the output may not be so easy to quantify. Production rates will have to be measured over a period of time. Similarly, the quantification of any by-products may require measurement.

*Step 8: Accounting for Wastewater.* On many sites significant quantities of both clean and contaminated water are discharged to sewer or to a watercourse. In many cases, this wastewater has environmental implications and incurs treatment costs. In addition, wastewater may wash out valuable unused raw materials from the process areas. It is extremely important to know how much wastewater is going down the drain and what the wastewater contains. The wastewater flows, from each unit operation as well as from the process as a whole, need to be quantified, sampled, and analyzed.

Identify the effluent discharge points; that is, where does wastewater leave the site? Wastewater may go to an effluent treatment plant or directly to a public sewer or watercourse. One factor that is often overlooked is the use of several discharge points - *it is important to identify the location, type, and size of all discharge flows*. Identify where flows from different unit operations or process areas contribute to the overall flow. In this way, it is possible to piece together the drainage network for your site. This can lead to startling discoveries of what goes where! Once the drainage system is understood, it is possible to design an appropriate sampling and flow measurement program to monitor the wastewater flows and strengths from each unit operation.

Plan your monitoring program thoroughly and try to take samples over a range of operating conditions such as full production, startup, shutdown and washing out. In the case of combined stormwater and wastewater drainage systems, ensure that sampling and flow measurements are carried out in dry weather. For small or batch wastewater flows it may be physically possible to collect all the flow for measurement using a pail and wristwatch. Larger or continuous wastewater flows can be assessed using flow measurement techniques.

The sum of the wastewater generated from each unit operation should be approximately the same as that input to the process. As indicated in Step 6, note that double-counting can occur where wastewater is reused. This emphasizes the importance of understanding your unit operation and their interrelationships.

The wastewater should be analyzed to determine the concentration of contaminants. You should include wastewater analyses such as:

- pH
- Chemical oxygen demand (COD)

- Biochemical oxygen demand ($BOD_5$)
- Suspended solids
- Grease and oil

Other parameters that should be measured depend on the raw material inputs. For example, an electroplating process is likely to use nickel and chromium. The metal concentrations of the wastewater should be measured to ensure that the concentrations do not exceed discharge regulations, but also to ensure that raw materials are not being lost to drain. Any toxic substances used in the process should be measured.

Take samples for laboratory analysis. Composite samples should be taken for continuously running wastewater. For example, a small volume, 100 ml, may be collected every hour through a production period of 10 hours to gain a 1 liter composite sample. The composite sample represents the average wastewater conditions over that time. Where significant flow variations occur during the discharge period, consideration should be given to varying the size of individual samples in proportion to flow rate in order to ensure that a representative composite sample is obtained. For batch tanks and periodic drain down, a single spot sample may be adequate (check for variations between batches before deciding on the appropriate sampling method). Wastewater flows and concentrations should be tabulated.

*Step 9: Accounting for Gaseous Emissions.* To arrive at an accurate material balance some quantification of gaseous emissions associated with the process is necessary. It is important to consider the actual and potential gaseous emissions associated with each unit operation from raw material storage through to product storage. Gaseous emissions are not always obvious and can be difficult to measure. Where quantification is impossible, estimations can be made using stoichiometric information. The following example illustrates the use of indirect estimation.

*Consider coal burning in a boiler house. The assessor may not be able to measure the mass of sulfur dioxide leaving the boiler stack because of problems of access and lack of suitable sampling ports on the stack. The only information available is that the coal is of soft quality containing 3% sulfur by weight and, on average, 1000 kg of coal is burned each day.*

First calculate the amount of sulfur burned:

1000 kg coal x 0.03 kg sulfur/kg coal
= 30 kg sulfur/day.

The combustion reaction is approximately:

$S + O_2 = SO_2$

The number of moles of sulfur burned equals the number of moles of sulfur dioxide produced. The atomic weight of sulfur is 32 and molecular weight of sulfur dioxide is 64. Therefore:

kg-mole S = 30 kg/32 kg per kg-mole = kg-mole Of $SO_2$ formed

kg $SO_2$ formed = (64 kg $SO_2$/kg-mole) x kg-moles$SO_2$
= 64 x 30/32 = 60 kg

*Thus, it may be estimated that an emission of 60 kg sulfur dioxide will take place each day from the boiler stack.*

These types of stoichiometric calculations are commonplace and can provide reliable estimates for the material balance. As with an calculation methods, one should list the assumptions in order to qualify the accuracy of the estimate. Limited field measurements can always be done later on to verify the estimated emissions. Record the quantified emission data in tabular form and indicate which figures are estimates and which are actual measurements. The assessor should consider qualitative characteristics at the same time as quantifying gaseous wastes. The following are some typical questions to address when developing the material balance around the gaseous emissions components.

- Are odors associated with a unit operation?
- Are there certain times when gaseous emissions are more prominent -- are they linked to temperature?
- Is any pollution control equipment in place?
- Are gaseous emissions from confined spaces (including fugitive emissions) vented to the outside?
- If gas scrubbing is practiced, what is done with the spent scrubber solution? Could it be converted to a useful product?
- Do employees wear protective clothing, such as masks?

*Step 10: Accounting for Off-Site Wastes.* Your process may produce wastes which cannot be treated on-site. These need to be transported off-site for treatment and disposal. Wastes of this type are usually nonaqueous liquids, sludges, or solids. Often, wastes for off-site disposal are costly to transport and to treat, and they represent a third-party liability. Therefore, minimization of these wastes yields direct cost benefits, both present and future. Measure the quantity and note the composition of any wastes associated with your process which need to be sent for off-site disposal. Record your results in a table.

It is useful to ask the following questions during the data-collection stage:

- Where does the waste originate from within our process operations?
- Could the manufacturing operations be optimized to produce less waste?
- Could alternative raw materials be used which would produce less waste?
- Is there a particular component that renders the whole waste hazardous - could this component be isolated? This can be a key question. Under RCRA for example, if we have a waste with only 1% of a carcinogenic material as a component, then the entire waste is classified as carcinogenic. By eliminating the hazardous, regulated component, we potentially eliminate a much larger waste problem.
- Does the waste contain valuable materials that could be recovered or possibly sold off-site?
- Wastes for off-site disposal need to be stored on-site prior to dispatch. Does storage of these wastes cause additional emission problems? For example, are solvent wastes stored in closed tanks?
- How long are wastes stored on-site, and are we in compliance with storage requirements under RCRA?
- Are stockpiles of solid waste secure or are dust storms a regular occurrence? Also, do waste piles result in stormwater runnoff issues?

*Steps 7, 8, 9, and 10 Summary.* At the end of Step 10 the pollution prevention assessment team should have collated all the information required for evaluating a material balance for each unit operation and for a whole process. All actual and potential wastes should be quantified. Where direct measurement is not possible, estimates based on stoichiometric information should be made. The data should be arranged in clear tables with standardized units. Throughout the data collection phase the assessors should make notes regarding actions, procedures and operations that could be improved.

*Step 11: Assembling Input and Output Information for Unit Operations.* From the law of conservation of mass, the total mass that goes into a process must equal the total of mass that comes out. Prepare a material balance at a scale appropriate for the level of detail required in your study. For example, you may require a material balance for each unit operation or one for a whole process may sufficient. Preparing a material balance is designed to gain a better understanding of the inputs and outputs, especially waste, of a unit operation, such that areas where information is inaccurate or lacking can be identified. Imbalances require further investigation. Do not expect a perfect balance -- your initial balance should be considered as a rough assessment to be refined and improved. Assemble the input and output information for each unit operation and then decide whether all the inputs and outputs need to be included in the material balance. For example, this is not essential where the cooling water input to a unit operation equals the cooling water output.

Make sure to standardize units of measurement (liters, tons, or kilograms) on a per day, per year, or per batch basis. Finally, summarize the measured values in standard units by reference to your process flow diagram. It may have been necessary to modify your process flow diagram following the in-depth study of the plant.

*Step 12: Deriving a Preliminary Material Balance for Unit Operations.* Now it is possible to complete a preliminary material balance. For each unit operation utilize the data developed in Steps 1 through 10 and construct the material balance. Display your information clearly.

Note that a material balance will often need to be carried out in weight units since volumes are not always conserved. Where volume measurements have to be converted to weight units, take account of the density of the liquid, gas, or solids concerned. Once the material balance for each unit operation has been completed for raw material inputs and waste outputs it might be worthwhile to repeat the procedure with respect to each contaminant of concern. It is highly desirable to carry out a water balance for all water inputs and outputs to and from unit operations because water imbalances may indicate serious underlying process problems such as leaks or spills. The individual material balances may be summed to give a balance for the whole process, a production area or factory.

*Step 13: Evaluating the Material Balance.* The individual and sum totals making up the material balance should be reviewed to determine information gaps and inaccuracies. If you do have a significant material imbalance then further investigation is needed. For example, if outputs are less than inputs look for potential losses or waste discharges (evaporation, or fugitive emissions not accounted for such as significant valve, pump, and reactor seal leakage, etc.). Outputs may appear to be greater than inputs if large measurement or estimating errors are made or some inputs have been overlooked.

At this stage you should take time to reexamine the unit operations to attempt to identify where unnoticed losses may be occurring. It may be necessary to repeat some data collection activities. Remember that you need to be thorough and consistent to obtain a satisfactory material balance. The material balance not only reflects the adequacy of your data collection, but by its very nature, ensures that you have a sound understanding of the processes involved.

*Step 14: Refining the Material Balance.* Now you can reconsider the material balance equation by adding those additional factors identified in the previous step. If necessary, estimates of unaccountable losses will have to be calculated. Note that, in the case of relatively simple manufacturing plants, preparation of a preliminary material balance and its refinement (Steps 13 and 14) can usefully be combined. For more complex pollution prevention assessments, however, two separate steps are likely to be more appropriate. An important rule to remember is that the inputs should ideally equal the outputs, but in practice this will rarely be the case and some judgment will be required to determine what level of accuracy is acceptable.

In the case of high concentrations or hazardous wastes, accurate measurements are needed to develop cost-effective waste reduction options. It is possible that the material balance for a number of unit operations will need to be repeated. Again, continue to review, refine, and, where necessary, expand your database. The compilation of accurate and comprehensive data is essential for a successful pollution prevention assessment and subsequent waste reduction action plan. But remember - you cannot reduce what you do not know is there!

*Steps 11, 12, 13, and 14 Summary.* By the end of Step 14, you should have assembled information covering process inputs and process outputs. These data should be organized and presented clearly in the form of material balances for each unit operation. These data form the basis for the development of an action plan for waste minimization. We now are ready to move onto the next phase in the process - which is to develop P2/waste minimization options, and to evaluate their financial merits.

### Phase 3: Synthesis

Phases 1 and 2 have covered planning and undertaking a pollution prevention audit, resulting in the preparation of a material balance for each unit operation. Phase 3 represents the interpretation of the material balance to identify process areas or components of concern. The material balance focuses the attention of the assessor. The arrangement of the input and output data in the form of a material balance facilitates your understanding of how materials flow through a production process. To interpret a material balance it is necessary to have an understanding of normal operating performance. How can you assess whether a unit operation is working efficiently if you do not know what is normal? Therefore, it is essential that a member of your team must have a good working knowledge of the process. To an experienced process engineer, with the aid of the team members - the material balance will indicate areas for concern and help to prioritize problem wastes.

You should use the material balance to identify the major sources of waste, to look for deviations from the norm in terms of waste production, to identify areas of unexplained losses and to pinpoint operations which contribute to flows that exceed national, local or site discharge regulations. Also, a good thing to remember is that from a practical standpoint, process efficiency is synonymous with waste minimization.

Different waste reduction measures require varying degrees of effort, time and financial resources. They can be categorized as two groups:

- *Group 1:* Obvious waste reduction measures, including improvements in management techniques and house-keeping procedures that can be implemented cheaply and quickly. These can be referred to as Low Cost/No Cost.
- *Group 2:* Long-term reduction measures involving process modifications or process substitutions to eliminate problem wastes.

Increased reuse/recycling to reduce waste falls between the immediate and the more substantial waste reduction measures. Steps 15, 16, and 17 describe how to identify waste reduction measures.

*Step 15: Examining Obvious Waste Reduction Measures.* It may have been possible to implement very obvious waste reduction measures already, before embarking on obtaining a material balance (refer back to Step 3). Now consider the material balance information in conjunction with visual observations made during the whole of the data collection period in order to pinpoint areas or operations where simple adjustments in procedure could greatly improve the efficiency of the process by reducing unnecessary losses.

Use the information gathered for each unit operation to develop better operating practices for all units. Significant waste reductions can often be achieved by improved operation, better handling and generally taking more care in performing operations and handling materials. Table 2 provides a list of waste reduction hints that can be implemented immediately with no or only small extra costs.

Table 2. Common Waste Reduction Hints

*Specifying and Ordering Materials*

- Do not over-order materials especially if the raw materials or components can spoil or are difficult to store.
- Try to purchase raw materials in a form which is easy to handle, for example, pellets instead of powders.
- It is often more efficient and certainly cheaper to buy in bulk.

*Receiving Materials*

- Demand quality control from suppliers by refusing damaged, leaking or unlabeled containers.
- Undertake a visual inspection of all materials coming on to the site.
- Check that a sack weighs what is should weigh and that the volume ordered is the volume supplied.
- Check that composition and quality are correct.

*Material Storage*

- Install high-level control on bulk tanks to avoid overflows.
- Bund tanks to contain spillages.
- Use tanks that can be pitched and elevated, with rounded edges for ease of draining and rinsing.
- Dedicated tanks, receiving only one type of material, do not need to be washed out as often as tanks receiving a range of materials.
- Make sure that drums are stored in a stable arrangement to avoid damaging drums while in storage.
- Implement a tank checking procedure -- dip tanks regularly and document to avoid discharging a material into the wrong tank.
- Evaporation losses are reduced by using covered or closed tanks.

*Material and Water Transfer and Handling*

- Minimize the number of times materials are moved on site.
- Check transfer lines for spills and leaks.
- Is flexible pipework too long?
- Catch drainings from transfer hoses.
- Plug leaks and fit flow restrictions to reduce excess water consumption.

*Process Control*

- Design a monitoring program to check the emissions and wastes from each unit operation.
- Regular maintenance of all equipment will help to reduce fugitive process losses.
- Feedback on how waste reduction is improving the process motivates the operators - it is vital that employees be informed of why actions are taken and what it is hoped to achieve.

*Cleaning Procedures*

- Minimize the amount of water used to wash out and rinse vessels -- on many sites indiscriminate water use contributes a large amount to wastewater flows. Ensure that hoses are not left running by fitting self-sealing valves.
- Investigate how washing water can be contained and used again before discharge to drains. The same applies to solvents used to clean; these can often be used more than once.

Tightening up housekeeping procedures can reduce waste considerably. Simple, quick adjustments could be made to your process to achieve a rapid improvement in process efficiency. However, where such obvious reduction measures do not solve the entire waste disposal problem, more detailed consideration of waste reduction options will be needed. These are addressed in Steps 16-18.

*Step 16: Targeting and Characterizing Problem Wastes.* Use the material balance for each unit operation to pinpoint the problem areas associated with your process. The material balance exercise may have brought to light the origin of wastes with high treatment costs or may indicate which wastes are causing process problems in which operations. The material balance should be used for your priorities for long-term waste reduction.

At this stage, it may be worthwhile considering the underlying causes as to why wastes are generated and the factors which lead to these; for example, poor or outdated technology, lack of maintenance, and noncompliance with company procedures may be contributing or even underlying factors. Additional sampling and characterization of your wastes might be necessary involving more in-depth analysis to ascertain the exact concentrations of contaminants. A worthwhile exercise is to list the wastes in order of priority for reduction actions. This will alert both the team and management to the most costly waste issues and also help to better define what resources may be needed to address them.

*Step 17: Segregation.*

Segregation of wastes can offer enhanced opportunities for recycling and reuse with resultant savings in raw material costs. Concentrated simple wastes are more likely to be of value than dilute or complex wastes. In contrast, the practice of mixing wastes can aggravate pollution problems. If a highly-concentrated waste is mixed with a large quantity of weak, relatively uncontaminated effluent the result is a larger volume of waste requiring treatment. Isolating the concentrated waste from the weaker waste can reduce treatment costs. The concentrated waste could be recycled/reused or may require physical, chemical and biological treatment to comply with discharge consent levels, whereas the weaker effluent could be reused or may only require settlement before discharge. Therefore, waste segregation can provide more scope for recycling and reuse while at the same time reducing treatment costs. Step 17 then is to review your waste collection and storage facilities to determine if waste segregation is possible. If so, then adjust your list of priority wastes accordingly.

*Step 18: Developing Long-Term Waste Reduction Options.* Waste problems that cannot be solved by simple procedural adjustments or improvements in housekeeping practices will require more substantial long-term changes. It is necessary to develop possible prevention options for the waste problems. Process or production changes which may increase production efficiency and reduce waste generation include:

- Changes in production process - continuous versus batch
- Equipment and installation changes
- Changes in process control - automation
- Changes in process conditions such as retention times, temperatures, agitation, pressure, catalysts
- Use of dispersants in place of organic solvents where appropriate
- Reduction in the quantity or type of raw materials used in production
- Raw material substitution through the use of wastes as raw materials or the use of different raw materials that produce less waste or less hazardous waste
- Process substitution with cleaner technology

Waste reuse can often be implemented if materials of sufficient purity can be concentrated or purified. Technologies such as reverse osmosis, ultrafiltration, electrodialysis, distillation, electrolysis, and ion exchange may enable materials to be reused and reduce or eliminate the need for waste treatment. Where waste treatment is necessary, a variety of technologies should be considered. These include physical, chemical, and biological treatment processes. In some cases the treatment method can also recover valuable materials for reuse. Another industry or factory may be able to use or treat a waste that you cannot treat on-site. It may be worth investigating the possibility of setting up a waste exchange bureau as a structure for sharing treatment and reuse facilities.

*Steps 15, 16, 17, and 18 Summary.* At the end of Step 18 you should have identified all the waste reduction options which could be implemented. It is now time to begin assessing whether options identified have economic incentives worth going after.

*Step 19: Environmental and Economic Evaluation of Waste Reduction Options.* In order to decide which options should be developed to formulate a waste reduction action plan each option should be considered in terms of environmental and economic benefits. It is often taken for granted that reduction of a waste will have environmental benefits. This is generally true; however, there are exceptions to the rule. For example, reducing one waste may give rise to pH imbalances or may produce another waste that is more difficult to treat, resulting in a net environmental disadvantage. Hence, there may be environmental trade-offs between status quo and the alternatives identified. In many cases, the benefits may be obvious such as the result of the removal of a toxic element from an aqueous effluent by segregating the polluted waste or by changing the process in such a way that the waste is prevented. In other cases the environmental benefits may be less tangible. Creating a cleaner, healthier workplace will increase production efficiency but this may be difficult to quantify. For each option a series of questions or issues should be considered.

Consider the effect of each option on the volume and degree of contamination of process wastes:

- Does a waste reduction option have cross-media effects? For example, does the reduction of a gaseous waste produce a liquid waste?
- Does the option change the toxicity, degradability, or treatability of the wastes?
- Does the option use more or fewer nonrenewable resources?
- Does the option use less energy?

The LCA principles outlined below should be applied at this stage. A comparative economic analysis of the waste reduction options and the existing situation should be undertaken. Where benefits or changes cannot be quantified (e.g., reduction in future liability, worker health and safety costs) some form of qualitative assessment should be made.

Economic evaluations of waste reduction options should involve a comparison of operating costs to illustrate where cost savings would be made. For example, a waste reduction measure that reduces the amount of raw material lost to drain during the process results in reduced raw material costs. Raw material substitution or process changes may reduce the amount of solid waste that has to be transported off-site. Therefore, the transport costs for waste disposal would be reduced.

In many cases, it is appropriate to compare the waste treatment costs under existing conditions with those associated with the waste reduction option. The size of a treatment plant and the treatment processes required may be altered significantly by the implementation of waste reduction options. This should be considered in an economic evaluation.

Calculate the annual operating costs for the existing process indicating waste treatment and estimate how these would be altered with the introduction of waste reduction options. Tabulate and compare the process and waste treatment operating costs for both the existing and proposed future waste management options. In addition, if there are any monetary benefits (e.g., recycled or reused materials or wastes), then these should be subtracted from the total process or waste treatment costs as appropriate.

Now that you have determined the likely savings in terms of annual process and waste treatment operating costs associated with each option, consider the necessary investment required to implement each option. Investment can be assessed by looking at the payback period for each option. Recall that payback period is the time taken for a project to recover its financial outlay. A more detailed investment analysis may involve an assessment of the internal rate of return (IRR) and net present value (NPV) of the investment based on discounted cash flows. An analysis of investment risk allows you to rank the options identified. Consider the environmental benefits and the savings in process and waste treatment operating costs along with the payback period for an investment, to decide which options are viable candidates. Once this is done, the audit team can develop draft recommendations to be included in the final report and presentation to management.

*Step 20: Developing and Implementing An Action Plan: Reducing Wastes and Increasing Production Efficiency.* Consider the immediate reduction measures identified in Step 15 along with the long-term waste reduction measures that have been evaluated in Steps 18 and 19. These measures should form the basis of the waste reduction action plan. Discuss your findings with members of staff and develop a workable action plan. Prepare the ground for the waste reduction action plan. Its implementation should be preceded by an explanation of the objectives behind undertaking a pollution prevention assessment. It is necessary to convince those who must work to new procedures that the change in philosophy from end-of-pipe treatment to waste prevention makes sense and serves to improve efficiency. Use posters around the site to emphasize the importance of waste reduction to minimize production and waste treatment/disposal costs and, where appropriate, for improving the health and safety of company personnel. Set out the intended action plan within an appropriate schedule. Remember it may take time for the staff to feel comfortable with a new way of thinking. Therefore, it is a good idea to implement waste reduction measures slowly but consistently to allow everyone time to adapt to these changes.

Set up a monitoring program to run alongside the waste reduction action plan so that actual improvements in process efficiency can be measured. For multiple pollution prevention projects, a P2 matrix is a good way to track and report overall performance. Relay these results back to the workforce as evidence of the benefits of waste reduction. Adopt an internal record keeping system for maintaining and managing data to support material balances and waste reduction assessments.

It is likely that you will have highlighted significant information gaps or inconsistencies during the pollution prevention assessment investigations. You should concentrate on these gaps and explore ways of developing the additional data. Ask yourself repeatedly - is outside help required?

A good way of providing waste reduction incentives is to set up an internal waste charging system, in which those processes that create waste in great volume or that are difficult and expensive to handle must contribute to the treatment costs on a proportional basis. Another method of motivating staff is to offer financial reward for individual waste-saving efforts, drawing on the savings gained from implementing waste reduction measures.

Pollution prevention assessments/audits should be a regular event -- attempt to develop a specific pollution prevention assessment approach for your own situation, keeping abreast of technological advances that could lead to waste reduction and the development of cleaner products. Train process employees to undertake material balance exercises. Training people who work on the process to undertake a pollution prevention assessment will help to raise awareness in the workforce. Without the support of the operators waste reduction actions will be ineffectual - these are the people who can really make a difference to process performance.

*Step 20: Summary*. The key elements in the final step of the auditing process are:

- Prepare the ground for the waste reduction action plan, ensuring that support for the assessment, and implementation of the results, is gained from senior management.
- Implement the plan slowly to allow the workforce to adjust.
- Monitor process efficiency. Relay results back to the workforce to show them the direct benefits.
- Train personnel to undertake your own pollution prevention assessment for waste reduction.

Although there are variations of the three-phase auditing process described in this chapter, the general philosophy and protocol are similar. A key concept to bear in mind is that the audit itself is only a tool. In order for pollution prevention to work, there must be strong management support, and there must be a team approach to implementing the audit. Without this mix, the process simply will not yield positive results.

## APPLICATION OF LIFE-CYCLE TOOLS

The application of life-cycle tools enables logical decisions on technology investments aimed at lowering the costs associated with waste management. By applying such tools, comparisons between alternative strategies for waste management and current practices can be made. Waste and pollution management strategies involve investments into technologies that are relied upon for many years. They are long-term investments, and as such require careful examination in order to select the most cost-effective approach.

The pre-assessment phase of the P2 assessment generally presents opportunities for cost savings in the form of no-cost/low- to moderate-cost initiatives. As many of these as possible should be implemented early on to help offset expenditures. These early returns also help to build the momentum needed by staff and management for further support of the continual improvement cycle. Many no-cost/low-cost P2 initiatives are housekeeping actions that provide incremental savings in materials or reductions in waste, energy, and pollution. Most of these opportunities tend to have relatively small economic benefits. As stand-alone initiatives they offer relatively small financial returns, even though their simple returns on investment or payback periods are oftentimes highly attractive. If, however, only five P2 initiatives are identified at one facility, each with average savings of between $10,000 and $20,000 per year, then collectively they add up to between $50,000 and $100,000. These represent significant offset costs for larger scale P2 initiatives, which may require substantial capital.

### DEVELOPING AND PLANNING HIGHER-COST P2 INITIATIVES

Developing and planning for higher-cost P2/waste minimization initiatives is best accomplished during the third phase of the P2 assessment -- that is, during the *life-cycle costing analysis*. Figure 1 summarizes series of steps for developing and planning higher-cost P2 initiatives. Engineering judgment should be heavily relied upon during this step to devise alternative strategies to replace pollution control technologies and improve overall efficiency. These initiatives should be bundled to form the initial basis for an overall strategy for waste reduction and P2. For those initiatives where the EMS/P2 Committee has the most confidence that recommendations are technically feasible, life-cycle costing and investment planning tools should be applied to assess the financial attractiveness of investments (Step 22). Other initiatives may require a *proof-of-principle* (POP) test. Some initiatives may require demonstration to gain sufficient confidence that they can be implemented on a commercial scale. This is known as a proof-of-principle exercise, or POP.

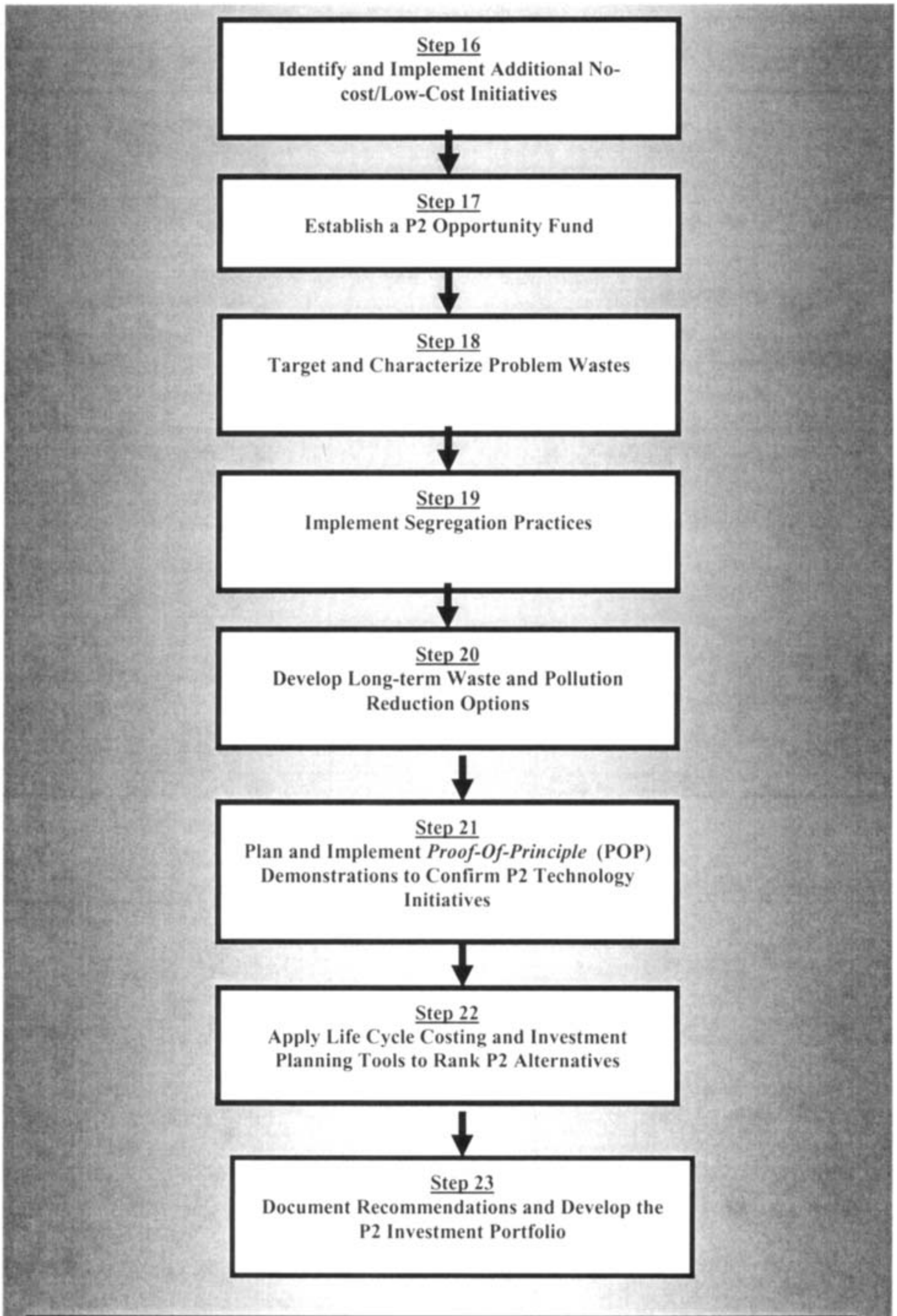

Figure 1. Third phase of a P2 assessment – the life-cycle cost analysis.

POPs may take the form of plant trials or a combination of plant and customer trials, or they may be preceded by bench-scale tests and/or trials in semi-works operations. The amount of effort and cost needed to confirm the feasibility and reliability of a proposed initiative depends on the complexity of the recommendations and the manufacturing process, as well as industry-specific regulations. In the pharmaceutical industry, for example, FDA (Food and Drug Administration) regulations generally mandate that even small proposed process or ingredient changes undergo formal approval including product testing before changes can be implemented. Many defense contract related industries have similar restrictions, which can greatly add to the costs for such technical feasibility studies. The company should carefully plan POP exercises to ensure that up-front costs are minimized. Standard engineering tools like design-for-experiments (DOE) should be applied to define the minimum number of plant and customer trials needed to demonstrate a technology or change to the manufacturing process.

The application of DOE in the planning stage will minimize the disruption of normal plant manufacturing campaigns, reduce disruption of customer operations and sales, and enable cost-effective feasibility studies to be implemented. If there is a need for further commercialization activities, then a separate program along with costs should be defined and made as a part of the overall recommendations to management under the P2 Investment Portfolio. The analysis of investment decisions and life-cycle costing (LCC, also life-cycle costs) are closely related techniques for evaluating investments involving expenditures for equipment, installation, service and/or training, etc. that have future benefits or will impact future costs. Readers familiar with business financial management will recognize the process of evaluating and selecting from among investment alternatives having the same objectives as *capital budgeting*. Among engineers this process is often referred to as *engineering economic analysis*. Whatever the term, this process of economic evaluation and comparison of investment alternatives encompasses a collection of analytical techniques that are tools for investment decision making. These tools enable a company to assess the financial benefits of alternative pollution management strategies and/or to compare these to the current situation. By ranking the potential investments in terms of costs, cost savings, and potential for reducing risk of environmental liability, an EMS/P2 Committee can recommend a "P2 investment portfolio" to top management. The objective of behind a P2 assessment is to recommend a series of P2 investments from which top management can select and allocate funds for implementation. The essence of any investment is a sacrifice now in favor of future benefits. A typical investment decision asks the fundamental question, do the future net benefits from the investment outweigh the initial costs? Benefits may be in the form of additional future income or revenue, or they may be intangible and possibly nonpecuniary in nature. LCC addresses the question of how best to accomplish a particular task. In other words, it assists in defining the least-cost method, taking into consideration both the initial outlay and future operating costs. LCC also involves risk assessment, in the sense that some of the strategies or initiatives under consideration will require larger initial outlays but achieve lower future costs than others. In developing criteria for an investment portfolio the EMS/P2 Committee must focus on the direct costs for investments, and on the potential for reducing long-term liabilities. This requires that attention to be given to the four cost tiers. Table 3 provides a summary of those cost/benefit tiers.

Table 3. Pollution Cost Tiers

| **Cost tier** | **Cost category** | **Typical cost components** |
|---|---|---|
| 1 | Usual or normal | Direct labor |
| | | Raw materials |
| | | Energy |
| | | Capital equipment |
| | | Site preparation |
| | | Tie-ins |
| | | Employee training |
| | | Permits |
| 2 | Hidden or direct | Monitoring |
| | | Permitting fees |
| | | Environmental transformation |
| | | Environmental impact assessments |
| | | H&S assessments |
| | | Service agreements |
| | | Legal |
| | | Control instrumentation |
| | | Maintenance and replacement |
| | | Reporting and recordkeeping |
| 3 | Future liabilities | Remedial actions |
| | | Personal injury |
| | | Health risks and injury to the public |
| | | More stringent compliance requirements |
| | | Inflation |
| 4 | Less tangible | Consumer response and loss of investor confidence |
| | | Employee relations |
| | | Establishing and extending lines of credit |
| | | Property values |
| | | Insurance premiums |
| | | Frequent environmental inspections and penalties |
| | | Leverage in negotiating with environmental regulators |

Tier 1 and 2 costs can be handled in a normal LCC calculation to identify the least cost initiatives when compared to a base case or among themselves. With the exception of inflation, Tier 3 and 4 cost/benefits must be addressed in other ways. These are best accounted for in the overall investment analysis by assigning levels of risks to supplement investment decisions. The levels of risk of certain liabilities or future events can be devised based on probabilities, which in turn can be qualified by the application of confidence limits.

An illustration of this is a company that is responsible for operations involving numerous USTs (underground storage tanks) that handle hazardous and regulated materials. A review of company historical records and/or industry trends will reveal the enormous costs associated with remediating contaminated groundwaters, plus the legal liabilities associated with off-site property damages and litigations stemming from leaking USTs. Should the P2 audit reveal that a significant number of the tanks are still single-walled vessels, or are not equipped with modern leak detection and cathodic protection technologies, overfill containment capabilities, or have old dispensing and transfer lines, then the company should assign a high probability for encountering the various costs and liabilities under the Tier 3 and 4 cost categories. The company might quantify this probability with a numerical value (e.g., 75% chance for incurring Tier 3 and/or 4 costs and liabilities for certain operations or facilities in the company), and further qualify the likelihood by assigning a level of confidence (e.g., 65% confident that leaking USTs could result in the liabilities and costs over 5 years or more). The basis for establishing confidence limits can be developed from subjective criteria. Examples of subjective criteria in this case include the following:

- Industry data reflect that 90% of buried single-walled steel vessels more than 15 years old leak.
- The company has had several LUSTs in the last five years with remediation costs exceeding several million dollars.
- Inventory balances from sales and purchases of the chemicals stored cannot be resolved on a consistent basis.
- Facilities are close to densely populated areas and pose high risks.

By incorporating subjective risk assessment principles to supplement LCC calculations, we can rank P2 initiatives that eliminate or reduce the risks of environmental costs and liabilities, and develop P2 investment priorities for recommendation to top management. In the UST example, the various strategies might include:

- Investing in cathodic protection technologies for some percentage of the USTs that are older than 10 years
- Implementing automated inventory gauging and interfacing data with a centralized computer as an early warning system for leaks
- Modernizing all USTs over the next several years

The EMS/P2 Committee's P2 investment recommendations for top management should:

- Rank the potential P2 investments in terms of net life-cycle Tier 1 and 2 costs, accounting for inflation
- Prioritize the most desirable of these in terms of mitigating or reducing Tier 3 and 4 liabilities
- Minimize the risks of potential investments by using probabilities and confidence limits to qualify estimated reductions in environmental liability

We may carry the analysis further by recommending integrated systems approaches which would provide management with options for implementing several P2 initiatives at once or for staging them over a period of time. This enables management to make long-term business growth decisions and is based upon *life cost planning* (LCP) techniques. LCP concerns the assessment and comparison of options and alternatives during the design and acquisition phases of a project. It considers all cost components within an asset's options over the asset's life. It does not directly consider the benefits or revenue streams that are generally assumed to be equal among the options being compared (benefits and revenues are considered in the evaluation of options). The subject of LCP and how it can be effectively applied to P2 investments is a subject that requires a separate volume. Suffice it here to say that the basic concepts that are used for long-term business financial planning purposes are applied through LCP.

## LIFE-CYCLE COSTING TOOLS

Life-cycle costing tools fall into two general categories: standard LCC calculations and supplemental measures or indicators of economic performance. In performing the analysis it is important to bear in mind that consideration must be given to the *time value of money* (TVM). This refers to the fact that money in hand right now could be invested elsewhere (in something that has a positive rate of interest). That money with accumulated interest would amount to more in the future than it does right now. As such, any money to be received or spent in the future is equivalent to a smaller sum of money to be received or spent right now.

The type of P2 initiative sets the pace for the analysis. Costs associated with a P2 initiative include:

- Initial investment costs
- Operation and maintenance costs
- Energy and water costs
- Residual values
- Financing costs

Life-cycle cost analysis, LCCA, is an economic method of project evaluation in which all costs arising from owning, operating, maintaining, and disposing of an investment are considered germane to the decision. The tools are particularly well-suited to the evaluation of design alternatives that satisfy a defined performance level, but that may have differing investment, operating, maintenance, or repair costs, and even possibly different life spans. LCCA tools can be applied to any capital investment decision. They are especially relevant in situations where high initial costs are traded for reduced future costs, and as such, LCCA is most relevant to evaluating moderate to high-cost P2 investments that eliminate or reduce future liabilities associated with current environmental management practices.

LCCA can be used to compare the costs of existing equipment over a given time period with the costs over the same time period of several alternative P2 measures proposed by the EMS/P2 Committee. The costs for performing a feasibility study including technology evaluations involving plant trials, setting up, and financing the P2 investment can all be included in the LCCA, as well as accounting for any offset costs or credits received from the no-cost/low-cost P2 initiatives that have already been implemented.

Individual P2 initiatives can be bundled together to optimize materials savings and improve efficiencies, costs, and the environmental performance benefits of a project. Various P2 investments that save significant amounts of energy, improve environmental performance, reduce greenhouse gas emissions, improve productivity, save on materials and water, and/or improve product quality may be bundled with other P2 investments so long as the overall project is cost-effective in life-cycle terms. All items in the bundle must be complementary: they must be an integral part of the project, and no single P2 initiative should be significantly cost-ineffective. The EMS/P2 Committee should take an integrated systems approach when defining the scope of a P2 investment portfolio. In some situations, a decision about one P2 initiative will directly affect the scope or type of other P2 strategies.

In order for P2 initiatives to be practical, they must be more financially attractive than the current situation. In some situations pollution control (end-of-pipe) technologies are the simplest and most cost-effective strategies, especially if a company calculates that the probability of long-term liabilities from disposal practices are low, or there are low probabilities for Tier 3 and 4 costs.

## How an LCC Calculation Works

LCC adds all the costs of alternatives over their lives, enabling evaluation on a common basis for the period of concern. This is usually done using *discounted* *costs*. This approach enables decisions on acquisitions or disposal to be made in light of full cost implications.

In developing estimates for LCCA, a breakdown of the assets into individual cost elements over time is needed. The level to which the cost elements are broken down depends on the purpose and scope of the LCC analysis, but generally requires identification of the following three elements:

- Components of the activity that are major cost generators
- The point in the life cycle when the work or activity is to be performed
- Relevant resource cost categories (e.g., labor, materials, energy, overhead, transportation)

Costs associated with LCC elements can be further allocated between recurring and nonrecurring costs, and they may also be estimated in terms of fixed and variable costs.

In the following discussion we point out the major formulae and calculation methods used to make an LCC calculation and the need for supplementary economic measures. Complex systems, especially those based on an integrated systems approach are best handled by LCCA models.

### Discounting and Inflation

It is critical that the same discount rate and inflation treatment be used in the LCC analysis of alternatives and multiple projects. Project-related costs occurring at different points in time must be discounted to their *present value* at the start date before they can be combined into the LCC estimate for that project. The discount rate used to discount future cash flows to present value is based on the TVM. The discount rate is based on the minimum acceptable rate of return (MARR) for investments of equivalent risk and duration. The MARR is somewhat subjective and depends on how little or how much risk individual companies and managers are willing to accept.

### Interest, Discounting, and Present Value

When faced with choosing among P2 investments, top management should be sensitive to the timing of cash flows or savings generated by each investment. In general, it's considered preferable to receive or save a dollar sooner rather than later. There are two reasons for this. First, dollars generally loose purchasing power over time because of inflation. Secondly, cash amounts received earlier can be reinvested earlier, thereby earning additional returns (another reason why early P2 savings from no-cost/low-cost P2 initiatives are so important).

When we invest a cash amount at a given interest rate, the future value of that cash amount at any point in time can be computed using *compound interest*. Consider than an initial sum of $P_0$ dollars is invested for t years at a rate of interest, i, compounded annually. In one year, the yield would be $iP_0$, which when added to the principal, $P_0$, gives:

$$P_1 = P_0 + iP_0 = P_0(1 + i).$$

The future compound amount after t years would be:

$$P_t = P_0(1 + i)^t.$$

Discount rates are essentially a special type of interest rate which makes an investor indifferent between cash amounts received at different points in time. An investor would just as soon have one amount received earlier as the other amount received later.

Calculations involving discounting are identical to those of compound interest. The discount rate, d, is used like the interest rate, i, to determine the present value (PV) of a cash amount received or paid at a future point in time. The PV of a future amount received at the end of year t, $F_t$, is calculated as follows:

$$PV = F_t/(1 + d)^t.$$

Note that costs that occur at different points in time over the life of the investment cannot be used directly in the LCC calculations because the dollars spent at different times have different values to the investor. These costs must first be discounted to their present-value equivalent amounts. Only then can the costs be added into the analysis to yield a meaningful LCC that can be compared with the LCC of other P2 investments or the current situation.

## The Importance of Inflation

Inflation reduces the purchasing power of the dollar over time (conversely, deflation increases it). When future amounts are stated in actual prices as of the year in which they are expected to occur, they are said to be in *current dollars*.

Current dollars are dollars of any one year's purchasing power, inclusive of inflation. In other words, they reflect changes in purchasing power of the dollar from year to year. In contrast, *constant dollars* are dollars of uniform purchasing power, exclusive of inflation. Constant dollars reflect what the same good or service would cost at different times if there were no change in the general price level (i.e., no general inflation or deflation). In other words, there is no change in the purchasing power of the dollar.

The discounting of future cash flows to present value is not the same as adjusting future costs for general inflation. Even when costs are expressed in terms of constant dollars, they must be discounted to reflect the TVM, which is usually greater than the rate of inflation. A discount rate used with constant-dollar amounts is different than from the discount rate used with current-dollar amounts. A real discount rate (net of general inflation) should be used with constant-dollar amounts. A nominal discount rate (inclusive of general inflation) should be used with current-dollar amounts.

### Cost Categories

There are several ways of classifying the cost components in LCCA. The most important ones to distinguish among are:

- Investment-related and operational costs
- Initial and future costs
- Single costs and annually recurring costs

LCC for P2 includes both investment costs and operational costs. The distinction between the two is most useful when calculating economic measures such as the savings-to-investment ratio (SIR) and the adjusted internal rate of return (AIRR). These economic measures evaluate savings in operation-related costs which generally are most critical for Tier 1 and 2 components. The SIR and the AIRR are measures that evaluate savings in operation-related costs with respect to capital investment costs. This distinction does not affect the LCC calculation itself, nor will it cause an investment alternative to change from being cost-effective to non-cost-effective or vice versa. However, it may change its ranking relative to other independent projects when allocating a limited capital investment budget.

When a company considers these elements, it should consider all acquisition costs - those associated with planning, design, purchase, and construction - investment-related costs. It should also take residual values (based on the value in place, resale value, salvage value, or scrap value, net of any selling, conversion, or disposal costs) and capital replacement costs into account in the investment calculus. Capital replacement costs are incurred when replacing major systems or components (a major upgrade on aeration tanks in a wastewater treatment plant, for example), and they must be paid for from capital funds. Operating, maintenance, and repair (OM&R) costs should include energy and process water costs. These are operational costs. Replacements that are related to maintenance or repair are also considered OM&R costs, not capital replacement costs. OM&R costs are best paid for from an annual operating budget and not from capital funds.

The distinction between initial investment costs and future costs is most appropriate when calculating *simple* or *discounted payback* indicators. Costs incurred in planning, design, construction, and/or the acquisition phase of a P2 investment can be classified as *initial investment costs*. These costs occur before a system or piece of equipment is placed into service. Costs that arise from the operation, maintenance, repair, replacement, and use of the equipment or system during the life of the operation are *future costs*. Residual values at the end of the system life, or at the end of the study period for the evaluation, are also future costs.

This brings us to single costs versus annually recurring costs. The distinction between these two determines the type of present-value factor most appropriate for discounting future cash flows to present value. Single costs are one-time costs. They occur at one or more times during the evaluation period (life of the investment) at non-annual intervals. Examples of single costs are initial investment costs, and replacement costs scheduled at intervals longer than 1 year. Repair costs may also be considered as single costs. The proper discount formulas to use in LCC are given in Table 4. In this table are included subformulas which can be used to compute a corresponding discount factor. The computed discount factor is a number by which an amount is multiplied to obtain a present value. For discounting one-time amounts to present value, the single present value (SPV) factor is used. The reader can find SPV factors in a number of LCC references (one we recommend is the *Life-Cycle Costing Manual for the Federal Energy Management Program* by S. K. Fuller and S. R. Petersen, U.S. Department of Commerce, NIST Handbook 135, 1995 edition).

Table 4. Present-Value Formulas and Subformulas Using Discount Factors

| **Formula application** | **Formula** | **Subformula with discount factor** |
|---|---|---|
| **PV formula for one-time amounts**: The SPV factor is used to calculate the PV of a future cash amount occurring at the end of year $t$, $F_t$, given a discount rate, $d$. | $PV = F_t \times 1/(1 + d)^t$ | $PV = F_t \times SPV_{(t,d)}$<br>Note: Use standard discount tables for values of the SPV factor. As an example, the SPV factor for $d$ = 3% and $t$ = 15 years is 0.642. |
| **PV formula for annually recurring uniform costs**: The UPV factor is used to calculate the PV of a | $PV = A_0 \times 1/(1 + d)^t =$<br>$A_0 \times [\{(1 + d)^n - 1\}/d\,(1 + d)^n]$ | $PV = A_0 \times UPV_{(n,d)}$<br>Note: Use standard discount tables for values of the UPV |

| **Formula application** | **Formula** | **Subformula with discount factor** |
|---|---|---|
| series of equal cash amounts, $A_0$, that recur annually over a period of n years, for a given d. | | factor. As an example, the UPV factor for $d = 3\%$ and $n = 15$ years is 11.94. |
| **PV formula for annually recurring nonuniform costs**: The UPV* factor is used to calculate the PV recurring annual amounts that change from year to year at a constant escalation rate, $e$ (i.e., $A_{t+1} = A_t \times (1 + e)$), over $n$ years, given $d$. Note that the escalation rate can be positive or negative. | $PV = A_0 \times [(1 + e)/(1 + d)]^t =$<br>$A_0[(1 + e)/(d - e)][1 - \{(1 + e)/(1 + d)\}^n]$ | $PV = A_0 \times UPV^*_{(n,d,e)}$<br>Note: Use standard discount tables for values of the UPV* factor. As an example, the UPV* factor for $e = 2\%$ and $n = 15$ years is 13.89. |

Annual recurring costs are defined as amounts that occur regularly every year during the life of the investment in approximately the same amount, or in an amount expected to change at a known rate. The types of costs that fall into this category are energy related, water, and routine annual maintenance. The appropriate present value factor to use with the subformulas given in Table 4 for annually recurring costs is the Uniform Present Value (UPV) factor or the uniform present value factor modified for price escalation (UPV*). If the annual amounts are expected to change at a known rate, the UPV* factor should be used for the present value factor. Again the reader is referred to the *Life-Cycle Costing Manual for the Federal Energy Management Program* by S. K. Fuller and S. R. Petersen, or a comparable publication for the factors.

## Timing Considerations and Cash-Flow Diagrams

LCCA requires that project-related costs be accounted for in terms of both their amounts and when they occur. This can complicate an LCC analysis, so the more common practice is to rely on simplifying or approximating models rather than to attempt to estimate the exact timing of all costs. For example, costs occurring at different time during a year may all be treated as occurring at the same time each year.

Another useful technique for dealing with time in LCC is to create a cash-flow diagram. A cash-flow diagram for a P2 investment is a graphic representation of all relevant costs and their timing. A horizontal time line represents the study period and marks each year and key dates (e.g., start date, dates of regularly schedule maintenance, dates of expected replacement costs, end of useful life). Years can be indicated in terms of calendar years or elapsed years from investment inception. There is no standard convention for cash-flow diagrams; however, the usual practice is to show positive costs above the time line and negative costs (e.g., residual values) below the time line.

### How to Treat Revenues

LCCA is most appropriately used to evaluate the relative costs of design alternatives or P2 investment options that can satisfy certain expectations (specific environmental performance targets); it is not generally appropriate for evaluating the cost-effectiveness of alternative revenue-generating projects. For example, if LCC were carried out on alternative building designs constructed to produce rental income, LCCA would not be appropriate. The same principle applies if a company considers off-site recycling markets in analyzing P2 alternatives. The potential attractiveness of these kinds of revenue generating strategies is most appropriately evaluated using benefit-cost analysis (BCA) and return-on-investment (ROI) indicators, which can supplement the LCC analysis. This is not necessarily a hard-and-fast rule. If there are small differences in revenue between one design alternative and another, then it may be appropriate to include them in LCCA by adding them to (when negative) or subtracting them from (when positive) annual operation-related costs.

### LCC Calculation Methodology

Input information needed for LCCA includes cost estimates, by year, for two or more competing alternatives, a discount rate, and a study period. In order to calculate an LCC the present value of each cost to be incurred during the study period must first be computed using appropriately chosen discount rates. These present values for each alternative must then be summed, yielding its LCC. If other performance features are similar among the alternatives being considered, the alternative with the lowest LCC is the most cost-effective of the P2 investment options.

Calculations can be performed manually for simple systems, and with the use of computer-based models for more complex systems and integrated systems. The following is the general formula for the LCC present-value analysis:

$$LCC = \{C_t/(1 + d)^t\}$$

where
LCC = Total LCC in present-value dollars of a given alternative
$C_t$ = Sum of all relevant costs, including initial and future costs, less any positive cash flows, occurring in year t
N = Number of years reflecting the life of the investment
d = Discount rate used to adjust cash flows to present value.

The formula requires that all costs be identified by year and by amount. Although the formula looks simple, the actual calculations can be quite tedious, especially when the life expectancy of the investment is more than a few years, and for annually recurring amounts for which future costs must first be calculated to include changes in price.

The LCC method provides a consistent means of accounting for all costs related to several potential P2 investments over a specified study period. The LCCA is needed to demonstrate that the additional cost for an investment alternative is more than offset by its corresponding reduction in operating and maintenance costs (including energy and water), relative to the current situation. LCCA allows for a relatively straightforward comparison between Tier 1 and Tier 2 costs for P2 and pollution control technologies, but often requires additional analysis in order to properly account for Tier 3 and Tier 4 costs. This additional analysis is referred to as *supplementary measures*, which are discussed below.

When using the LCC method for evaluating potential P2 investments a company should:

- Try to choose among two or more mutually exclusive alternatives on the basis of lowest LCC
- Design all alternatives to meet specific minimum performance requirements
- Evaluate all alternatives using the same start date, service date, study period, and discount rate
- Subtract positive cash flows (if any) from costs
- Ensure that any effects of a P2 investment not accounted for in money terms are either insignificant or uniform across all investment options, or are accounted for in some other way

## Using Supplementary Measures of Economic Performance

Supplementary measures most often used to complement LCCA are:

- Net savings (NS) measure
- Savings-to-investment ratio (SIR)
- Adjusted internal rate of return (AIRR)

- Discounted payback (DPB)
- Simple payback (SPB)

Each of these supplementary measures is a relative measure of economic performance. They are most appropriately computed for a potential investment relative to the current situation. For assessing P2 investments, the "current situation" is most often a pollution control technology. The pollution control technology usually has lower investment costs (because it's already in place) and higher operational costs than the alternatives being considered. The main reason for LCCA of a P2 alternative is to demonstrate that its operational savings are sufficient to justify its additional investment cost.

The *net benefits (NB) measure* of economic performance is the difference between present-value benefits and present-value costs for an investment over its useful life. The NB measure is used in situations where positive cash flows are intended to justify an investment. A P2 example for this would be investment in a technology for producing biosolids for soil conditioning and agricultural markets from municipal wastewater sludge.

The *net savings (NS) measure* is a variation of the NB measure. The NS measure is used when benefits occur mainly in the form of future operational cost reductions, such as energy or water or chemical feedstock cost savings. The NS measure calculates the net amount that a P2 investment is expected to save over its life, in present-value dollars. Since the calculation is made in present-value terms, the savings computed represent savings over and above the amount that would have been earned from investing the same money at the minimum acceptable rate of return (the discount rate). The NS measure for a P2 investment relative to the current situation is calculated by subtracting the LCC of the P2 alternative from the LCC of the current situation.

$$NS = LCC_{BC} - LCC_{P2}.$$

As long as $NS > 0$, the investment is considered to be cost effective relative to the current situation. Hence, the requirement for a financially attractive P2 investment is that its LCC be lower than the LCC of the current situation. For multiple, mutually exclusive P2 alternatives, the alternative with the greatest NS measure is the same alternative that has the lowest LCC. As such, LCCs and NS measures are consistent with each other and the analyses are interchangeable. One advantage of LCC over an NS measure when evaluating several alternatives is that the former does not require that the "current situation" be brought directly into the calculations.

The NS measure can also be calculated from individual cost differences between the current situation and a P2 alternative. In other words, the differences between initial investment costs, energy costs, OM&R costs, and other costs can be used as the basis for the NS calculation. Although this requires more calculations than the simplified method already presented, we prefer the latter approach because costs within the four tiers can be tracked in the computations. Furthermore, these same calculations are required to compute the SIR and the AIRR. These economic performance measures should be calculated along with the NS measure in order to assess P2 investment options more thoroughly.

The NS calculation based on individual cost differences can be computed from the following equation:

$$NS_{A:BC} = S_t/(1 + d)^t - I_t/(1 + d)^t$$

where:
$NS_{A:BC}$ = NS in present value dollars of alternative A relative to the base case (BC)
$S_t$ = Savings in year t in operational costs associated with the P2 alternative
$I_t$ = Additional investment-related costs in year t associated with the alternative
t = Year of occurrence (0 would be the base date)
d = Discount rate
N = Number of years in the evaluation period

The *SIR* expresses the relationship between the cost savings resulting from a P2 investment and its incremental investment cost (in present-value terms) as a ratio. The SIR is a variation of the benefit-to-cost ratio (BCR) described in *Green Profit* and elsewhere. In fact, we recommend computing both. The SIR and BCR are used when benefits occur primarily as reductions in operation-related costs. Both are relative measures of performance that can only be calculated in relation to the current situation or an alternative investment, a "base case." The same base date, study period, and discount rate must be used both for the base case and the P2 alternative. A P2 alternative is considered economically justified relative to the current situation when the SIR > 1.0. This means that savings as a result of the P2 investment exceed its incremental investment costs, and that its net savings are greater than zero. The SIR is only useful as a means of ranking projects relative to other independent projects. The SIR should never be used as a basis for choosing among mutually exclusive investment alternatives, but rather strictly as a guide for allocating limited investment funds.

The general formula for the SIR is

$$SIR_{A:BC} = \{ S_t/(1 + d)^t\}/\{ I_t/(1 + d)^t\}$$

where $SIR_{A:BC}$ is the ratio of PV savings to additional PV investment costs of the (mutually exclusive) P2 alternative relative to the base case, and all other parameters are defined as before.

The *AIRR* requires that the SIR for an investment (relative to the base case) be calculated first. The following formula can be used:

$$AIRR = (1 + r)\, SIR^{N-1}$$

where r is the reinvestment rate (expressed as percent).

The AIRR is an economic measure of performance expressed in terms of the annual rate of return on an investment. A single investment alternative is cost-effective relative to the base case when the AIRR exceeds the appropriate discount rate. When computing the AIRR of an alternative P2 investment relative to its base case (the current situation or an alternative investment), the same study period and discount rate must be used. As with the SIR, the AIRR can be used to evaluate a single P2 investment relative to a base case, and may be used to rank independent projects when allocating a limited budget. Effects that are not measured in dollars are not included in the analysis and must be accounted for in some other manner.

The most common supplementary economic measure of performance is the *payback*, of which there are two calculation methods. Both methods focus on the time required to recover initial investment costs.

The *DPB* calculation requires that cash flows occurring each year be discounted to present value before accumulating them as savings and costs. If the DPB is less than the length of the service period, the investment is generally cost-effective. This is consistent with the requirement that the LCC of the P2 investment be lower than the LCC of the base case. An alternative payback criterion is more commonly used (i.e., the number of years allowed for the payback to occur) by choosing a time period that is considerably shorter than the project's intended service period. A drawback with this calculation is that capital replacement costs or increased OM&R costs can occur after the year of payback, and this could cancel out the apparent cost-effectiveness of the investment.

The *SPB* does not rely on discounted cash flows in the calculation. The SPB also ignores any changes in prices, such as energy, water, and labor escalation prices, during the payback period. As with the DPB, the acceptable SPB for an investment is set at an arbitrary time period that is considerably less than the intended service period. Calculations based on the SPB will generally result in a shorter year of payback since undiscounted cash flows are greater than their discounted counterparts (this assumes a positive discount rate).

The general formula for a payback calculation is

$$[(S_t - I_t)/(I + d)^t] \quad I_0$$

where:
y = The minimum length of time (in years) over which future net cash flows have to be accumulated in order to offset initial investment costs
$S_t$ = Savings in operational costs in year t associated with a given alternative
$I_0$ = Initial investment costs
$I_t$ = Additional investment-related costs in year t, other than initial investment costs
d = Discount rate.

Between the DPB and SPB calculation, the former is preferred. However, both payback measures ignore all costs and savings, and residual values occurring after the payback date. Payback calculations should only be used as a basis for screening potential P2 investments. The value in these calculations is their ability to help identify single P2 investments that are so clearly economical that the time, effort, and expense of a full LCC are not warranted. If there is uncertainty about the useful life of an investment, then the DPB method can also be used to determine an acceptable lower bound on its usefulness. Finally, it is important to note that a payback calculation is not a proper basis for selecting among alternative mutually exclusive P2 investments. Only the LCC and NS methods should be used for this purpose. In addition, payback methods should not be used for ranking potential investments for funding allocation purposes.

## A SHORT REVIEW

P2 programs work best within the framework of an EMS. As noted in *Green Profits* (Chapter 1): "An environmental management system is an approach... a tool... a set of procedures ... a planned and organized way of doing things..." In other words, an EMS is a systematic approach for a company to manage its environmental concerns. Most people tend to separate the functions of an EMS and pollution prevention in their minds, or think of these as related only in the sense that P2 is the preferred way of addressing environmental aspects of a company's operations that have been identified through an EMS. But in fact, a pollution prevention program must be fully integrated with an EMS in order to maximize the benefits a company can achieve through its EMS.

In many cases P2 practices are based on recognizable opportunities with well-defined Tier 1 and 2 cost savings. A few successes often encourage companies to promote the spirit of P2, and indeed many environmental policy statements often incorporate a commitment to reducing pollution at the source. However, when one examines how P2 is implemented, we see that it is only a small element of the EMS and is rarely applied on a dedicated and continual basis. This creates two problems. First, the benefits of continual P2 improvements to environmental performance, such as cumulative efficiency gains, costs savings, and reductions of long-term liabilities, can never really be achieved. Second, P2 activities are often implemented for the wrong reasons, and hence the most cost-effective strategies are never applied.

The proper way to think of a P2 program is that it is a systematic approach to pollution management through the reduction of as many of the cost components that lie within the four cost tiers. By comparing the total costs of different technology options that achieve comparable levels of compliance, the most cost-effective strategies become apparent. When a company analyzes these strategies from a cost-benefit standpoint, what it's really doing is developing an investment strategy. In many cases, going beyond minimum environmental compliance requirements leads to the most cost-effective pollution management strategy because through that a company captures Tier 3 and 4 cost savings.

Logical investment strategies can only be planned by properly applying life-cycle cost analysis (LCCA). LCCA is an economic evaluation method in which all costs associated with a project or investment are considered from cradle to grave. The analysis considers all costs arising from owning, operating, maintaining, and ultimately disposing of a project to be potentially important to making a decision on whether an investment is worthwhile.

In the context of pollution prevention, a company seeks to evaluate whether or not a strategy is more cost-effective in the long run compared to the status quo of managing its environmental aspects. LCCA is particularly well suited for evaluating the financial merits of a P2 investment because it can be applied to any capital investment decision in which higher initial costs are traded for reduced future cost obligations. Since P2 is an approach that has a direct impact on future cost obligations, especially those associated with long-term liabilities (i.e., Tier 3 costs), LCCA yields a significantly better assessment of the long-term cost effectiveness than alternative economic methods that focus only on initial investment costs or on operating-related costs in the short run.

In contrast, the most common alternative method of economic evaluation is the *payback method*. The payback method generally focuses on how quickly the *initial investment* can be recovered. As such, it is not a measure of *long-term* economic performance or profitability. The method typically ignores all costs and savings occurring after the point in time in which the payback for the capital investment is reached. It also does not differentiate between project alternatives having different lives, and often uses an arbitrary payback threshold. The most serious shortcoming with this method is that it ignores the *time value of money* (TVM) when comparing future streams of savings against the initial investment cost.

The references listed below are key resources that the reader should refer to. The United Nations EP3 project (1) provides a similar step-by-step methodology for implementing a pollution prevention audit. Bernstein (2) has provided a good overview of waste management issues and approaches to waste minimization and pollution prevention. The USEPA study (3) on industry motivation for pollution prevention also provides some general background reading material. EPA's "Cleaner Technologies Substitute Assessment" guide (4) is a very different approach from pollution prevention, but still offers some useful information that can be incorporated into a P2 audit. Finally, Chopey and Hicks (6) provide examples of mass and energy balances that are needed in quantitative evaluations in the audit.

## RECOMMENDED RESOURCES

1. United Nations Environmental Program, Environmental Pollution Prevention Project (EP3) Training Manual, New York, March 1995.
2. Bernstein, J. D., Alternative Approaches to Pollution Control and Waste Management, Urban Management Programme, World Bank, Washington, D.C., 1993.
3. Prototype Study of Industry Motivation for Pollution Prevention, USEPA, EPA Document Number 100-R-96-001, June 1996.
4. Cleaner Technologies Substitute Assessments: A Methodology and Resource Guide, USEPA, EPA Document Number EPA 744-R-95-002, December 1996.
5. Chopey, N. P. and T. G. Hicks, *Handbook of Chemical Engineering Calculations*, McGraw-Hill Book Company, New York, 1984.

The following reference materials can be accessed through the World Wide Web:

**Initial Costs vs. Operational Costs. A Study of Building Improvement Projects in Fourteen Schools in the School District of Greenville County, South Carolina**: Chan, Tak Cheung (Office of School Facilities Planning, The School District of Greenville County, Greenville, SC , 1980); To determine whether initial facility improvement costs were paid back by the reduced operational costs resulting from the improvement projects, this study examined the relationship between initial costs and operational costs of fourteen school buildings improved during the 1978-79 school year in Greenville County, South

Carolina. With energy conservation as a goal, windows were replaced, roofs were insulated and HVAC systems were modified or replaced. Estimated annual dollar savings (from electricity payment records) were divided into the amount spent on improvement to determine the number of years required for payback. The findings indicated that ten of the fourteen buildings became more energy efficient and eight were able to pay back the initial improvement costs within their expected life span. A relationship between initial improvement costs and operational costs of school buildings was supported in that the initial costs of improvement could be repaid by the resultant reduction in operational costs. ERIC NO: ED208492; TO ORDER: ERIC Document Reproduction Services; http://www.edrs.com

**Value Engineering. "A Working Tool for Cost Control in the Design of Educational Facilities."** Lawrence, Jerry, (Paper presented at the Annual Meeting of the American Association of School Administrators, Atlanta, GA , Feb 13, 1981), Value Engineering (VE) is a cost optimizing technique used to analyze design quality and cost-effectiveness. The application of VE procedures to the design and construction of school facilities has been adopted by the state of Washington. By using VE, the optimum value for every life cycle dollar spent on a facility is obtained by identifying not only initial costs but also operations, maintenance, and replacement costs. This paper outlines the contents of a manual to be prepared that would assist school districts to implement VE procedures in specific school facilities projects. 24p., ERIC NO: ED206041; TO ORDER: ERIC Document Reproduction Services; http://www.edrs.com

**Life-Cycle Costing Manual for the Federal Energy Management Program. 1995 Edition**: http://www.fire.nist.gov/bfrlpubs/build96/art121.html; Fuller, S. K.; Petersen, S. R., ( National Institute of Standards and Technology, Building and Fire Research Laboratory, Gaithersburg, MD , 1996 ); Guide to understanding the life-cycle cost methodology and criteria established by the Federal Energy Management Program (FEMP) for the economic evaluation of energy and water conservation projects and renewable energy projects on all federal buildings. 210p.

**Value Engineering : Practical Applications for Design, Construction, Maintenance and Operations**: Dell'isola, Alphonse, J.,(R.S. Means Company, Inc., Kingston, MA , 1998); Complete system for understanding and conducting Value Engineering and Life Cycle Costing Studies--for design, construction, and facilities operation. Along with step-by-step instructional chapters, includes seven case studies on major facility types, with currently applicable data and examples. 450p.; ISBN: 0876294638; TO ORDER: R.S.Means Company, Inc., P.O. Box 800, 63 Smiths Lane, Kingston, MA 02364; Toll free: 800-334-3509; http://www.rsmeans.com

# GLOSSARY OF ENVIRONMENTAL AND WASTE MANAGAMENT TERMS

## A

**Abiotic Factors** - Nonliving; moisture, soil, nutrients, fire, wind, temperature, climate.

**Abrasion-Resistant Material** - Material that is hard and resistant to physical wear caused by friction.

**Absolute Filtration Rating (Largest Particle Passed)** - The diameter of the largest hard spherical particle that will pass through a filter under specified test conditions. This is an indication of the largest opening in the filter cloth.

**Absorption** - Assimilation of molecules or other substances into the physical structure of a liquid or solid without chemical reaction.

**Absorption Capacity** - A measure of the quantity of a soluble substance that can be absorbed by a given quantity of a solid substance.

**Absorption Field** - A system of properly sized and constructed narrow trenches partially filled with a bed of washed gravel or crushed stone into which perforated or open joint pipe is placed. The discharge from the septic tank is distributed through these pipes into trenches and surrounding soil. While seepage pits normally require less land area to install, they should be used only where absorption fields are not suitable and well-water supplies are not endangered.

**Acclimation** - (1) The dynamic response of a system to the addition or deletion of a substance until equilibrium is reached. (2) Adjustment to a change in the environment.

**Accuracy** - The degree of agreement between the quantity measured and the true quantity.

**Acetogenic Bacterium** - Prokaryotic organism that uses carbonate as a terminal electron acceptor and produces acetic acid as a waste product.

**Acetylene-Block Assay** - Estimates denitrification by determining release of nitrous oxide (NO) from acetylene-treated soil.

**Acetylene-reduction Assay** - Estimates nitrogenase activity by measuring the rate of acetylene reduced to ethylene.

**Acid** - A substance that dissolves in water with the formation of hydrogen ions, contains hydrogen which may be replaced by metals to form salt, and/or is corrosive.

**Acid-Forming Bacteria** - Microorganisms that can metabolize complex organic compounds under anaerobic conditions. This metabolic activity is the first step in the two-step anaerobic fermentation process leading to the production of methane.

**Acid Rain** - You first need to understand acid deposition: a complex chemical and atmospheric phenomenon that occurs when emissions of sulfur and nitrogen compounds and other substances are transformed by chemical processes in the atmosphere, often far from the original sources, and then deposited on earth in either wet or dry form. The wet forms (precipitation) are popularly called "acid rain" and fall as rain, snow, or fog. The dry forms are acidic gases or particulates.

**Acid Soil** - Soil with a pH value $<6.6$.

**Acidity** - The capacity of water or wastewater to neutralize bases. Acidity is expressed in mol/l of equivalent calcium carbonate. Acidity is not the same as pH.

**Acidophile** - Organism that grows best under acid conditions (down to a pH of 1).

**Acre-foot (ac-ft)** - A volume of water 0.3 m (1 ft) deep and 4047 $m^2$ (1 ac) in area, or 1234 $m^3$ (43,560 cu ft).

**Actinomycete** - Nontaxonomic term applied to a group of high G + C base composition, Gram-positive bacteria that have a superficial resemblance to fungi. Includes many but not all organisms belonging to the order *Actinomycetales*.

**Activated Carbon** - Carbon that has undergone a process of activation that greatly increases its surface area and therefore sites for adsorption. It is not unusual to have over 3,000 square feet of surface per gram of carbon. Its uses in water treatment are many, including the adsorption of taste, odor and color. A laboratory use is for the concentration of organic matter for waste treatment analysis.

**Activated Silica** - Sodium silicate that has been systematically precipitated by reducing the pH to below 9, usually by chlorine.

**Activated Sludge** - Sludge particles produced in raw or settled wastewater (primary effluent) by the growth of organisms (including zoogleal bacteria) in aeration tanks in the presence of dissolved oxygen. The term 'activated' comes from the fact that the particles are teeming with fungi, bacteria, and protozoa. Activated sludge is different from primary sludge in that the sludge particles contain many living organisms which can feed on the incoming wastewater.

**Activated Sludge Loading** - The unit mass of biological oxygen demand in the applied liquid per unit volume of aeration capacity or per unit mass of activated sludge per day.

**Activated Sludge Process** - A sewage treatment process by which bacteria that feed on organic wastes are continuously circulated and put in contact with organic waste in the presence of oxygen to increase the rate of decomposition.

**Activation Energy** - Amount of energy required to bring all molecules in one mole of a substance to their reactive state at a given temperature.

**Active Ingredient** - In any pesticide product, the component that kills, or otherwise controls, target pests. Pesticides are regulated primarily on the basis of active ingredients.

**Active Site** - Region of an enzyme where substrates bind.

**Acute Effect** - An adverse effect on any living organism in which severe symptoms develop rapidly and often subside after the exposure stops.

**Acute Toxicity** - Adverse effects that result from a single dose or single exposure of a chemical; any poisonous effect produced within a short period of time, usually less than 96 hours. This term normally is used to describe effects in experimental animals.

**Adenosine Triphosphate (ATP)** - Common energy-donating molecule in biochemical reactions. Also, an important compound in transfer of phosphate groups.

**Administrative Order on Consent** - A legal agreement signed by EPA and an individual, business, or other entity through which the violator agrees to pay for correction of violations, take the required corrective or cleanup actions, or refrain from an activity. The order describes the actions to be taken, may be subject to a comment period, applies to civil actions, and can be enforced in court.

**Administrative Record** - All documents which EPA considered or relied on in selecting the remedy at a Superfund site, culminating in the record of decision for remedial action, or an action memorandum for removal actions.

**ADP** - Adenosine diphosphate.

**Adsorption** - Physical adhesion of molecules or colloids to the surface of solids without chemical reaction.

**Adsorption Water** - Water held on the surface of solid particles by molecular forces with the emission of heat (heat of wetting).

**Advanced Wastewater Treatment** - Any physical, chemical, or biological treatment process used to accomplish a degree of treatment greater than that achieved by secondary treatment.

**Aerate, Aeration** - (1) The bringing about of intimate contact between air and a liquid by (a) spraying the liquid in the air, (b) bubbling air through the liquid, or (c) agitating the liquid to promote surface absorption of air. (2) The supplying of air to confined spaces under nappes, downstream from gates in conduits, and so on, to relieve low pressures and to replenish air entrained and removed from such confined spaces by flowing water. (3) Relief of the effects of cavitation by admitting air to the affected section.

**Aeration** - The act of mixing a liquid with air (oxygen).

**Aeration Period** - (1) The theoretical time, typically expressed in hours, during which mixed liquor is subjected to aeration in a biological reactor while undergoing activated sludge treatment. It is equal to the volume of the tank divided by the volumetric rate of flow of the wastewater and return sludge. (2) The theoretical time during which water is subjected to aeration.

**Aeration Tank** - Serves as a chamber for injecting air into water.

**Aerobe** - An organism that requires free oxygen for growth.

**Aerobic** - (1) Having molecular oxygen as a part of the environment. (2) Growing only in the presence of molecular oxygen, as in aerobic organisms. (3) Occurring only in the presence of molecular oxygen, as in certain chemical or biochemical processes such as aerobic respiration.

**Aerobic Bacteria (Aerobes)** - Bacteria that require free elemental oxygen to sustain life.

**Aerobic Organism** - An organism, usually in reference to bacteria, that thrives in the presence of oxygen.

**Aerotolerant Anaerobes** - Microbes that grow under both aerobic and anaerobic conditions, but do not shift from one mode of metabolism to another as conditions change. They obtain energy exclusively by fermentation.

**Agar** - Complex polysaccharide derived from certain marine algae that is a gelling agent for solid or semisolid microbiological media. Agar consists of about 70% agarose and 30% agaropectin. Agar can be melted at temperature above 100°C; gelling temperature is 40 to 50°C.

**Agarose** - Nonsulfated linear polymer consisting of alternating residues of d-galactose and 3,6-anhydro-l-galactose. Agarose is extracted from seaweed, and agarose gels are often used as the resolving medium in electrophoresis.

**Agglomerate** - To gather fine particulates together into a larger mass.

**Agglomeration** - Coalescence of dispersed suspended matter into larger flocs or particles.

**Agitator** - Mechanical apparatus for mixing or aerating. A device for creating turbulence.

**Agricultural Waste** - Poultry and livestock manure, and residual materials in liquid or solid form generated from the production and marketing of poultry, livestock, furbearing animals, and their products. Also includes grain, vegetable, and fruit harvest residue.

**Air Bound** - Obstructed, as to the free flow of water, because of air entrapped in a high point. Used to describe a pipeline or pump in such condition.

**Air Chamber** - A closed pipe chamber installed on the discharge line of a reciprocating pump to adjust for irregular hydraulic conditions and to reduce shocks caused by pulsating flow.

**Air Diffuser** - Devices of varied design that transfer oxygen from air to a liquid.

**Air Diffusion** - The transfer of air to a liquid through an oxygen-transfer device. See *Diffusion*.

**Air Flow/Air Permeability** - Measure of the amount of air that flows through a filter - a variable of the degree of contamination, differential pressure, total porosity, and filter area. Expressed in either cubic feet/minute/square foot or liters/minute/square centimeter at a given pressure.

**Air Injector** - A component of an air-lift pump made up of an air supply line and diffuser.

**Air-Lift Pump** - A vertical pipe with an air injector submerged in a well. Air bubbles are introduced into the bottom of the well so that the denser water surrounding it lifts or pushes the aerated water up through the discharge pipe. These pumps can be used to pump smaller flows of untreated wastewater or return sludge.

**Air-Powered Diaphragm Pump** - A type of reciprocating pump in which compressed air flexes a membrane that is pushed or pulled to contract or enlarge an enclosed cavity. The most common application is to pump sludge from primary sedimentation tanks and gravity thickeners.

**Air Quality Standards** - The level of selected pollutants set by law that may not be exceeded in outside air. Used to determine the amount of pollutants that may be emitted by industry.

**Air Stripping** - Removal of volatile substances from a solution using the principles of Henry's Law to transfer volatile pollutants from a solution of high concentration into an air stream of lower concentration. The process ordinarily is designed so that the solution containing the volatile pollutant contacts large volumes of air.

**Air Supply Valve** - A valve used to throttle or isolate an air supply line.

**Akinete** - Thick-walled resting cell of cyanobacteria and algae.

**Alar** - Trade name for daminozide, a pesticide that makes apples redder, firmer, and less likely to drop off trees before growers are ready to pick them. Alar also is used to a lesser extent on peanuts, tart cherries, concord grapes, and other fruits.

**Alga (plural, Algae)** - Phototrophic eukaryotic microorganism. Algae could be unicellular or multicellular. Blue-green algae are not true algae; they belong to a group of bacteria called *cyanobacteria*.

**Algaecide** - A chemical highly toxic to algae, such as copper sulfate, preferably having selective toxicity in the proper concentration for algae with negligible toxicity for other forms of life.

**Algal Assay** - An analytical procedure that uses specified nutrients and algal inoculum to identify the limiting algal nutrient in water bodies.

**Algal Bloom** - Large masses of microscopic and macroscopic plant life, such as green algae, occurring in bodies of water.

**Aliphatic** - Organic compound in which the main carbon structure is a straight chain.

**Alkali** - Typically, any substance that has highly basic properties; used particularly with reference to the soluble salts of sodium, potassium, calcium, and magnesium.

**Alkaline** - The condition of water, wastewater, or soil that contains a sufficient amount of alkali substances to raise the pH above 7.0.

**Alkaline Soil** - Soil having a pH value $>7.3$.

**Alkaline Substance** - Chemical compounds in which the basic hydroxide (OH-) ion is united with a metallic ion, such as sodium hydroxide (NaOH) or potassium hydroxide (KOH). These substances impart alkalinity to water and are employed for neutralization of acids. Lime is the most commonly used alkaline material in wastewater treatment.

**Alkalinity** - The capacity of water to neutralize acids; a property imparted by carbonates, bicarbonates, hydroxides, and occasionally borates, silicates, and phosphates. It is expressed in milligrams of equivalent calcium carbonate per liter (mg/l $CaCO_3$).

**Alkalophile** - Organism that grows best under alkaline conditions (up to a pH of 10.5).

**Alkane** – Straight-chain or branched organic structure that lacks double bonds.

**Alkene** – Straight-chain or branched organic structure that contains at least one double bond.

**Allochthonous Flora** - Organisms that are not indigenous to the soil but that enter soil by precipitation, diseased tissues, manure, and sewage. They may persist for some time but do not contribute in a significant way to ecologically significant transformations or interactions.

**Allosteric Site** - Site on the enzyme other than the active site to which a nonsubstrate compound binds. This may result in a conformational change at the active site so that the normal substrate cannot bind to it.

**Alternating Current (AC)** - An electric current that reverses its direction at regularly recurring intervals.

**Alum** - Astringent crystalline double sulfate of an alkali. $K_2SO_4AL_2\ (SO_4)_3\ 24H_2O$. Used in the processing of pickles and as a flocking agent. Excess aluminum in the environment can be hazardous.

**Alum, Aluminum Sulfate** - Used as a coagulant in filtration. Dissolved in water, alum hydrolyzes into aluminum hydroxide and sulfuric acid. To precipitate the hydroxide, as needed for coagulation, the water must be alkaline.

**Ambient** - Typically refers to the prevailing dynamic environmental conditions in a given area.

**Ambient Temperature** - Temperature of the surroundings.

**Amensalism (Antagonism)** - Production of a substance by one organism that is inhibitory to one or more other organisms. The terms *antibiosis* and *allelopathy* also describe cases of chemical inhibition.

**Amino Group** - An $-NH_2$ group attached to a carbon skeleton, as in the amines and amino acids.

**Ammeter** - An instrument for measuring electric current, either alternating or direct, in units of amperes.

**Ammonia ($NH_3$), Ammonium ($NH_4^+$)** - Dissolved degradation products of urea and proteins in raw wastewater. Typically, raw wastewater contains 30 to 50 mg/l of $NH_3$. Reactions between chlorine and ammonia are important in disinfection.

**Ammonia Nitrogen ($NH_3$-N)** - Ammonia, a nutrient, is also toxic to fish, so maintaining low levels of ammonia is important. Naturally present in surface waters, ammonia is not leached readily from soils, but is produced from organic nitrogen-containing compounds and from urea.

**Ammonia Oxidation** - Test drawn during manufacturing process to evaluate the ammonia oxidation rate for the nitrifiers.

**Ammoniator** - Apparatus used for applying ammonia or ammonium compounds to water.

**Ammonification** - Liberation of ammonium (ammonia) from organic nitrogenous compounds by the action of microorganisms.

**Amoeba (plural, Amoebae)** - Protozoa that can alter their cell shape, usually by the extrusion of one or more pseudopodia.

**Ampere** - Standard unit of electric current measurement. One ampere represents the flow of 1 coulomb of electricity per second. A flow of 1 ampere is produced in a resistance of 1 ohm by a potential difference of 1 volt.

**Amphoteric** - Capable of reacting in water either as a weak acid or as a weak base. For example, aluminum salts hydrolyze in water to produce a compound that may be considered a weak base or a weak acid. A property of certain oxides makes them reactive both with acids and bases.

**Anabolism** - Metabolic processes involved in the synthesis of cell constituents from simpler molecules. An anabolic process usually requires energy.

**Anaerobe** - An organism that lives and reproduces in the absence of dissolved oxygen, instead deriving oxygen from the breakdown of complex substances.

**Anaerobic Bacteria (Anaerobes)** - Microorganisms that grow only in the absence of free and dissolved oxygen.

**Anaerobic Respiration** - Metabolic process whereby electrons are transferred from organic or, in some cases, inorganic compounds to an inorganic acceptor molecule other than oxygen. The most common acceptors are nitrate, sulfate, and carbonate.

**Anamorph** - Asexual stage of fungal reproduction in which cells are formed by the process of mitosis.

**Angular Misalignment** - A type of shaft misalignment that results from a pump shaft and a motor shaft coming together without having parallel axial alignment.

**Anhydrous** - Very dry. No water or dampness is present.

**Anhydrous Ammonia ($NH_3$)** - Water-soluble colorless gas composed of molecules containing one nitrogen atom and three hydrogen atoms. Typically, ammonia is detectable because of its characteristic pungent and irritating odor. Not to be confused with aqueous ammonia, which is a 15 to 30% solution of ammonia in water.

**Anion** - A negatively charged ion resulting from dissociation of salts, acids, or alkalis in aqueous solution.

**Anion Exchange Capacity** - Sum total of exchangeable anions that a soil can adsorb. Expressed as centimoles of negative charge per kilogram of soil.

**Anionic** - The condition of a polymer, colloid, or large particle having exchangeable cations on its surface and an opposite, negative charge on the substrate.

**Anionic Flocculant** - A polyelectrolyte with a net negative electrical charge.

**Anode** - In electrolysis or electrochemical corrosion, a site where metal goes into solution as a cation leaving behind an equivalent number of electrons to be transferred to an opposite electrode, called a cathode.

**Anodizing** - The treatment of a metal surface whereby the metal is made anodic.

**Anoxic** - Condition in which oxygen is available in the combined form only; there is no free oxygen. Anoxic sections in an activated sludge plant may be used for denitrification.

**Anoxygenic Photosynthesis** - Type of photosynthesis in green and purple bacteria in which oxygen is not produced.

**Antagonism** - Detrimental interaction between two entities.

**Antagonist** - Biological agent that reduces the number or disease-producing activities of a pathogen.

**Antheridium** - Male gametangium found in the phylum Oomycota (Kingdom Stramenopila) and phylum Ascomycota (Kingdom Fungi).

**Anthropogenic** - Derived from human activities.

**Antibiosis** - Inhibition or lysis of an organism mediated by metabolic products of the antagonist; these products include lytic agents, enzymes, volatile compounds, and other toxic substances.

**Antibiotic** - Organic substance produced by one species of organism that in low concentrations will kill or inhibit growth of certain other organisms.

**Antibody** - Protein that is produced by animals in response to the presence of an antigen and that can combine specifically with that antigen.

**Antichlors** - Reagents, such as sulfur dioxide, sodium bisulfite, and sodium thiosulfate, that can be used to remove excess chlorine residuals from water by conversion to an inert salt.

**Antifoam Agent** - A material having low compatibility with foam and a low surface tension.

**Antigen** - Substance that can incite the production of a specific antibody and that can combine with that antibody.

**Antiseptic** - Agent that kills or inhibits microbial growth but is not harmful to human tissue.

**Antisiphoning Spring** - A spring added to discharge valves in systems where pumps are located below the liquid level in the suction tank. The spring closes the discharge valve when the pump is off to prevent fluid from moving through the system by siphoning action.

**Antistatic** - Material that minimizes static charge generation, provides "controlled" static charge dissipation, or both.

**API Gravity** - An index of specific gravity defined by the American Petroleum Institute.

**API Separator** - A simple gravity separator meeting the design standards of the American Petroleum Institute for separation of oil and solids from wastewater.

**Appurtenances** - Machinery, appliances, or auxiliary structures attached to a main structure enabling it to function, but not considered an integral part of it.

**Aqueous Vapor** - The gaseous form of water.

**Aquifer** - A porous, subsurface geological structure carrying or holding water, such as a well.

**Armature** - Rotating member of a brushed direct-current motor in which electromotive force is produced by magnetic induction or a stationary component with the same function in an alternating-current motor.

**Aromatic** - Organic compounds which contain a benzene ring, or a ring with similar chemical characteristics.

**Arthropod** - Invertebrate with jointed body and limbs (includes insects, arachnids, and crustaceans).

**Asbestos** - Insulation from mineral asbestos. Frequently used in ceiling and high-temperature insulation.

**Ascoma (plural, Ascomata)** - Fungal fruiting body that contains ascospores; also termed an *ascocarp*.

**Ascospore** - Spores resulting from karyogamy and meiosis that are formed within an ascus. Sexual spore of the Ascomycota.

**Ascus (plural, Asci)** - Saclike cell of the sexual state formed by fungi in the phylum Ascomycota containing *ascospores*.

**Aseptic** - Free from living germs of disease, fermentation, or putrefaction

**Aseptic Technique** - Manipulating sterile instruments or culture media in such a way as to maintain sterility.

**Assimilate** - To take in, similar to eating food.

**Assimilative Capacity** - The ability of a natural body of water to receive wastewaters or toxic materials without harmful effects and without damage to aquatic life.

**Assimilatory Nitrate Reduction** - Conversion of nitrate to reduced forms of nitrogen, generally ammonium, for the synthesis of amino acids and proteins.

**Associative Dinitrogen Fixation** - Close interaction between a free-living diazotrophic organism and a higher plant that results in an enhanced rate of dinitrogen fixation.

**Associative Symbiosis** - Close but relatively casual interaction between two dissimilar organisms or biological systems. The association may be mutually beneficial but is not required for accomplishment of a particular function.

**Attached Growth Processes** - Wastewater treatment processes in which the microorganisms and bacteria treating the wastes are attached to the media in the reactor. The wastes being treated flow over the media. Trickling filters, bio-towers, and RBCs are attached growth reactors. These reactors can be used for removal of BOD, nitrification, and denitrification.

**Attenuation** - Reduction of the signal power of field strength as a function of distance through a material. Also refers to *shielding effectiveness*.

**Autoclave** - Vessel for heating materials under high steam pressure. Used for sterilization and other applications.

**Autolysis** - Spontaneous lysis.

**Automatic Oiler** - A type of oiler that automatically regulates the oil reservoir level to keep a bearing properly lubricated.

**Automatic Recording Gauge** - An automatic instrument for measuring and recording graphically and continuously.

**Automatic Sampling** - Collecting of samples of prescribed volume over a defined time period by an apparatus designed to operate remotely without direct manual control.

**Autoradiography** - Detecting radioactivity in a sample, such as a cell or gel, by placing it in contact with a photographic film.

**Autotroph** - Organism which uses carbon dioxide as the sole carbon source.

**Autotrophic Bacteria** - Microorganisms that obtain their carbon and energy for growth from inorganic compounds. Most autotrophic bacteria are photosynthetic and use light as a source of energy to assemble the organic molecules they require. Some autotrophic bacteria carry out chemosynthesis, making organic molecules by using energy derived from the oxidation of inorganic compounds in the environment.

**Autotrophic Nitrification** - Oxidation of ammonium to nitrate through the combined action of two chemoautotrophic organisms, one forming nitrite from ammonium and the other oxidizing nitrite to nitrate.

**Autotrophic Organism** - An organism capable of consuming inorganic matter and converting it to organic matter.

**Autotrophy** - A unique form of metabolism found only in bacteria. Inorganic compounds (e.g., $NH_3$, $NO_2^-$, $S_2$, and $Fe_2^+$) are oxidized directly (without using sunlight) to yield energy. This metabolic mode also requires energy for $CO_2$ reduction, like photosynthesis, but no lipid-mediated processes are involved. This metabolic mode has also been called chemotrophy, chemoautotrophy, or chemolithotrophy.

**Available Water Holding Capacity** - The capacity of soil to hold water between field capacity and the wilting point of plants. It is the pool from which growing plants obtain the water necessary for plant growth.

**Average** - An arithmetic mean obtained by adding quantities and dividing the sum by the number of quantities.

**Average Daily Flow** - The total flow past a point over a period of time divided by the number of days in that period.

**Average Flow** - Arithmetic average of flows measured at a given point.

**Average Velocity** - The average velocity of a stream flowing in a channel or conduit at a given cross section or in a given reach is equal to the discharge divided by the cross-sectional area of the section or the average cross-sectional area of the reach. Also called *mean velocity*.

**AWT** - Advanced Waste Treatment. Any process of water renovation that upgrades treated wastewater to meet reuse requirements.

**Axenic** - Literally "without strangers." A system in which all biological populations are defined, such as a pure culture.

**Axial Flow Impeller** - Impellers that resemble propellers. Pumps incorporating this type of impeller are used for pumping treated effluent or clean water. They are less useful for raw wastewater or sludge because the tight tolerances of the impellers cannot easily handle solids or stringy material.

## B

**Bacillus** - Bacterium with an elongated, rod shape.

**Back-Pressure Valve** - A valve provided with a disk hinged on the edge so that it opens in the direction of normal flow and closes with reverse flow. Also called a *check valve*.

**Backflow Prevention System** - (1) A system of check valves and pressure relief valves used to prevent the flow of water through a line in a direction opposite to normal or intended flow. A typical system consists of two spring-loaded check valves in series separated by a pressure relief valve. (2) Any effective device, method, or construction used to prevent backflow into a potable water system.

**Backflushing** - The action of reversing the flow through a conduit for the purpose of cleaning the conduit of deposits.

**Backwashing** - The operation of cleaning a filter by reversing the flow of liquid through it and washing out matter previously captured in it. Filters include true filters such as sand and diatomaceous earth, but not other treatment units such as trickling filters.

**Bacteria** - Living organisms, microscopic in size, which consist of a single cell. Most bacteria use organic matter for their food and produce waste products as a result of their life processes.

**Bactericide** - A pesticide used to control or destroy bacteria, typically in the home, schools, or on hospital equipment.

**Bacterial Analysis** - The examination of water and wastewater to determine the presence, number, and identity of bacteria; more commonly called *bacterial examination*. See *bacteriological count.*

**Bacterial Photosynthesis** - A light-dependent, anaerobic mode of metabolism. Carbon dioxide is reduced to glucose, which is used for both biosynthesis and energy production. Depending on the hydrogen source used to reduce $CO_2$, both photolithotrophic and photoorganotrophic reactions exist in bacteria.

**Bacterial Slime** - A polysaccharide slime that is produced by many types of bacteria. This slime helps to hold activated sludge floc together.

**Bacteriochlorophyll** - Light-absorbing pigment found in green sulfur and purple sulfur bacteria.

**Bacteriocin** - Agent produced by certain bacteria that inhibits or kills closely related isolates and species.

**Bacteriological Count** - A means for quantifying numbers of organisms. See *MPN index.*

**Bacteriophage** - Virus that infects bacteria, often with destruction or lysis of the host cell.

**Bacteroid** - Altered form of cells of certain bacteria. Refers particularly to the swollen, irregular vacuolated cells of rhizobia in nodules of legumes.

**Baffles** - Deflector vanes, guides, grids, gratings, or similar devices constructed or placed in flowing water, wastewater, or slurry systems as a check or to produce a more uniform distribution of velocities; absorb energy; divert, guide, or agitate the liquids; and check eddies.

**Ball Check Valve** - A nonreturn valve in which a ball sits within a cylindrical fluid line.

**Bar Screen** - A screen composed of parallel bars, either vertical or inclined, placed in a waterway to catch debris. Trapped materials (screenings) are raked from it either manually or automatically. Also called *bar rack.*

**Barminutor** - A bar screen of standard design fitted with an electrically operated shredding device that sweeps vertically up and down the screen cutting up material retained on the screen.

**Base** - A compound that dissociates in aqueous solution to yield hydroxyl ions. The pH of a base is more than 7.0.

**Base Composition** - Proportion of the total bases consisting of guanine plus cytosine or thymine plus adenine base pairs. Usually expressed as a guanine + cytosine (G+C) value, e.g., 60% G+C.

**Basic Data** - Records of observations and measurements of physical facts, occurrences, and conditions, as they have occurred, excluding any material or information developed by means of computation or estimate. In the strictest sense, basic data include only the recorded notes of observations and measurements, although in general use it is taken to include computations or estimates necessary to present a clear statement of facts, occurrences, and conditions.

**Basidioma (plural, Basidiomata)** - Fruiting body that produces basidia; also termed a *basidiocarp.*

**Basidiospore** - Spore resulting from karyogamy and meiosis that usually is formed on a basidium. Sexual spore of the Basidiomycota.

**Basidium (plural, Basidia)** - Clublike cell of the sexual state formed by fungi in the phylum Basidiomycota.

**BAT**- Best Available Technology economically achievable.

**Batch Process** - A treatment process in which a tank or reactor is filled, the wastewater (or solution) is treated, or a chemical solution is prepared and the tank is emptied. The tank may then be filled and the process repeated. Batch processes are also used to cleanse, stabilize, or condition chemical solutions for use in industrial manufacturing and treatment processes.

**Bauxite** - The raw material for aluminum sulfate manufacture.

**BCT** - Best Control Technology, regardless of cost.

**Bearing Housing** - A protective outer shell that contains lubricants and prevents contaminants from getting into the bearing.

**Beggiatoa** - A filamentous organism whose growth is stimulated by hydrogen sulfide.

**Beneficial Use** - Use of a product with a defined benefit, such as biosolids used as soil amendment. Disposal, such as landfilling or incineration, is not beneficial use.

**Bell** - The enlarged (female) end of a pipe into which an adjoining (male) pipe fits.

**Belt Dressing** - An aerosol product that increases operating efficiency and extends the life of drive belts. Belt dressing can reduce stiffness, restore flexibility, and stop squealing.

**Belt Screen** - A continuous band or belt of wire mesh, bars, plates, or other screening medium that passes around upper and lower rollers and from which the material caught on the screen is typically removed by gravity, brushes, or other means.

**Bench-Scale Analysis** - Also known as *bench test*. A method of studying different ways of treating wastewater and solids on a small scale in a laboratory.

**Benthic Organism** - Any of a diverse group of aquatic plants and animals that lives on the bottom of marine and fresh bodies of water. The presence or absence of certain benthic organisms can be used as an indicator of water quality.

**Benzene** - An aromatic hydrocarbon which is a colorless, volatile, flammable liquid. Benzene is obtained chiefly from coal tar and is used as a solvent for resins and fats in dye manufacture.

**Best Available Control Technology (BACT)** - The application of the most advanced methods, systems, and techniques for eliminating or minimizing discharges and emissions on a case-by-case basis as determined by EPA. BACT represents an emission limit based on the maximum degree of reduction of each pollutant as described in regulations under the Clean Air Act (CAA). The determination of BACT takes into account energy, environmental, economic effects, and other costs.

**Best Available Technology Economically Achievable (BATEA)** - Originally described under Section 304(b)(2)(B) of the Clean Water Act, this level of control is generally described as the best technology currently in use and includes controls on toxic pollutants.

**Best Management Practices (BMP)** - Procedures or controls other than effluent limitations to prevent or reduce pollution of surface water (includes runoff control, spill prevention, and operating procedures).

**Bicarbonate Alkalinity** - Alkalinity caused by bicarbonate ions.

**Binary Fission** - The division of a single-celled organism into two daughter cells.

**Binomial Nomenclature** - System of having two names, genus and specific epithet, for each organism.

**Bio-Tower** - An attached culture system. A tower filled with a media similar to rachet or plastic rings in which air and water are forced up a counterflow movement in the tower.

**Bioaccumulation** - Accumulation of a chemical substance in living tissue.

**Bioassay** - (1) An assay method using a change in biological activity as a qualitative or quantitative means of analyzing a material's response to biological treatment. (2) A method of determining the toxic effects of wastes and wastewaters using viable organisms under controlled conditions.

**Biocatalysis** - Chemical reactions mediated by biological systems (microbial communities, whole organisms or cells, cell-free extracts, or purified enzymes aka catalytic proteins).

**Biochemical** - (1) Chemical change resulting from biological action. (2) Pertaining to the chemistry of plant and animal life.

**Biochemicals** - Chemicals that are either naturally occurring or identical to naturally occurring substances. Examples include hormones, pheromones, and enzymes. Biochemicals function as pesticides through nontoxic, nonlethal modes of action, such as disrupting the mating pattern of insects, regulating growth, or acting as repellants. Biochemicals tend to be environmentally compatible and are thus important to Integrated Pest Management programs.

**Biochemical Oxidation** - Oxidation brought about by biological activity resulting in the chemical combination of oxygen with organic matter.

**Biochemical Oxygen Demand (BOD)** - A measure of the quantity of oxygen used in the biochemical oxidation of organic matter in a specified time, at a specific temperature, and under specified conditions.

**Biochemical Oxygen Demand Load** - The biochemical oxygen demand content, typically expressed in kilograms or pounds per unit of time, of wastewater passing into a treatment system or water body.

**Biocide** - A chemical used to control the population of troublesome microbes.

**Biodegradable** - Substance capable of being decomposed by biological processes.

**Biodegradation** - The breakdown of organic materials by microorganisms in soils, bodies of water, and wastewater treatment systems.

**Biodiversity** - The number and variety of different organisms in the ecological complexes in which they naturally occur. Organisms are organized at many levels, ranging from complete ecosystems to the biochemical structures that are the molecular basis of heredity. Thus, the term encompasses different ecosystems, species, and genes that must be present for a healthy environment. A large number of species must characterize the food chain, representing multiple predator-prey relationships.

**Biofilm** - A slime layer which naturally develops when bacteria attach to an inert support that is made of a material such as stone, metal, or wood. There are also nonfilamentous bacteria that will produce an extracellular polysaccharide that acts as a natural glue to immobilize the cells. In nature, non-filament-forming microorganisms will stick to the biofilm surface, locating within an area of the biofilm that provides an optimal growth environment (i.e., pH, dissolved oxygen, nutrients). Since nutrients tend to concentrate on solid surfaces, a microorganism saves energy through cell adhesion to a solid surface rather than by growing unattached and obtaining nutrients randomly from the medium. *Pseudomonas* and *Nitrosomonas* strains are especially well known for their ability to form a strong biofilm.

**Bioflocculation** - The clumping together of fine, dispersed organic particles by the action of certain bacteria and algae.

**Biogeochemistry** - Study of microbially mediated chemical transformations of geochemical interest, such as nitrogen or sulfur cycling.

**Biological Denitrification** - The transformation of nitrate nitrogen to inert nitrogen gas by microorganisms in an anoxic environment in the presence of an electron donor.

**Biological Floc** - A very fine, fluffy mass formed by the aggregation of fine suspended particles, as in a precipitate formed by biological activity.

**Biological Materials** - Biological materials which may be present in waste streams, including dissolved solids and coliform bacteria (BOD and COD).

**Biological Nutrient Removal (BNR)** - An adaptation of the conventional activated-sludge process where anaerobic and anoxic zones are added to biological reactors to create the correct conditions under which bacteria and other microorganisms are able to remove nitrogen and phosphorous from wastewater.

**Biological Oxidation** - The process by which living organisms, in the presence of oxygen, convert organic matter to a more stable or mineral form.

**Biological Pesticides** - Certain microorganisms, including bacteria, fungi, viruses, and protozoa that are effective in controlling target pests. These agents usually do not have toxic effects on animals and people and do not leave toxic or persistent chemical residues in the environment.

**Biological Process** - (1) The metabolic activities of bacteria and other microorganisms, as in during the breakdown of complex organic materials into simple, more stable substances during sludge digestion and secondary wastewater treatment. (2) Any chemical process involving living organisms and their life activities. Also called *biochemical process*.

**Biological Reactors** - In wastewater treatment, the tanks where aerobic, anaerobic, or anoxic conditions are created to produce healthy mixed liquor and facilitate biological treatment processes.

**Biomagnification** - Increase in the concentration of a chemical substance as it progresses to higher trophic levels of a food chain.

**Biomass** - A mass or clump of living organisms feeding on the wastes in wastewater, dead organisms, and other debris.

**Bioremediation** - Use of microorganisms to remove or detoxify toxic or unwanted chemicals from an environment.

**Biosolids** - The solid organic matter recovered from wastewater treatment processes and used, especially as fertilizer.

**Biosphere** - Zone incorporating all forms of life on earth. The biosphere extends from deep in sediment below the ocean to several thousand meters elevation in high mountains.

**Biostimulation** - Any process that increases the rates of biological degradation, usually by the addition of nutrients, oxygen, or other electron donors and acceptors so as to increase the number of indigenous microorganisms available for degradation of contaminants.

**Biosynthesis** - Production of needed cellular constituents from other, usually simpler, molecules.

**Biota** - All living organisms of a specified region.

**Biotechnology** - Use of living organisms to carry out defined physiochemical processes having industrial or other practical application.

**Biotic Potential** - All the factors that contribute to a species increasing its number: reproduction, migration, adaptation, etc.

**Biotrophic** - Nutritional relationship between two organisms in which one or both must associate with the other to obtain nutrients and grow.

**Bleed** - (1) To drain a liquid or gas, as to vent accumulated air from a water line or to drain a trap or a container of accumulated water. (2) The exuding, percolation, or seeping of a liquid through a surface.

**Blinding** - The clogging of the filtering medium of a microscreen or a vacuum filter when the holes or spaces in the medium become sealed off by a buildup of grease or the material being filtered. (1) Clogging of the filter cloth of a vacuum filter, belt press, belt thickener, or pressure filter. (2) Obstruction of the fine medium of a sand filter.

**Bloom, Algae Bloom** - A readily visible concentration of algae growth usually occurring in the absence of an algaecide when weather, sunlight, and nutrient conditions favor a logarithmic phase of growth.

**Blower** - A compressor designed to provide air to a biological reactor or aerobic digester to provide adequate dissolved oxygen in the fluid to support biological processes.

**BMP** - Best Management Practices (BMP) are operating methods that ensure the proper land application of biosolids for protection of the environment. BMP include agronomic loading rates, slope limitations, soil pH limitations, buffer zones, public access restrictions, grazing deferments, soil conservation practices, restrictions for saturated and frozen soils, protection of endangered species, and other site restrictions.

**BOD** - Biochemical Oxygen Demand. The dissolved oxygen required by organisms for the aerobic decomposition of organic matter present in water. It is used as a measure in determining the efficiency of a sewage treatment plant.

**BOD Load for Trickling Filter** - Pounds of BOD per day, in waste applied, per 1000 cu ft of filter volume.

**BOD Percent Reduction** - The percent BOD is reduced through treatment. It is a useful figure in the calculation of waste plant efficiency if not misused.

**BOD Test** - A procedure that measures the rate of oxygen use under controlled conditions of time and temperature. Standard test conditions include dark incubation at 20°C for a specified time (usually 5 days).

**Bolting Cloth (Silk)** - Screens woven of twisted multifilament natural silk.

**Bolting Grade (Wire Cloth)** - Weaves that are uniformly woven of stainless steel to provide high strength and the largest possible pore openings.

**Boom** - (1) A floating device used to contain oil on a body of water. (2) A piece of equipment used to apply pesticides from a tractor or truck.

**Bottom Contraction** - The reduction in the area of overflowing water caused by the crest of a weir contracting the nappe.

**Bound Water** - (1) Water held strongly on the surface or in the interior of colloidal particles. (2) Water associated with the hydration of crystalline compounds.

**Boundary Layer Viscous Drag** - A force caused by the movement of a body through a fluid. The direction of this force is along the axis parallel to the movement. This force is used to create the pumping action in disc pumps.

**BPT** - Best Practical Technology currently available.

**Breakpoint Chlorination** - Addition of chlorine to water or wastewater until the chlorine demand has been satisfied, with further additions resulting in a residual that is directly proportional to the amount added beyond the breakpoint.

**Brown Rot Fungus** - Fungus that attacks cellulose and hemicellulose in wood, leaving dark-colored lignin and phenolic materials behind.

**Brownian Movement** - The bombardment of colloidal particles by molecules of the dispersing medium which keeps the colloid agitated and suspended indefinitely.

**Brush Aerator** - A surface aerator that rotates about a horizontal shaft with metal blades attached to it; commonly used in oxidation ditches.

**BS&W** - Bottom Sediment and Water. A measure of oil quality based on the volume percent of sediment and water that can be centrifuged from a sample.

**Bubble (Bubble Policy)** - Existing sources of air pollution with several facilities may control more than is required at one emission point where control costs are lower, in return for comparable relaxation at a second point where costs are higher or more difficult to achieve.

**Bubble Point Test** - A test to determine the maximum pore size opening of a filter.

**Bubbler Level Measurement** - A fluid measuring device that operates on the principle that a small constantly regulated air supply bubbling into a liquid will produce a back pressure equal to the static head. Typically, the bubbler pressure is converted to a voltage or current signal that is fed into an electronic network. Variations in the signal level are used to turn pumps on or off, or adjust their speed.

**Buffer** - A solution or liquid whose chemical makeup neutralizes acids or bases without a great change in pH.

**Bulk Density, Soil** - Mass of dry soil per unit bulk volume (combined volume of soil solids and pore space).

**Bulked Yarn** - A yarn that has been geometrically changed to give it the appearance of having greater volume than a conventional yarn of the same linear density.

**Bulking** - Inability of activated sludge solids to separate from the liquid under quiescent conditions; may be associated with the growth of filamentous organisms, low DO, or high sludge loading rates. Bulking sludge typically has a sludge volume index greater than 150 ml/g.

**Bulking Sludge** - Clouds of billowing sludge that occur throughout secondary clarifiers and sludge thickeners when sludge becomes too light and will not settle properly. In the activated sludge process, bulking is usually caused by filamentous bacteria.

**Buoyancy** - The upward force exerted on an object immersed in a fluid. The "buoyant force" depends on the object's volume. The greater an object's volume, the greater the amount of fluid it displaces, therefore, the greater the buoyant force.

**Butt Square Joints** - Joints in which the materials being joined butt against each other rather than overlap.

**Butterfly Valve** - A valve in which the disc, as it opens or closes, rotates about a spindle supported by the frame of the valve. The valve is opened at a stem. At full opening, the disc is in a position parallel to the axis of the conduit.

**Bypass** - An arrangement of pipes, conduits, gates, and valves by which the flow may be passed around a hydraulic structure appurtenance or treatment process; a controlled diversion.

**Bypass Line** - Typically a short segment of piping with isolation valves that allow flow to be diverted around a hydraulic structure, component, or treatment unit that may require periodic maintenance. The bypass line allows the main line to stay in service while the unit or component is worked on.

**By-product** - Materials, other than the intended product, generated as a result of an industrial process.

## C

**Cake** - The solids discharged from a dewatering apparatus.

**Calcite** - A high purity form of calcium carbonate.

**Calcium Hypochlorite [$(Ca(OCl)_2$]** - A solid that, when mixed with water, liberates the hypochlorite ion $OCl^-$ and can be used for disinfection. Commercial grades contain 70% available chlorine.

**Calcium Oxide (CaO)** - A calcined chemical material known as *lime*. Used in lime and soda ash water treatment, but must first be slaked to calcium hydroxide [$Ca(OH)_2$]. Also called *burnt lime*, *quicklime*, and *unslaked lime*.

**Calendering** - A process by which fabric or wire is passed through a pair of heavy rolls to reduce thickness, to flatten the intersections of the threads/wires and to control air permeability. Rolls are heated when calendering synthetic materials.

**Calibration** - (1) The determination, checking, or rectifying of the graduation of any instrument giving quantitative measurements. (2) The process of taking measurements or of making observations to establish the relationship between two quantities.

**Calorie** - The amount of heat necessary to raise the temperature of 1 g of water at 15°C by 1 degree.

**Cap** - A fairly impermeable seal, usually composed of clay-type soil or a combination of clay soil and synthetic liner, which is placed over a landfill during closure. The cap serves to minimize leachate volume during biodegradation of the waste by keeping precipitation from percolating through the landfill. The cap also keeps odors down and animal scavengers from gathering.

**Capacitance** - The ability to store an electric charge, measured in farads. The capacitance of a capacitor is 1 farad when 1 coulomb of electricity changes the potential between the plates by 1 volt.

**Capacity** - (1) The quantity that can be contained exactly, or the rate of flow that can be carried out exactly. (2) The load for which a machine, apparatus, station, or system is rated.

**Capacity Assurance Plan** - A plan which assures that a state has the ability to treat and dispose of hazardous wastes generated within its borders over the next 20 years. Section 104 of SARA required the first plan to be submitted to EPA in October 1989. But even though capacity has been certified, the state is not required to treat or dispose of hazardous wastes at home; many are exporting to other states that have commercial facilities, permitted landfills, and incinerators.

**Capital Cost** - The amount of cash or credit needed initially to complete a project, such as the construction of a wastewater treatment plant.

**Carbon** - (1) A chemical element essential for growth. (2) A solid material used for adsorption of pollutants.

**Carbon Dioxide** - A compound that has a great effect on water treatment. It is often a major factor affecting alkalinity, buffer capacity, stability, corrosion, floc settling, filter gassing, and a host of minor effects.

**Carbonaceous Biochemical Oxygen Demand (CBOD)** - A quantitative measure of the amount of dissolved oxygen required for the biological oxidation of carbon-containing compounds in a sample. See *biochemical oxygen demand.*

**Carbonate Hardness** - Hardness caused by the presence of carbonates and bicarbonates of calcium and magnesium in water. Such hardness may be removed to the limit of solubility by boiling the water. When the hardness is numerically greater than the sum of the carbonate alkalinity and bicarbonate alkalinity, the amount of hardness is equivalent to the total alkalinity and is called *carbonate hardness*. It is expressed in milligrams of equivalent calcium carbonate per liter (mg/l $CaCO_3$). See *hardness*.

**Carbonation** - The diffusion of carbon dioxide gas through a liquid to render the liquid stable with respect to precipitation or dissolution of alkaline constituents.

**Carbonized Threads** - Nylon or polyester threads that have been treated to include varrying degrees of carbon.

**Carcinogenic** or **Carcinogen** - Capable of causing cancer. A suspected carcinogen is a substance that may cause cancer in humans or animals but for which the evidence is not conclusive.

**Carrying Capacity** - The maximum rate of flow that a conduit, channel, or other hydraulic structure is capable of passing.

**Carryover** or **Pin Point Carryover** - That part of the floc that has not flocculated to settleable size or has been mechanically sheared or torn up so that it carries over and settles on the filters. It is a measure of coagulation and mechanical flocculation efficiency.

**Cascade Aerator** - An aerating device built in the form of steps or an inclined plane on which staggered projections are arranged to break up the water and bring it into contact with air.

**Catalysis** - Addition of a material (catalyst) that does not take a direct part in a chemical reaction but increases the rate of the reaction.

**Catchbasin** - Buried basins that collect runoff from the streets and other ground surfaces, and are typically located below curb grates seen in the streets. They capture solid materials in the runoff and provide for the conveyance of the cleaner runoff through catchbasin leads (piping) to the sewer system.

**Cation** - A positively charged ion resulting from dissociation of molecules in solution.

**Cation Exchange Capacity** - The ability of a soil or other solid to exchange cations (positive ions such as calcium) with a liquid.

**Cationic** - The condition of a polymer, colloid, or large particle having exchangeable anions on its surface and an opposite, positive charge on the substrate.

**Cationic Flocculant** - A polyelectrolyte with a net positive electrical charge.

**Caustic Alkalinity** - The alkalinity caused by hydroxyl ions. See *alkalinity*.

**Caustic Soda (Sodium Hydroxide)** - A white crystalline solid that, when dissolved in water, exhibits strong alkalinity and corrosiveness. Commonly called *lye*.

**Cavitation** - A phenomenon common in centrifugal pumps that occurs when the pump attempts to discharge more flow than it is pulling in through the suction. Reduced internal pressure causes gases to expand and form bubbles around the impeller, which violently implode, potentially causing severe damage to the pump.

**Celsius** - The international name for the centigrade scale of temperature, on which the freezing point and boiling point of water are 0°C and 100°C, respectively, at 101 kPa (1 atm) of pressure. By international agreement, the term *Celsius* has replaced the term *Centigrade*.

**Centigrade** - By international agreement, the term *Celsius* has replaced the term *Centigrade*.

**Centrate** - Liquid removed by a centrifuge typically containing high concentrations of suspended, nonsettling solids.

**Centrifugal Blower** - A blower that typically is made up of multiple stages to achieve design airflow requirements. Each stage consists of an impeller rotating on a common shaft, enclosed within a casing.

**Centrifugal Non-clog Pump** - A type of centrifugal pump in which the impellers are rounded and free of sharp corners to minimize the chance of collecting rags and stringy objects, and the impeller is specially designed to pass larger solids.

**Centrifugal Pump** - A pump consisting of an impeller fixed on a rotating shaft and enclosed in a casing having an inlet and a discharge connection. The rotating impeller creates pressure in the liquid by the velocity derived from centrifugal force.

**CERCLIS** *(Pronounced SERK-liss)* - The federal Comprehensive Environmental Response, Compensation, and Liability Information System. This database includes all sites which have been nominated for investigation by the Superfund program and the actions that have been taken at these sites. If the site investigation reveals contamination, the site is ranked and may be included on the National Priorities List for Superfund cleanup. Inclusion in the CERCLIS database does not necessarily mean that a property is a hazardous waste site. An emergency action may have been conducted there or a simple investigation which concluded that no further action was required.

**Certification** - A program to substantiate the capabilities of personnel by documentation of experience and learning in a defined area of endeavor.

**Cess Pools** - This system is similar to a septic tank in performance. Sewage water usually seeps through the open bottom and portholes in the sides of the walls. These can also clog up with overuse and the introduction of detergents and other material which slow up the bacterial action.

**CFU** - Viable microorganisms (bacteria, yeasts, mold) capable of growth under the prescribed conditions (medium, atmosphere, time, and temperature) develop into visible colonies (colony-forming units) which are counted. The term *colony-forming unit* (CFU) is used because a colony may result from a single microorganism or from a clump/cluster of microorganisms.

**Chain and Sprocket** - A device used for the transmission of power where shafts are separated and the use of gears is impractical. Sprockets take the place of gears and drive one another by means of the chain passing over the sprocket teeth. A sprocket is a wheel with teeth shaped to mesh with the chain.

**Change of State** - The process by which a substance passes from one to another of the solid, liquid, and gaseous states, and in which marked changes in its physical properties and molecular structure occur.

**Channel** - (1) A perceptible natural or artificial waterway that periodically or continuously contains moving water or forms a connecting link between two bodies of water. It has a definite bed and banks that confine the water. (2) The deep portion of a river or waterway where the main current flows.

**Channel Roughness** - That roughness of a channel including the extra roughness owing to local expansion or contraction and obstacles, as well as the roughness of the stream bed proper; i.e., friction offered to the flow by the surface of the bed of the channel in contact with the water. It is expressed as the roughness coefficient in velocity formulas.

**Check Valve** - A valve with a disc hinged on one edge so that it opens in the direction of normal flow and closes with reverse flow. An approved check valve is of substantial construction and suitable materials, is positive in closing, and permits no leakage in a direction opposite to normal flow.

**Chelating Agents** - Organic compounds having the ability to withdraw ions from their water solutions into soluble complexes.

**Chemical Analysis** - Analysis by chemical methods to show the composition and concentration of substances.

**Chemical Abstract Service (CAS)** - Since the 1890s, CAS has been assigning identification numbers to chemicals that companies register with them. Every year, CAS updates and writes new chemical abstracts on well over a million different chemicals, including their composition, structure, characteristics, and all the different names of that chemical. CAS On-Line is a computer network available to individual and business account holders to receive information about specific chemicals of concern. Each abstract is accompanied by the CAS number.

**Chemical Coagulation** - The destabilization and initial aggregation of colloidal and finely divided suspended matter by the addition of an inorganic coagulant. See *flocculation*.

**Chemical Conditioning** - Mixing chemicals with a sludge prior to dewatering to improve the solids separation characteristics. Typical conditioners include polyelectrolytes, iron salts, and lime.

**Chemical Dose** - A specific quantity of chemical applied to a specific quantity of fluid for a specific purpose.

**Chemical Equilibrium** - The condition that exists when there is no net transfer of mass or energy between the components of a system. This is the condition in a reversible chemical reaction when the rate of the forward reaction equals the rate of the reverse reaction.

**Chemical Equivalent** - The weight (in grams) of a substance that combines with or displaces 1 g of hydrogen. It is found by dividing the formula weight by its valence.

**Chemical Feeder** - A device for dispensing a chemical at a predetermined rate for the treatment of water or wastewater. The change in rate of feed may be effected manually or automatically by flow rate changes. Feeders are designed for solids, liquids, or gases.

**Chemical Fixation** - The term *chemical fixation* implies transformation of toxic contaminants to new, nontoxic forms. As with stabilization/solidification, chemical fixation typically requires mechanical mixing or blending of reagents with the contaminated mass. These specially designed or proprietary reagents, incorporated during the mixing process, effect destruction, alteration, or chemical bonding of the contaminant(s). Although the treated mass is less or non-toxic, chemical fixation may be more costly than stabilization/solidification, depending upon the type of reagents required.

**Chemical Gas Feeder** - A feeder for dispensing a chemical in the gaseous state. The rate is typically graduated in gravimetric terms. Such devices may have proprietary names.

**Chemical Metering** - The use of a variable-speed pump to control the dose of a chemical being used for a particular application.

**Chemical Oxidation** - The oxidation of compounds in wastewater or water by chemical means. Typical oxidants include ozone, chlorine, and potassium permanganate.

**Chemical Oxygen Demand (COD)** - A quantitative measure of the amount of oxygen required for the chemical oxidation of carbonaceous (organic) material in wastewater.

**Chemical Precipitation** - (1) Formation of particulates by addition of chemicals. (2) The process of softening water by the addition of lime or lime and soda to form insoluble compounds; typically followed by sedimentation or filtration to remove the newly created suspended solids. Precipitation induced by addition of chemicals; the process of softening water by the addition of lime and soda ash as the precipitants.

**Chemical Reaction** - A transformation of one or more chemical species into other species, resulting in the evolution of heat or gas, color formation, or precipitation. It may be initiated by a physical process such as heating or by the addition of a chemical reagent, or it may occur spontaneously.

**Chemical Reagent** - A chemical added to a system to induce a chemical reaction.

**Chemical Slurry** - A thin mixture or suspension of fine particles of a chemical in a liquid, typically water.

**Chemical Solution Tank** - A tank in which chemicals are added in solution before they are used in a water or wastewater treatment process.

**Chemical Tank** - A tank in which chemicals are stored before they are used in a water or wastewater treatment process.

**Chemical Treatment** - Any treatment process involving the addition of chemicals to obtain a desired result such as precipitation, coagulation, flocculation, sludge conditioning, disinfection, or odor control.

**Chemoautotroph** - An organism that obtains its energy from the oxidation of chemical compounds and uses only organic compounds as a source of carbon. Example: nitrifiers.

**Chemotroph** - An organism that obtains its energy from the oxidation of chemical compounds.

**Chezy Formula** - Commonly used during sewer design to predict the minimum velocity required for the sewer to be "self-cleaning."

**Chloramine** - Combined chlorine formed by the reaction of ammonia. These are reported to be effective bactericides, although with a slower rate of kill. They are used where difficulty is experienced in maintaining a free chlorine residual and occasionally where phenolic taste makes chlorine undesirable due to the resulting chlorophenol taste. Chloramines are also formed by reaction with nitrogenous portions of the chlorine demand.

**Chlorination** - The application of chlorine to water or wastewater, generally for the purpose of disinfection, but frequently for accomplishing other biological or chemical results.

**Chlorinator** - Any metering device used to add chlorine to water or wastewater.

**Chlorine** - An element widely used in water and waste treatment for disinfection and sterilization; a valuable oxidizing agent. It is a greenish gas under normal conditions, choking and highly toxic on inhalation.

**Chlorine Dioxide** - A powerful oxidizing agent. It is unstable and is produced in water and waste plants by adding sodium chlorite (not chloride) to raw water containing an excess of chlorine. Caution: reacts violently with most organic material.

**Chlorine Dose** - The amount of chlorine applied to a wastewater, typically expressed in milligrams per liter (mg/l) or pounds per million gallons (lb/mil. gal).

**Chlorine Free** - Chlorine in solution uncombined or unreacted with other materials. This can obviously be obtained only after the entire chlorine demand has been satisfied. This is the most effective bactericidal state. It is common practice to refer to chlorine, hypochlorous acid, and hypochlorite as free chlorine residual.

**Chlorine Ice** - A yellowish ice formed in a chlorinator when chlorine gas comes in contact with water at 9°C (49°F) or lower. Chlorine ice is detrimental to the performance of a chlorinator if it is formed in quantities sufficient to interfere with the safe operation of float controls or to cause plugging of openings essential to flow indication, control, or rate of application.

**Chlorine Room** - A separate room or building for housing chlorine and chlorination equipment, with arrangements for protecting personnel and plant equipment.

**Chlorine Toxicity** - Detrimental effects on biota caused by the inherent properties of chlorine.

**Chlorofluorocarbons (CFCs)** - A family of chemicals commonly used in air conditioners and refrigerators as coolants and also as solvents and aerosol propellants. CFCs drift into the upper atmosphere where their chlorine components destroy ozone. CFCs are thought to be a major cause of the ozone hole over Antarctica.

**Chromatography** - The generic name of a group of separation processes that depend on the redistribution of the molecules of a mixture between a gas or liquid phase in contact with one or more bulk phases. Types of chromatography are adsorption, column, gas, gel, liquid, thin-layer, and paper.

**Chronic Dermatitis** - Skin disorder characterized by a superficial inflammation of the skin exhibiting erythema, oozing, crushing, scaling, and often vesicular formation. Also known as *eczema*, the term constitutes at least one half of all clinical dermatological conditions.

**Chronic Effect** - An adverse effect on any living organism in which symptoms develop slowly over a long period of time or recur frequently.

**Cilia** - Hairlike projections used by some microorganisms for feeding and locomotion.

**Ciliated Protozoa** - Microorganisms with cilia; common in trickling filters and healthy activated sludge. Free-swimming ciliates are present in the bulk liquid; stalked ciliates are commonly attached to solids matter in the liquid.

**Ciliates** - A class of protozoans distinguished by short hairs on all or part of their bodies.

**Clarification** - Any process or combination of processes whose primary purpose is to reduce the concentration of suspended matter in a liquid; formerly used as a synonym for *settling* or *sedimentation*. In recent years, the latter terms are preferred to describe settling processes.

**Clarifier** - Settling tank, sedimentation basin. A tank or basin in which wastewater is held for a period of time, during which the heavier solids settle to the bottom and the lighter material will float to the water surface.

**Class A Biosolids** — Material that has met the Class A pathogen reduction requirements or equivalent treatment by a Process to Further Reduce Pathogens (PFRP) in accordance with 40 CFR 503. Processes include composting, heat drying, heat treatment, thermophilic aerobic digestion, beta or gamma irradiation, and pasteurization.

**Class B Biosolids** — Material that has met the Class B pathogen reduction requirements or equivalent treatment by a Process to Significantly Reduce Pathogens (PSRP) in accordance with 40 CFR 503. Processes include aerobic digestion, composting, anaerobic digestion, lime stabilization, and air drying.

**Clean-out Hole** - Hole or port that is provided for inspection and maintenance purposes.

**Clean Water Organisms** - The association or ecological balance of many species that are found in an unpolluted environment. Attempts are made to use these as a measure of pollution. The same is true of polluted water organisms.

**Clear Cut** - Harvesting all the trees in one area at one time, a practice that destroys vital habitat and biodiversity and encourages rainfall or snowmelt runoff, erosion, sedimentation of streams and lakes, and flooding.

**Climate Change** - This term is commonly used interchangeably with "global warming" and "the greenhouse effect," but is a more descriptive term. Climate change refers to the buildup of man-made gases in the atmosphere that trap the sun's heat, causing changes in weather patterns on a global scale. The effects include changes in rainfall patterns, sea level rise, potential droughts, habitat loss, and heat stress. The greenhouse gases of most concern are carbon dioxide, methane, and nitrous oxides. If these gases in our atmosphere double, the earth could warm up by 1.5 to 4.5 degrees by the year 2050, with changes in global precipitation having the greatest consequences.

**Cloning** - In biotechnology, obtaining a group of genetically identical cells from a single cell; making identical copies of a gene.

**Close-coupled Pump** - A type of pump in which the pump shaft is integral with the motor shaft.

**Closed Conduit** - Any closed artificial or natural duct for conveying fluids.

**Closure** - The procedure an operator must go through when a landfill reaches the legal capacity for solid waste. No more waste can be accepted and a cap usually is placed over the site. The cap is then planted with grasses and other ground covers. Post-closure care includes monitoring ground water, landfill gases, and leachate collection systems, sometimes for as long as 30 years.

**Coagulant** - (1) A simple electrolyte, typically an inorganic salt containing a multivalent cation of iron, aluminum, or calcium (for example, $FeCl_3$, $FeCl_2$, $Al_2(SO_4)_3$, and CaO). (2) An inorganic acid or base that induces coagulation of suspended solids.

**Coagulant Aid** - Any material that substantially aids coagulation and/or flocculation but which would not function as a coagulant alone. Such materials are usually highly selective, and the dose is critical depending upon raw water conditions. They are widely diverse compounds, a few of which are clays, agar, gelatin, sodium silicate (activated silica) synthetic polymers, and natural or modified starch.

**Coagulant or Flocculant Aid** - An insoluble particulate used to enhance solid-liquid separation by providing nucleating sites or acting as a weighting agent or sorbent. Also used colloquially to describe the action of flocculants in wastewater treatment.

**Coagulation** - The conversion of colloidal ($<$ 0.001 mm) or dispersed (0.001 to 0.1 mm) particles into small visible coagulated particles (0.1 to 1 mm) by the addition of a coagulant, compressing the electrical double layer surrounding each suspended particle, decreasing the magnitude of repulsive electrostatic interactions between particles, and thereby destabilizing the particle. See *flocculation*.

**Coagulation Basin** - A basin used for the coagulation of suspended or colloidal matter, with or without the addition of a coagulant, in which the liquid is mixed gently to induce agglomeration with a consequent increase in the settling velocity of particulates.

**Coating** - A material applied to the inside or outside of a pipe, valve, or other fixture to protect it primarily against corrosion.

**Cocci** - Sphere-shaped bacteria.

**COD** - Chemical Oxygen Demand. The amount of oxygen in mg/l required to oxidize both organic and oxidizable inorganic compounds.

**Code of Federal Regulations (CFR)** - A periodic publication of the regulations established by U.S. law.

**Coefficient of Viscosity** - A numerical factor that is a measure of the internal resistance of a fluid to flow; the greater the resistance to flow, the larger the coefficient. It is equal to the shearing force in dynes per square centimeter (dyne/cm$^2$) transmitted from one fluid plane to another parallel plane 1 cm distant, and is generated by a difference in fluid velocities in the two planes of 1 cm/s in the direction of the force. The coefficient varies with temperature. Also called *absolute viscosity*. The unit of measure is the *poise*, a force of 1 dyne/cm$^2$.

**Cohesion** - The force of molecular attraction between the particles of any substance that tends to hold them together.

**Coliform** - A bacteria group used as an indicator of fecal contamination. Except for special cases they are considered benign. A positive test indicates the possibility of the presence of enteric pathogens, disease germs originating in the intestine.

**Coliform Bacteria** - Current identification and enumeration methods for particular pathogenic bacteria, virus, and protozoa are tedious, time-consuming, and expensive. It is not feasible to test for each individual microorganism that may be present. It is therefore necessary to test for indicator organisms: organisms which are not pathogenic themselves but indicate there is a source of biological contamination which may contain pathogenic organisms. The coliform group of bacteria is used as the principal indicator of suitability of a water for domestic, industrial, or other uses. Fecal coliforms are those coliform bacteria present in the gut and feces of warm-blooded animals; therefore, their presence in water is an indication of fecal contamination and the possible presence of enteric pathogens. The absence of coliform bacteria does not guarantee the absence of pathogens.

**Coliform-Group Bacteria** - Microorganisms predominantly inhabiting the intestines of humans and other animals, but also occasionally found elsewhere. They include all aerobic and facultative anaerobic, Gram-negative, nonspore-forming, rod-shaped bacteria that ferment lactose with the production of gas. Also included are all bacteria that produce a dark, purplish-green metallic sheen by the membrane filter technique used for coliform identification.

**Coliform Organisms** — Microorganisms found in the intestinal tracts of humans and animals. Their presence in water indicates fecal pollution and potentially adverse contamination by pathogens.

**Collection System** - In wastewater, a system of conduits, typically underground pipes, that receive and convey sanitary wastewater or storm water. In a water supply, a system of conduits or canals used to capture a water supply and convey it to a common point.

**Colloid, Colloidal** - Small solid particles dispersed in a water medium is the class of colloidal dispersion normally dealt with in water and waste treatment. The particle size is from 1 to 100 millimicrons, although the actual size may be open to argument, especially at the smaller end of the scale. The particles are charged and exhibit Brownian movement and the Tyndall effect.

**Colloids** - Very small, finely divided solids (particles that do not dissolve) that remain dispersed in a liquid for a long time because of their small size and electrical charge.

**Colony** - A discrete mass of microorganisms on a surface as opposed to dispersed growth throughout a liquid culture medium.

**Color** - Any dissolved solids that impart a visible hue to water.

**Colorimeter** - An instrument that quantitatively measures the amount of light of a specific wavelength absorbed by a solution.

**Combined Available Chlorine** - The concentration of chlorine which is combined with ammonia ($NH_3$) as chloramine or as other chloro derivatives, yet is still available to oxidize organic matter.

**Combined Sewer** - A sewer intended to receive both wastewater and stormwater.

**Combined Sewer Overflow (CSO)** - A mixture of wastewater and runoff found in combined sewers during rainfall or snowmelt events that spills to the environment untreated. CSOs enter the environment either directly or through a storm sewer, as the result of the capacities of the interceptor sewers and/or treatment plants being exceeded.

**Combined Sewer System** - A system of sewers designed to collect and convey wastewater and runoff from urban areas to the receiving stream or to a treatment plant if one is available. This is an old style of providing sewer service and drainage and was discontinued in the 1950s in favor of separate storm and sanitary sewers.

**Combustible-Gas Indicator** - A device for measuring the concentration of potentially explosive fumes. The measurement is based on the catalytic oxidation of a combustible gas on a heated platinum filament that is part of a Wheatstone bridge. Also known as an *explosimeter*.

**Commensalism** - When two organisms coexist, and one organism benefits, while the other is not affected.

**Commercial Waste** - All solid waste from businesses. This category includes, but is not limited to, solid waste originating in stores, markets, office buildings, restaurants, shopping centers, and theaters.

**Commercial Waste Management Facility** - A treatment, storage, disposal, or transfer facility that accepts wastes from a variety of sources for profit. A commercial facility manages a broader spectrum of wastes than a private facility, which normally manages a limited volume or type of waste.

**Comminution** - Shredding. A mechanical treatment process which cuts large pieces of waste into smaller pieces so that they won't plug pipes or damage equipment.

**Comminutor** - A device for the catching and shredding of heavy solid matter in the primary stage of waste treatment.

**Community Relations** - Two-way communications with the public to foster understanding of EPA programs and actions and to increase citizen input into EPA decisions. Specific community relations activities such as holding public meetings and comment periods and opening information repositories are required at Superfund sites.

**Complete Mix** - Activated-sludge process whereby wastewater is rapidly and evenly distributed throughout the biological reactor.

**Composite Sample** - A combination of individual samples of water or wastewater taken at preselected intervals to minimize the effect of the variability of the individual sample. Individual samples may be of equal volume or may be proportional to the flow at time of sampling.

**Compost** - Decomposed organic material that is produced when bacteria in soil break down garbage and biodegradable trash, making organic fertilizer. Making compost requires turning and mixing and exposing the materials to air. Gardeners and farmers use compost for soil enrichment.

**Composting** - This is the process in which solid organic materials are decomposed in the presence of oxygen through the action of bacteria and other microorganisms. Dewatered biosolids are mixed with sawdust or wood chips that act as bulking agent by absorbing water and increasing the porosity of the mixture. This mix is then composted and cured for a minimum of 6 weeks. High temperatures (103 to 150°F) generated during this process pasteurize the mixture. A peatlike product is the end result. Composted biosolids are easier to handle, store, and use than liquid and dewatered biosolids.

**Compressed Air** - Air that has been reduced in volume and thereby exerts a pressure.

**Compression Ring** - A fitting used in certain kinds of pump seals to maintain pressure against the shaft packing.

**Concentration** - (1) The amount of a given substance dissolved in a discrete unit volume of solution or applied to a unit weight of solid. (2) The process of increasing the dissolved solids per unit volume of solution, typically by evaporation of the liquid. (3) The process of increasing the suspended solids per unit volume of sludge as by sedimentation or dewatering.

**Concentrator** - A solids contact unit used to decrease the water content of sludge or slurry.

**Concentric Reducer** - A pipe fitting that has flanges on both ends and that is used to transition between pipes with different sizes. These circular flanges share a common center.

**Condensate** - Condensed steam from any heat exchanger.

**Condensation** - The process by which a substance changes from the vapor state to the liquid or solid state.

**Condenser** - Any device for reducing gases or vapors to liquid or solid form.

**Conditionally Exempt Generators** - Small quantity facilities that produce fewer than 220 pounds of hazardous waste per month. Exempt from most regulations, conditionally exempt generators are required to determine whether their waste is hazardous and to notify local waste management agencies. These generators may treat or dispose of the waste on site or ensure that the waste is sent to a permitted disposal or recycling facility.

**Conditioning** - The chemical, physical, or biological treatment of sludges to improve their dewaterability.

**Conductivity** - The ability of a substance to conduct heat or electricity. Electrical conductivity is usually expressed in microsiemens per centimeter.

**Cone of Depression** - A lowering in the water table that develops around a pumped well.

**Connecting Rod** - A plunger pump component that connects the shaft to the plunger.

**Consent Decree** - A legal document submitted by the Department of Justice on behalf of the EPA for approval by a federal judge to settle a case. A consent decree can be used to formalize an agreement reached between EPA and potentially responsible parties (PRPs) for cleanup at a Superfund site. Consent decrees also are signed by regulated facilities to cease or correct certains actions or processes that are polluting the environment and include payment of penalties. The Clean Water Act, Clean Air Act, Toxic Substances Control Act, and others all use consent decrees.

**Conservation** - Preserving and renewing natural resources to ensure their highest economic or social benefit over the longest period of time. Clean rivers and lakes, wilderness areas, a diverse wildlife population, healthy soil, and clean air are natural resources worth conserving for future generations.

**Consistency** - In the pulp/paper industry, a term for the density in percent by weight dry matter, of a slurry of pulp.

**Construction and Demolition Waste** - Waste building materials, dredging materials, tree stumps, and rubble resulting from construction, remodeling, repair, and demolition operations on houses, commercial buildings and other structures, and pavements. May contain lead, asbestos, or other hazardous materials.

**Contact Stabilization** - Contact stabilization is a modification of the conventional activated sludge process. In contact stabilization, two aeration tanks are used. One tank is for separate reaeration of the return sludge for at least 4 hours before it is permitted to flow into the other aeration tank to be mixed with the primary effluent requiring treatment.

**Contact Tank** - A tank used in water or wastewater treatment to promote contact among treatment chemicals or other materials and the liquid treated.

**Contact Time** - The period of time that the material being processed is exposed to another substance, such as activated sludge or activated carbon, for completion of the desired reaction. See *detention time.*

**Contaminant** - Any foreign component present in another substance.

**Contamination** - The introduction into water of microorganisms, chemicals, wastes, or wastewater in a concentration that makes the water unfit for its intended use.

**Continuous Discharge** - A permitted release of pollutants into the environment that occurs without interruption, except for infrequent shutdowns for maintenance, process changes, etc.

**Continuous-flow Tank** - A tank through which liquid flows continuously at its normal rate of flow, as distinguished from a fill-and-draw or batch system.

**Contracted Weir** - A rectangular notched weir with a crest width narrower than the channel across which it is installed and with vertical sides extending above the upstream water level, producing a contraction in the stream of water as it leaves the notch.

**Controlled Discharge** - Regulation of effluent flow rates to correspond with flow variations in receiving waters to maintain established water quality.

**Controlled Reaction** - A chemical reaction at temperature and pressure conditions that are maintained within safe limits to produce a desired product.

**Controller** - A device or group of devices that govern in some predetermined measure the electrical power delivered to the apparatus to which it is connected.

**Convection** - In physics, mass motions within a fluid resulting in the transport and mixing of the properties of that fluid, caused by the force of gravity and by differences in density resulting from nonuniform temperature.

**Conventional Aeration** - Process design configuration whereby the aeration tank organic loading is higher at the influent end than at the effluent end. Flow passes through a serpentine tank system, typically side-by-side, before passing on to the secondary clarifier. Also called *plug flow.*

**Conventional Treatment** - Well-known or well-established water or wastewater treatment processes, excluding advanced or tertiary treatment. It typically consists of primary and secondary treatment.

**Conversion** - Changing from one substance to another., e.g., as food matter is changed to cell growth or to carbon dioxide.

**Conveyance Loss** - The loss of water from a conduit due to leakage, seepage, evaporation, or evapotranspiration.

**Copper Sulfate** - Cupric sulfate, bluestone. Its major use in water treatment is as an algaecide.

**Copperas** - An industrial by-product varying between manufacturers in chemical content, impurities, and physical properties. The iron content is bivalent. Its use by mistake instead of ferric sulfate could be harmful, since if not fully oxidized to the ferric state it will carry through to the finished water. Both ferrous and ferric sulfates can be called iron sulfate in generic terminology.

**Copperas Chlorinated** - Ferrous sulfate oxidized with chlorine in order to function as a coagulant. Theoretically, 1 pound of chlorine is required to oxidize 8 pounds of copperas. In practice, an excess of chlorine is needed. If the copperas is not totally oxidized, soluble ferrous iron will carry through to the finished water.

**Core Sampler** - A long, slender pole with a foot valve at the bottom end that allows the depth of the sludge blanket to be measured.

**Correlation** - The degree of relative correspondence, as between two sets of data.

**Corrosion** - A term usually used in reference to metals. It is the result of a chemical or galvanic reaction in which the metal is solubilized or changed to a soluble metal salt thereby losing weight and being weakened. Where iron is corroded in finished water, the solubilized iron results in water quality problems.

**Corrosion Control** - (1) In water treatment, any method that keeps the metallic ions of a conduit from going into solution, such as increasing the pH of the water, removing free oxygen from the water, or controlling the carbonate balance of the water. (2) The sequestration of metallic ions and the formation of protective films on metal surfaces by chemical treatment.

**Corrosive** - A substance that eats or wears away materials gradually by chemical action.

**Corrosive Industrial Waste** - Liquid waste that is sufficiently acidic or alkaline to dissolve and wear away metal.

**County Emergency Operations Plan** - A plan required by Federal Emergency Management Agency regulations that describes actions the county will take to respond to emergency situations such as natural disasters, major fires, transportation incidents, or chemical releases.

**Coupling** - A mechanical device for connecting two adjacent parts together, such as connecting a motor to a shaft of a pump.

**Covered Facility** - A facility having one or more of the 366+ extremely hazardous substances in amounts higher than the quantity designated by EPCRA. These facilities must file reports with the SERC and LEPC.

**Cracking** - An oil-refining process that breaks large molecules into smaller ones.

**Cradle-to-Grave or Manifest System** - A procedure in which hazardous wastes are identified as they are produced and are followed through further treatment, transportation, and disposal by a series of permanent, linkable, descriptive documents.

**Criteria** - Descriptive factors taken into account by EPA in setting standards for pollutants. For example, water quality criteria describe the concentration of pollutants that most fish can be exposed to for an hour without showing acute effects.

**Critical Depth** - The depth of water flowing in an open channel or partially filled conduit corresponding to one of the recognized critical velocities.

**Critical Flow** - (1) A condition of flow in which the mean velocity is at one of the critical values, ordinarily at Belanger's critical depth and velocity. Also used in reference to Reynolds' critical velocities, which define the point at which the flow changes from streamline or nonturbulent flows to turbulent flow. (2) The maximum discharge of a conduit that has a free outlet and has the water ponded at the inlet.

**Crops** - Crops are plants grown for human or animal consumption and use. Crops used directly for human consumption are those eaten by humans with only superficial washing in water. Crops may be processed for human consumption by many means, most of which reduce the likelihood of contact with or ingestion of pathogens. Food chain crops are those crops ultimately used for food by humans and other animals.

**Cross Connection** - (1) A physical connection through which a supply of potable water could be contaminated or polluted. (2) A connection between a supervised potable water supply and an unsupervised supply of unknown potability.

**CRT** - Cell residence time - the amount of time in days that an average bug remains in the process. Also termed *sludge age.*

**Cryogenic Oxygen Generation** - The production of high-purity liquid oxygen by cooling air to very low temperatures (i.e., 40 K).

**Cryptosporidium** - Cryptosporidium is also a parasite, found in the feces of warm-blooded animals, including livestock, wildlife, and humans. The cyst form of cryptosporidium is called an oocyst. Crytosporidium causes severe diarrhea which can be fatal to immunocompromised persons (e.g. AIDS victims, elderly, chemotheraphy patients). As with giardia, analyses for cryptosporidium take 3 days to be completed.

**Cubic Foot per Second (cfs)** - The rate of flow equal to 1 cubic foot of material per second; used for measurement of water, wastewater, or gas. Equivalent to 2.832 x $10^{-2}$ $m^3/s$.

**Cubic Meter per Second (cms)** - The rate of flow equal to 1 cubic meter of material per second; used for measurement of water, wastewater, or gas.

**Culture** - Any organic growth that has been developed intentionally by providing suitable nutrients and a suitable environment.

**Culture Media** - Substances used to support the growth of microorganisms in analytical procedures.

**Current Meter** - A device used to measure the water velocity or current in a river.

**Curtain Drain** - A drain constructed at the upper end of the area to be drained, to intercept surface or ground water flowing toward the protected area from higher ground, and carry it away from the area. Also called an *intercepting drain*.

## D

**D/I Unit** - Deionizing unit, frequntly used to maintain water quality in aquariums. Advantages: does not waste water like the R/O unit, is designed to be hooked up to either a faucet or household piping system, the anion and cation resins can be regenerated (with another expensive unit) indefinitely, and these systems allow a larger water flow (up to 2,000 gallons a day), than an R/O system. However, they also cost dramatically more.

**DAF** - Dissolved Air Flotation - one of many designs for waste treatment.

**Data** - Records of observations and measurements of physical facts, occurrences, and conditions reduced to written, graphical, or tabular form.

**Day-Second Foot (dsf)** - A volume equivalent to a flow of 1 cubic foot per second maintained for 1 day.

**Decant** - To draw off the upper layer of liquid after the denser material (a solid or another liquid) has settled.

**Decantation** - Separation of a liquid from solids or from a liquid of higher density by drawing off the upper layer after the heavier material has settled.
**Dechlorination** - The partial or complete reduction of residual chlorine by any chemical or physical process. Sulfur dioxide is frequently used for this purpose.

**Decitex (dtex)** - The mass in grams of 10,000 m of fiber or yarn. A direct yarn numbering system used to define size of fiber or yarn. The higher the number, the coarser (larger) the yarn.

**Declining Growth** - A growth phase in which the availability of food begins to limit cell growth.

**Declining Growth Phase** - Period of time between the log growth phase and the endogenous phase, where food is in short supply, leading to ever-slowing bacterial growth rates.

**Decomposition** - The breakdown of complex material into simpler substances by chemical or biological processes.

**Decomposition of Wastewater** - (1) The breakdown of organic matter in wastewater by bacterial action, either aerobic or anaerobic. (2) Chemical or biological transformation of organic or inorganic materials contained in wastewater.

**Deep Well Injection** - A process by which waste fluids are injected deep below the surface of the earth.

**Defoamer** - A material having low compatibility with foam and a low surface tension. Defoamers are used to control, prevent, or destroy various types of foam, the most widely used being silicone defoamers. A valuable property of most defoamers is their effectiveness in extremely low concentration. Defoamers for special purposes are based on polyamides, vegetable oils, and stearic acid. Also referred to as *antifoam agents*.

**Degasification** - (1) The removal of a gas from a liquid medium. (2) In water treatment, the removal of oxygen from water to inhibit corrosion.

**Degradation** - A growth phase in which the availability of food begins to limit cell growth.

**Degreasing** - (1) The process of removing greases and oils from waste, wastewater, sludge, or solids. (2) The industrial process of removing grease and oils from machine parts or iron products.

**Degree** - (1) On the Celsius thermometer scale, 1/100 of the interval from the freezing point to the boiling point of water under standard conditions; on the Fahrenheit scale, 1/180 of this interval. (2) A unit of angular measure; the central angle subtended by 1/360 of the circumference of a circle.

**Deinking** - The process of removing ink from secondary fibers.

**Deionization** - Any process removing ions from water, but most commonly an ion exchange-process where cations and anions are removed independently by each other.

**Deionized Water** - Water that goes through an ion-exchange process in which all positive and negative ions are removed.

**Delist** - Use of the petition process (1) to have a chemical's toxic designation rescinded; (2) to remove a site from the National Priority List; or (3) to exclude a particular waste from regulation even though it is a listed hazardous waste.

**Demineralization** - Any process used to remove minerals from water; however, commonly the term is restricted to ion exchange processes.

**Denier** - The mass in grams of 9000 m of fiber or yarn. A direct numbering system used to define size of fiber or yarn. The higher the number, the coarser (larger) the yarn.

**Denitrification** - An anaerobic biological reduction of nitrate nitrogen to nitrogen gas, the removal of total nitrogen from a system, and/or an anaerobic process that occurs when nitrite ions are reduced to nitrogen gas and bubbles are formed as a result of this process. The bubbles attach to the biological floc in the activated sludge process and float the floc to the surface of the secondary clarifiers. This condition is often the cause of rising sludge observed in secondary clarifiers or gravity thickeners. (See *nitrification*).

**Density Current** - A flow of water through a large body of water that retains its unmixed identity because of a difference in density.

**Deoxygenation** - The depletion of dissolved oxygen in a liquid either under natural conditions associated with the biochemical oxidation of the organic matter present or by addition of chemical reducing agents.

**Deoxygenation Constant** - A constant that expresses the rate of the biochemical oxidation of organic matter under aerobic conditions.

**Deposition** - The act or process of settling solid material from a fluid suspension.
**Depth Filter** - A filter medium consisting of randomly distributed particles or fibers resulting in openings with a nonuniform and tortuous path.

**Depth of Blanket** - Level of sludge in the bottom of a secondary clarifier.

**Desalination** - The removal of inorganic dissolved solids from water.

**Desalting** - The removal of salt from crude oil.

**Designated Beneficial Use** - Desirable uses that water quality should support (e.g., drinking water, recreation, aquatic life). Each designated use has a unique set of water quality requirements that must be met for the use to be realized.

**Design Criteria** - (1) Engineering guidelines specifying construction details and materials. (2) Objectives, results, or limits that must be met by a facility, structure, or process in performance of its intended functions.

**Design Flow** - Engineering guidelines that typically specify the amount of influent flow that can be expected on a daily basis over the course of a year. Other design flows can be set for monthly or peak flows.

**Design Loadings** - Flow rates and constituent concentrations that determine the design of a process unit or facility necessary for proper operation.

**Destruction and Removal Efficiency (DRE)** - A percentage that represents the number of molecules of a compound removed or destroyed in an incinerator. A DRE of 99.99% means that 9999 molecules are destroyed for every 10,000 that enter.

**Detackify** - Treatment of solids from a paint spray booth to eliminate their sticky properties.

**Detention Time** - The period of time that a water or wastewater flow is retained in a basin, tank, or reservoir for storage or completion of physical, chemical, or biological reaction. See *contact time*.

**Detergent** - (1) Any of a group of synthetic, organic, liquid, or water-soluble cleaning agents that are inactivated by hard water and have wetting and emulsifying properties but, unlike soap, are not prepared from fats and oils. (2) A substance that reduces the surface tension of water.

**Detoxification** - Physical or chemical treatment to reduce or eliminate the toxicity of a material.

**Detritus** - Dead plant and animal matter, usually consumed by bacteria, but some remains.

**Dewater** - (1) To extract a portion of the water present in a sludge or slurry. (2) To drain or remove water from an enclosure. A structure may be dewatered so that it can be inspected or repaired.

**Dewatering, Dewatered Biosolids** - A process used to remove water from biosolids producing dewatered biosolids that contain equal to or greater than 20% dry solids.

**Dewpoint** - The temperature at which air with a given concentration of water vapor must be cooled to cause condensation of the vapor.

**Dialysis** - A separation process that depends on differences in diffusion rates of solutes across a permeable membrane.

**Diaphragm** - A dividing membrane or thin flexible partition.

**Diaphragm Pump** - A positive-displacement pump in which a flexible diaphragm, typically made of rubber or other resilient material, is the operating part. The diaphragm is fastened at the edges in a vertical cylinder. When the diaphragm is raised, suction is exerted, and when it is depressed, the liquid is forced through a discharge valve.

**Diaphragm-type Pressure Gauge** - The measurement from this type of gauge is taken from the movement of the diaphragm, located near the connection to the main line, due to pressure changes in the line. These types of gauges are very useful for measuring the pressure of sludge lines because they are not as prone to clogging as conventional gauges.

**Diatomaceous Earth** - A fine, siliceous (made of silica) "earth" composed mainly of the skeletal remains of diatoms (single cell microscopic algae with rigid internal structure consisting mainly of silica). Tests prove that DE leaches unacceptable amounts of silicate into the water for fish health. If used as a filter substance, a silicone removing resin should be employed afterwards.

**Diatoms** - Organisms related to algae, having a brown pigmentation and a siliceous skeleton.

**Differential Pressure** - The difference in pressure between two points of a system, such as between two sides of an orifice.

**Diffused Aeration** - Injection of air under pressure through submerged porous plates, perforated pipes, or other devices to form small air bubbles from which oxygen is transferred to the liquid as the bubbles rise to the water surface.

**Diffused Air** - A technique by which air under pressure is forced into sewage in an aeration tank. The air is pumped down into the sewage through a pipe and escapes out through holes in the side of the pipe.

**Diffused-Air Aeration** - A diffused-air activated-sludge plant takes air, compresses it, and then discharges the air below the water surface of the aerator through some type of air diffusion device.

**Diffuser** - A porous plate, tube, or other device through which air is forced and divided into minute bubbles for diffusion in liquids. In the activated-sludge process, it is a device for dissolving air into mixed liquor. It is also used to mix chemicals such as chlorine to process streams.

**Diffusion** - (1) The transfer of mass from one fluid phase to another across an interface, for example, liquid to solid or gas to liquid. (2) The spatial equalization of one material throughout another.

**Diffusion Aerator** - An aerator that blows air under low pressure through submerged porous plates, perforated pipes, or other devices so that small air bubbles rise continuously through the water or wastewater.

**Digester** - A tank in which sludge is placed to allow decomposition by microorganisms. Digestion may occur under anaerobic (most common) or aerobic conditions.

**Digestion** - (1) The biological decomposition of the organic matter in sludge, resulting in partial liquefaction, mineralization, and volume reduction. (2) The process carried out in a digester.

**Digestion, Digester** - A term generally used to describe a process of anaerobic decomposition of putrifiable solids to methane and carbon dioxide. Total detention time is reported to be from 10 to 30 days to 2 to 3 months. Sometimes aerobic digestion is used.

**Dilution Factor** - The effect of a large volume of liquid dilution.

**Direct Current (DC)** - An electric current that flows in one direction only and is substantially constant in value.

**Discharge** - (1) Flow from a canal, conduit, pump, stack, tank, or treatment process. (2) The volume of the liquid flowing through a cross section per unit of time, often denoted as Q. See *effluent*.

**Discharge Area** - The cross-sectional area of a waterway. Used to compute the discharge of a stream, pipe, conduit, or other carrying system.

**Discharge Capacity** - The maximum rate of flow that a conduit, channel, or other hydraulic structure is capable of passing.

**Discharge Head** - A measure of the pressure exerted by a fluid at the point of discharge, typically from a pump.

**Discharge Pressure Switch** - A switch used to provide feedback on the operation status of the pump. The switch is mounted on the discharge side of the pump and energized at preset pressures.

**Discharge Rate** - Determination of the quantity of water flowing per unit of time in a stream channel, conduit, or orifice at a given point by means of a current meter, rod float, weir, pitot tube, or other measuring device or method. The operation includes not only the measurement of velocity of water and the cross-sectional area of the stream of water but also the necessary subsequent computations.

**Discharge Valve** - A valve located immediately downstream of a pump that can be used for throttling or isolating the discharge piping from the pump.

**Discrete Sedimentation** - Sedimentation in which removal of suspended solids is a function of terminal settling velocity.

**Disinfectant** - A substance used for disinfection and in which disinfection has been accomplished.

**Disinfected Wastewater** - Wastewater to which a disinfecting agent has been added.

**Disinfection** - (1) The killing of waterborne fecal and pathogenic bacteria and viruses in potable water supplies or wastewater effluents with a disinfectant; an operational term that must be defined within limits, such as achieving an effluent with no more than 200 colonies fecal coliform/100 ml. (2) The killing of the larger portion of microorganisms, excluding bacterial spores, in or on a substance with the probability that all pathogenic forms are killed, inactivated, or otherwise rendered nonvirulent.

**Dispersant** - A chemical which causes particulates in a water system to remain in suspension.

**Dispersion** - (1) Scattering and mixing. (2) The mixing of polluted fluids with a large volume of water in a stream or other body of water. (3) The repelling action of an electric potential on fine particles in suspension in water, as in a stream carrying clay. (4) In a continuous flow treatment unit, the phenomenon of short circuiting.

**Dispersion Model** - A mathematical prediction of how pollutants from a discharge or emission source will be distributed in the surrounding environment under given conditions of wind, temperature, humidity, and other environmental factors.

**Displacement Pump** - A type of pump in which the water is induced to flow from the source of supply through an inlet pipe and valve and into the pump chamber by a vacuum created therein by the withdrawal of a piston or pistonlike device which, on its return, displaces a certain volume of the water contained in the chamber and forces it to flow through discharge valves and pipes.

**Disposal** - Release to the environment.

**Disposal Facility** - A landfill, incinerator, or other facility which receives waste for disposal. The facility may have one or many disposal methods available for use. Does not include wastewater treatment.

**Dissolved Oxygen** - Oxygen dissolved in system above requirements for BOD and COD. Measure of water quality.

**Dissolved Pollutants** - Dissolved organic or inorganic material that, at certain concentrations, can render water unfit for potable or nonpotable uses by living organisms.

**Dissolved Solids (DS)** - Technically any material that has been dissolved becoming a true solution. Finely divided and colloidal solids sometime are reported as DS or total dissolved solids TDS. These are more correctly included as suspended solids, although State Health Department procedures usually are followed.

**Distillation** - In waste treatment, consists of heating the effluent and then removing the vapor or steam. When the steam is returned to a liquid it is almost pure water. The pollutants remain in the concentrated residue.

**Distributed Control System (DCS)** - An instrumentation control system of microprocessors located near the equipment they control and linked through a communications network. The overall status of the system can be monitored and operating parameters can be changed from a central operator control station.

**Distribution Box** - Serves to distribute the flow from the septic tank evenly to the absorption field or seepage pits. It is important that each trench or pit receive an equal amount of flow. This prevents overloading of one part of the system.

**Distributor** - The rotating mechanism that distributes the wastewater evenly over the surface of a trickling filter or other process unit.

**Diurnal** - (1) Recurring every day. (2) Occurring during the daytime, but not at night.

**DMR** - Discharge Monitoring Reports.

**DO** - Dissolved Oxygen. A measure of the oxygen dissolved in water expressed in milligrams per liter.

**Domestic Wastewater** - Wastewater derived principally from nonindustrial sources (e.g., dwellings, business buildings, institutions).

**Dose** - In terms of monitoring exposure levels, the amount of a toxic substance taken into the body over a given period of time.

**Dose Response** - How an organism's response to a toxic substance changes as its overall exposure to the substance changes. For example, a small dose of carbon monoxide may cause drowsiness; a large dose can be fatal.

**Dosing Tank** - Any tank used in applying a dose; specifically used for intermittent application of wastewater to subsequent processes.

**DOT** - Department of Transportation.

**Double-Suction Pump** - An impeller with two suction inlets, one on each side of the impeller.

**DOUR** - Dissolved Oxygen Uptake Ratio.

**Downstream Side** - The side of a product stream that has already passed through a given filter system; portion located after the filtration unit.

**Drag** - The resistance offered by a liquid to the settlement or deposition of a suspended particle.

**Drag Coefficient** - A measure of the resistance to sedimentation or flotation of a suspended particle as influenced by its size, shape, density, and terminal velocity. It is the ratio of the force per unit area to the stagnation pressure and is dimensionless.

**Drain** - (1) A conduit or channel constructed to carry off, by gravity, liquids other than wastewater, including surplus underground, storm, or surface water. It may be an open ditch, lined or unlined, or a buried pipe. (2) In plumbing, any pipe that carries water or wastewater in a building drainage system.

**Drain Valve** - A valve located at a low point on a pump that can be opened when the pump is taken out of service to allow it to drain by gravity.

**Drawdown** - (1) The magnitude of the change in surface elevation of a body of water as a result of the withdrawal of water. (2) The magnitude of the lowering of the water surface in a well, and of the water table or piezometric surface adjacent to the well, resulting from the withdrawal of water from the well by pumping. (3) In a continuous water surface with accelerating flow, the difference in elevation between downstream and upstream points.

**Drip-Proof Motor** - A type of squirrel cage motor designed to be open to the atmosphere for cooling the windings. The ventilation openings on these motors are constructed so that water falling on the motor from a vertical angle of no greater than 15 degrees will not enter the motor. These motors are used for indoor or weatherproof and dust-free applications.

**Dry-Bulb Temperature** - The temperature of air measured by a conventional thermometer.

**Dry Feeder** - A feeder for dispensing a chemical or other fine material to water or wastewater at a rate controlled manually or automatically by the rate of flow. The constant rate may be either volumetric or gravimetric.

**Dry Suspended Solids** - The weight of the suspended matter in a sample after drying for a specified time at a specific temperature.

**Dry Weather Flow** - (1) The flow of wastewater in a combined sewer during dry weather. Such flow consists mainly of wastewater, with no stormwater included. (2) The flow of water in a stream during dry weather, typically contributed entirely by groundwater.

**Dry Weight Basis** - Calculated on the basis of having been dried at 105°C until reaching a constant mass (i.e., essentially 100% solids).

**Dry Well** - A dry compartment in a pumping station, near or below pumping level, where the pumps are located.

**Dual Chamber Test Method** - Measures near field shielding effectiveness by indicating the signal attenuation caused by passage through test material.

**Dump** - A land site where wastes are discarded in a disorderly or haphazard fashion without regard to protecting the environment. Uncontrolled dumping is an indiscriminate and illegal form of waste disposal. Problems associated with dumps include multiplication of disease-carrying organisms and pests, fires, air and water pollution, unsightliness, loss of habitat, and personal injury.

**Duplex Pump** - A reciprocating pump consisting of two cylinders placed side by side and connected to the same suction and discharge pipe; the pistons move so that one exerts suction while the other exerts pressure, resulting in continuous discharge from the pump.

**Dyeing** - The process of adding color to textiles in either fiber, yarn, or fabric form.

**Dynamic Head** - (1) When there is flow, (a) the head at the top of a waterwheel; (b) the height of the hydraulic grade line above the top of a waterwheel; or (c) the head against which a pump works. (2) That head of fluid that would produce statically the pressure of a moving fluid.

**Dynamic Suction Head** - In systems where the pump is located below the free surface of the liquid to be pumped, it is the vertical distance from the surface of the liquid to the centerline of the suction end of the pump minus the velocity head and entrance and friction losses. Internal pump losses are not subtracted.

**Dynamic Suction Lift** - In systems where the pump is situated at a higher elevation than the free surface of the liquid to be pumped, it is the vertical distance from the surface of the liquid to the center line of the suction end of a pump plus velocity head and entrance and friction losses. Internal pump losses are not added.

## E

***E. coli*** - *Escherichia coli* is one of the nonpathogenic coliform organisms used to indicate the presence of pathogenic bacteria in water.

**Ecology** - The study of the relationships between all living organisms and the environment, especially the totality or pattern of interactions; a view that includes all plant and animal species and their unique contributions to a particular habitat.

**Eccentric Disc** - A disc with an axis that is offset from its true center so that it is capable of imparting a reciprocating motion when it revolves.

**E-Field (Electric Field)** - The dominant component of a high impedance electromagnetic field produced by a near field source such as a short diapole, or the electric component of a far-field plane wave. Expressed in V/m.

**Eccentric Reducer** - A pipe fitting with two different sized flanges at each end that is used to join two pipes of different sizes. These circular flanges are offset eccentrically (i.e., they share a common invert).

**Ecology** -The study of all aspects of how organisms interact with each other and/or their environment.

**Ecosystem** - Groupings of various organisms interacting with each other and their environment.

**Eductor** - (1) A device for mixing air with water. (2) A liquid pump operating under a jet principle, using liquid under pressure as the operating medium to entrain air in the liquid. See *ejector*.

**Effective Area** - The total area of the porous medium exposed to flow in a filter element.

**Effective Size** - The diameter of the particles of a hypothetical sample of granular material-composed of particles that are spherical in shape, equal in size, and arranged in a given manner-that would have the same transmission constant as the actual material under consideration.

**Effervescence** - The vigorous escape of small gas bubbles from a liquid, especially as a result of chemical action.

**Efficiency** - The ratio of the useful energy delivered by a dynamic system to the energy supplied to it.

**Effluent** - Wastewater or other liquid, partially or completely treated or in its natural state, flowing out of a reservoir, basin, treatment plant, or industrial treatment plant, or part thereof.

**Effluent Guidelines** - Technical documents developed by EPA which set discharge limits for particular types of industries and specific pollutants.

**Effluent Limitations** - Limits on the amounts of pollutants which may be discharged by a facility; these limits are calculated so that water quality standards will not be violated even at low stream flows.

**Effluent Quality** - The physical, biological, and chemical characteristics of a wastewater or other liquid flowing out of a basin, reservoir, pipe, or treatment plant.

**EGL** - Energy Grade Line. A line that represents the elevation of energy head in feet of water flowing in a pipe, conduit, or channel.

**Ejector** - A device for moving a fluid or solid by entraining it in a high-velocity stream of air or water.

**Elbow** - A pipe fitting that connects two pipes at an angle. The angle is always 90 degrees unless another angle is stated. Also called an *ell.*

**Electrodialysis** - A process which utilizes direct current and an arrangement of permeable-active membranes to achieve separation of the soluble minerals from the water.

**Electrolysis** - This is simply passing a high electrical current through the effluent, producing by electrolysis hydrogen, oxygen, and heat. This method certainly sterilizes very well, but partly so because of the chlorine produced from saline water.

**Electrolytic Process** - A process that causes the decomposition of a chemical compound by the use of electricity.

**Electromagnetic Capability (EMC)** - The capability of electronic equipment of systems to be operated in the intended operational electromagnetic environment at designed levels of efficiency.

**Electromagnetic Interference (EMI)** - Electromagnetic energy that causes interference in the operation of electronic equipment. Can be conducted, coupled or radiated. Can be natural or man-made.

**Elevation Head** - The energy possessed per unit weight of a fluid because of its elevation above some point. Also called *position head* or *potential head.*

**Elution** - The process of extracting one solid from another. Often used incorrectly to describe the regeneration of an ion exchanger.

**Elutriation** - (1) A waste treatment term. The washing of sludge to remove soluble materials, which may inhibit coagulation and compacting which, reduces the final volume of sludge. (2) The process of separating lighter particles of a powder from the heavier ones by means of an upward directed stream of fluid (gas or liquid).

**Emergency Broadcasting System (EBS)** - Used to inform the public about an emergency and the protective actions to take. The EBS is a service of local radio and television stations, activated as needed and approved by a local emergency management agency.

**Emergency and Hazardous Chemical Inventory** - An annual report by facilities having one or more extremely hazardous substances or hazardous chemicals above certain weight limits, as specified in Section 311 and 312 of EPCRA.

**Emergency Lighting** - Battery-operated lighting units to provide illumination in the event of a power failure.

**Emergency Preparedness Coordinator** - The local government official designated to be notified immediately of chemical emergencies (e.g., spills, chemical releases, explosions, or fires) under EPCRA.

**Emission** - Discharge of a liquid, solid, or gaseous material.

**Emission Standards** - Government standards that establish limits on discharges of pollutants into the environment (usually in reference to air).

**Emulsifying Agent** - An agent capable of modifying the surface tension of emulsion droplets to prevent coalescence. Examples are soap and other surface-active agents, certain proteins and gums, water-soluble cellulose derivatives, and polyhydric alcohol esters and ethers.

**Emulsion** - A heterogeneous liquid mixture of two or more liquids not typically dissolved in one another, but held in suspension by forceful agitation or by emulsifiers that modify the surface tension of the droplets to prevent coalescence.

**Endangered Species** - Animals, plants, birds, fish, or other living organisms threatened with extinction by man-made or natural changes in the environment.

**End Suction Pump** - A type of horizontal centrifugal pump that has an intake located on the side of the pump parallel to the pump shaft.

**Endogenous Respiration** - Autooxidation by organisms in biological processes.

**Endotoxin** - A toxin produced by bacteria. The toxin is present in the environment only after death of the bacteria.

**Energy Recovery** - To capture energy from waste through any of a variety of processes (e.g., burning). Many new technology incinerators are waste-to-energy recovery units.

**Enhanced Primary Treatment** - In addition to normal primary treatment, enhanced primary treatment removes some of the lighter organic material and some phosphorus, and includes disinfection to reduce bacteria levels.

**Enteric** - Of intestinal origin, especially applied to wastes or bacteria.

**Enterococci** - A group of cocci that normally inhabit the intestines of man and animals. Not to be confused with fecal streptococci.

**Entrainment** - The trapping of bubbles in a liquid produced either mechanically through turbulence or chemically through a reaction.

**Environment** - The sum of all external influences and conditions affecting the life and development of an organism. Total environment is a redundant term used to emphasize the effect of slight and often momentary changes usually induced by man.

**Environmental Assessment (EA)** - A preliminary, written, environmental analysis required by NEPA (see the Federal Law section) to determine whether a federal activity such as building airports or highways would significantly affect the environment; may require preparation of a more detailed Environmental Impact Statement.

**Environmental Audit** - An independent assessment (not conducted by EPA) of a facility's compliance policies, practices, and controls. Many pollution prevention initiatives require an audit to determine where wastes may be reduced or eliminated or energy conserved. Many supplemental environmental projects that offset a penalty use audits to identify ways to reduce the harmful effects of a violation.
**Environmental Equity** - Equal protection from environmental hazards for individuals, groups, or communities regardless of race, ethnicity, or economic status.

**Environmental Impact Statement (EIS)** - A document prepared by or for EPA which identifies and analyzes, in detail, environmental impacts of a proposed action. As a tool for decision-making, the EIS describes positive and negative effects and lists alternatives for an undertaking, such as development of a wilderness area.

**Environmental Justice** - The fair treatment of people of all races, cultures, incomes, and educational levels with respect to the development and enforcement of environmental laws, regulations, and policies. Fair treatment implies that no population should be forced to shoulder a disproportionate share of exposure to the negative effects of pollution because of lack of political or economic strength.
**Environmental Resistance** - All biotic and abiotic factors combining to limit explosion.

**Environmental Response Team (ERT)** - EPA's group of highly trained scientists and engineers based in Edison, NJ and Cincinnati, OH who back up the federal On-Scene Coordinator. The ERT's capabilities include multimedia sampling and analysis, hazard assessment, hazardous substance and oil spill cleanup techniques, and technical support.

**Enzyme** - Organic substances (proteins) produced by living organisms that act as catalysts to speed up chemical changes.

**EPA** - Environmental Protection Agency. Formed in 1970. Administers nine Federal Environmental Laws: CAA - Clean Air Act, CWA - Clean Water Act, SDWA - Safe Drinking Water Act, CERCLA - Comprehensive Environmental Response Compensation and Liability Act (SUPERFUND); RCRA - Resource Conservation and Recovery Act; FIFRA - Federal Insecticide, Fungicide & Rodenticide Act; MPRSA - Marine Protection Research and Sanctuaries Act, UMTRCA - Uranium Mill Tailings Radiation Control Act, TSCA -Toxic Substances Control Act.

**Epidemic** - A disease that occurs simultaneously in a large fraction of the community.

**Epidemiologist** - A medical scientist who studies the various factors involved in the incidence, distribution, and control of disease in a population.

**Equalization** - In wastewater systems, the storage and controlled release of wastewater to treatment processes at a rate determined by the capacity of the processes, or at a rate proportional to the flow in the receiving stream; used to smooth out variations in temperature and composition, and flow.

**Equalizing Basin** - A holding basin in which variations in flow and composition of a liquid are averaged. Such basins are used to provide a flow of reasonably uniform volume and composition to a treatment unit. Also called balancing reservoir.

**Equilibrium Constant** - A value that describes the quantitative relationship between chemical species in a system at equilibrium.

**Equivalent Calcium Carbonate** - A common form of expressing the hardness, acidity, total alkalinity, carbon dioxide, carbonate, bicarbonate, noncarbonate, or hydroxide content of water expressed in milligrams per liter (mg/l). It is calculated by multiplying the number of chemical equivalents of any of these constituents present in 1 liter by 50, the equivalent weight of calcium carbonate. See *chemical equivalent.*

**Essential Nutrients** - Inorganic substances such as nitrogen, phosphorus, and iron that are required in small quantities for biological processes to occur.

**Estuaries** - Bodies of water which are located at the lower end of a river and are subject to tidal fluctuations.

**Euglena** - A motile unicellular freshwater autotrophic organism traditionally classified as a plantlike member of the kingdom Protista (algae).

**Eurythermal** - Bodies of water which are located at the lower end of a river and are subject to tidal fluctuations.

**Eutrophication** - Nutrient enrichment of a lake or other water body, typically characterized by increased growth of planktonic algae and rooted plants. It can be accelerated by wastewater discharges and polluted runoff.

**Evaporation** - (1) The process by which water becomes a vapor. (2) The concentration of dissolved solids by driving off water through the application of heat.

**Evaporation Opportunity** - The ratio of the rate of evaporation from a land or water surface in contact with the atmosphere to evaporation under existing atmospheric conditions; that is, the ratio of the actual to the potential rate of evaporation. Also called *relative evaporation.*

**Evaporation Rate** - The quantity of water, expressed in terms of depth of liquid water, evaporated from a given water surface per unit of time. It is typically expressed in inches or millimeters per day, month, or year.

**Evapotranspiration** - Water withdrawn from soil by evaporation or plant transpiration; considered synonymous with consumptive use.

**Evapotranspiration Potential** - Water loss that would occur if there was never a deficiency of water in the soil for use by vegetation.

**Exceptional Value Waters** - A stream or watershed which constitutes an outstanding national, state, regional or local resource, such as waters of national, state, or county parks or forests, or waters which are used as a source of unfiltered potable water supply, or waters of wildlife refuges or state game lands, or waters which have been characterized by the Fish Commission as "Wilderness Trout Streams," and other waters of substantial recreational or ecological significance.

**Explosimeter** - A device for measuring the concentration of potentially explosive fumes. Also called a *combustible-gas indicator.*

**Explosive Gases or Vapors** - Ignitable or flammable gases or vapors (e.g., acetylene, hydrogen, gasoline, and ethylene).

**Explosive Limits (chemical)** - The amounts of vapor in air that form explosive mixtures. These limits are expressed as lower and upper values and give the range of vapor concentrations in air that will explode if an ignition source is present.

**Exponential Growth Phase** - A phase of microbial population growth rate where the number of cells doubles during a certain period of time. Environmental conditions are ideal (ample food, suitable temperature, etc) for exponential growth to occur.

**Exposure** - Radiation or pollutants that come into contact with the body and present a potential health threat. The most common routes of exposure are through the skin, mouth, or by inhalation.

**Extended Aeration** - A modification of the activated-sludge process using long aeration periods to promote aerobic digestion of the biological mass by endogenous respiration. The process includes stabilization of organic matter under aerobic conditions and disposal of the gaseous end products into the air. Effluent contains finely divided suspended matter and soluble matter.

**Extractables** - Substances that can be leached from a filter during the filtration process or under other specified conditions.

**Extraction** - The process of dissolving and separating out particular constituents of a liquid by treatment with solvents specific for those constituents.

**Extremely Hazardous Substances (EHS)** - Any of approximately 366 chemicals or hazardous substances identified by EPA on the basis of hazard or toxicity and listed under EPCRA. The list is periodically revised.

## F

F - Food. Represents BOD in the F/M ratio. Expressed in pounds.

**F/M** - A ratio of the amount of food to the amount of organisms. Used to control an activated sludge process.

**Facultative** - Having the ability to live under different conditions, such as with or without free oxygen.

**Facultative Anaerobe** - A bacterium capable of growing under aerobic conditions or anaerobic conditions in the presence of an inorganic ion, i.e., $SO_4$, $NO_3$.

**Facultative Bacteria** - Bacteria that can grow and metabolize in the presence and absence of dissolved oxygen.

**Facultative Pond** - The most common type of pond in current use. The upper portion (supernatant) is aerobic, while the bottom layer is anaerobic. Algae supply most of the oxygen to the supernatant.

**Fahrenheit** - A temperature scale in which water freezes at 0°C (32°F) and boils at 100°C (212°F) at atmospheric pressure.

**Fallow, Fallow Land** - Land is considered fallow if it is kept free of growing plants during the growing season (March to October) using cultivation. The process is called *fallowing*.

**Faraday Cage** - A spherical cage made of conductive material. Static fields and discharges do not pass through it. Electromagnetic energy passing through the skin or shield is attenuated to varying degrees.

**Fat** - Basically insoluble animal fat.

**Fats (Wastes)** - Triglyceride esters of fatty acids. The term is erroneously used as a synonym for *grease*.

**Fauna** - The entire animal life of a specific region.

**FDA** - Food and Drug Administration.

**Fecal Coliform Bacteria** - Aerobic and facultative, Gram-negative, non-spore-forming, rod-shaped bacteria capable of growth at 44.5°C (112°F) and associated with fecal matter of warm-blooded animals. Their presence in water or sludge is an indicator of pollution and possible contamination by pathogens.

**Fecal Indicators** - Fecal coliform, fecal streptococci, and other bacterial groups originating in human or other warm-blooded animals, indicating contamination by fecal matter.

**Fecal Streptococci** - The subgroup of enterococci that is of particular concern in water and wastewater.

**Feed** - The material entering a filter processing unit for treatment.

**Feedstock** - Raw material supplied to a machine or processing plant from which other products can be made. For example, polyvinyl chloride and polyethylene are raw chemicals used to produce plastic tiles, mats, fenders, cushions, and traffic cones.

**Fermentation** - A type of heterotrophic metabolism in which an organic compound rather than oxygen is the terminal electron (or hydrogen) acceptor. Less energy is generated from this incomplete form of glucose oxidation than is generated by respiration, but the process supports anaerobic growth.

**Ferric Chloride ($FeCl_3$)** - A soluble iron salt often used as a sludge conditioner to enhance precipitation or bind up sulfur compounds in wastewater treatment. See *coagulant.*

**Ferric Hydroxide** - The end product and floc former resulting from the use of ferric iron coagulants. In natural water the floc is composed of complex chemicals including ferric hydroxide, but the chemical characteristics are analogous. Ferric hydroxide is insoluble at all normal pH values encountered in water and waste treatment since it is nonamphoteric.

**Ferric Sulfate ($Fe_2(SO_4)_3$)** - A water-soluble iron salt formed by reaction of ferric hydroxide and sulfuric acid or by reaction of iron and hot concentrated sulfuric acid. Also obtainable in solution by reaction of chlorine and ferrous sulfate. Used in conjunction with lime as a sludge conditioner to enhance precipitation.

**Ferrous Sulfate ($FeSO_4$ $7H_2O$)** - A water-soluble iron salt, sometimes called copperas; used in conjunction with lime as a sludge conditioner to enhance precipitation.

**FFDCA** - Federal Food and Drug and Cosmetics Act. Responsible for pesticides in food.

**Filamentous Growth** - Intertwined, threadlike biological growths characteristic of some species of bacteria, fungi, and algae. Such growths reduce sludge settleability and dewaterability.

**Filamentous Organisms** - Organisms that grow in a thread or filamentous form. Common types are *Thiothrix Actinomycetes* and *Cyanobacteria* (aka blue-green algae). This is a common cause of sludge bulking in the activated sludge process. Variously known as "pond scum," "blue-green algae," or "moss" when it appears in a pond/lake, and confused with algae because it looks much like algae. Cyanobacteria form a symbiotic relationship with some varieties of algae, making the combination very difficult to combat in lakes and ponds. Filamentous organisms and Actinomycetes will naturally stick to solid surfaces. Common types of Cyanobacteria are *Oscillatoria Anabaen* and *Synechococcus.* Other filament formers include *Spirogyra Cladophora Rhizoclonium Mougeotia Zygnema,* and *Hydrodictyon. Nocardia* is another filament former, which causes foaming and interferes with flocculation in a waste treatment plant.

**Filter** - A device or structure for removing solid or colloidal material, typically of a type that cannot be removed by sedimentation, from water, wastewater, or other liquid. The liquid is passed through a filtering medium, typically a granular material but sometimes finely woven cloth, unglazed porcelain, or specially prepared paper.

**Filter, Capped** - A portion of the top level of a sand filter is replaced with anthracite medium. This gives longer filter runs with the safety of sand filters. Results have generally been good.

**Filter, High Rate** - An apparently successful attempt to increase the rate of sand filtration and utilization of the entire bed rather than the top four to eight inches. The medium is graded by density so the large medium is on the surface with the particle size decreasing with depth. It is relatively new, but excellent results have been observed.

**Filter, Laboratory** - The choice of filters and methods will depend on the size of the particulate matter to be removed or the size or amount of particles that can be tolerated in the filtrate. Ordinary laboratory filter papers vary widely in the porosity. Usually the higher the number designating the paper, the smaller the particle it will remove.

**Filter, Rapid Sand** - The filter medium is sand graded by size with the smallest size being on the surface. The normal filter rate is approximately 2 gal/min/sq ft before loss of head and backwash. It is reported that only the top 4 to 8 inches is utilized.

**Filter Aid** - A chemical (usually a polymer) added to water to help remove fine colloidal suspended solids.

**Filter Cloth** - A fabric stretched around the drum of a vacuum filter.

**Filter Life** - Measure of the duration of a filter's useful service. This is based on the amount of standard contaminant required to cause differential pressure to increase to an unacceptable level-typically 2-4 times the initial differential pressure, a 50 to 80% drop in initial flow, or a downstream measure of unacceptable particulate.

**Filter Media** - Porous materials for separating suspended particulate matter from fluid.

**Filter Medium** - The permeable portion of a filtration system that provides the liquid-solid separation, such as screens, papers, non-wovens, granular beds and other porous media.

**Filter Pressures** - Mainly used in industrial water treatment, but occasionally found in municipal treatment plants. It is a filter entirely enclosed in a metal tank except for inlet and outlet connections. The medium varies widely.

**Filtered Wastewater** - Wastewater that has passed through a mechanical filtering process.

**Filters, Anthracite, Anthrafilt** - It is graded similarly to a sand filter, but is considerably coarser and lighter. It requires less backwash pressure, but the coarseness (0.72 mm) sometimes allows particulate and bacterial migration or breakthrough requiring frequent backwashing.

**Filtrate** - The liquid remaining after removal of solids as a cake in a filter.

**Filtration** - A process used for the separation of particulates (suspended matter) from wither a gas-solid or liquid-solid suspension. For gas-solid suspensions the process is commonly referred to as gas cleaning (examples are baghouses). Filtration may be applied for pollution control, product recovery, or product quality purposes.

**Final Effluent** - The effluent from the final treatment unit of a wastewater treatment plant.

**Final Sedimentation** - The separation of solids from wastewater in the last settling tank of a treatment plant.

**Financial Assurance** - A means (such as insurance, guarantee, surety bond, letter of credit, or qualification as a self-insurer) by the operator of a facility such as a landfill to assure financial capability for cleaning up possible environmental releases and closure of that facility.

**Five-Day Biochemical Oxygen Demand ($BOD_5$)** - A standard test to assess oxygen demand because of biochemical oxidation of carbonaceous material over a period of 5 days under controlled conditions of temperature (20°C).

**Fixed Solids** - The residue of total suspended or dissolved solids after ignition or heating for a specified time at a specified temperature.

**Flagellates** - A varied group of one-celled organisms in the kingdom Protista that possess flagella, which are used for locomotion.

**Flame Arrester** - (1) A device incorporating a fine-mesh wire screen or tube bundle inserted in a vent or pipe and designed to resist the flashback of flame. (2) Device consisting of multiple number of corrugated stamped sheets in a gas tight housing. As a flame passes through the sheets, it is cooled below the ignition point.

**Flammable** - Describes any material that can be ignited easily and that will burn rapidly.

**Flange** - A projecting rim, edge, lip, or rib.

**Flanged Coupling** - A type of rigid coupling consisting of two flanged rigid members with several bolt holes for connecting the two pieces.

**Flap Gate** - A gate that opens and closes by rotation around a hinge or hinges at the top side of the gate.

**Flap Valve** - A valve that is hinged at one edge and opens and shuts by rotating about the hinges. See *check valve*.

**Flare** - A device that burns gaseous materials to prevent them from being released into the environment. Flares may operate continuously or intermittently and are usually found on top of a stack. Flares also burn off methane gas in a landfill.

**Flash** - The portion of a superheated fluid converted to vapor when its pressure is reduced.

**Flash Mix, Fast Mix** - This stage along with accurate chemical feed is the heart of every water plant and waste plant utilizing coagulation. The coagulant must be completely mixed with the raw water or waste within seconds to obtain optimum results from coagulation.

**Flash Mixer** - A device for uniform, quick dispersal of chemicals throughout a liquid.

**Flash Point** - The temperature at which a gas, volatile liquid, or other substance ignites.

**Flat-Crested Weir** - A weir with a horizontal crest in the direction of flow and of appreciable length when compared with the depth of water passing over it.

**Flexible Coupling** - A coupling that transmits driving torque as well as accommodates minor misalignments between pump and motor shafts.

**Floating Matter** - Matter which passes through a 2000 micron sieve and separates by flotation for an hour.

**Floc** - Clumps of bacteria and particulate impurities or coagulants that have come together and formed a cluster. Found in aeration tanks and secondary clarifiers.

**Flocculation** - The process of agglomerating or building of the macrofloc that resulted from coagulation into large agglomerates until the shear force of water movement prevents further building or until it settles out. There is academic argument over the mechanisms; however, it is generally held that the greatest effects on flocculation are caused by the quality of the earlier chemical coagulation stage, and from that point the mechanical efficiency designed into the plant; therefore, flocculation is basically a mechanical process.

**Flocculator** - That portion of a water or waste plant following the flash mix but prior to settling. The purpose of the flocculator is to gently agitate the macrofloc from the flash mix giving it the opportunity to build larger without shearing or tearing up the floc in any way. This non-shearing requirement is ignored in some plant designs resulting in poor efficiency, high chemical costs, short filter runs, and marginal quality finished effluent.

**Floodplain** - Mostly level land along rivers and streams that may be submerged by floodwater. A 100-year floodplain is an area which can be expected to flood once in every 100 years.

**Flora** - The entire plant life of a specific region.

**Flotation** - A process of separating solids from water by developing a froth in a vessel in such fashion that the solids attach to air particles and float to the surface for collection.

**Flow Equalization System** - A device or tank designed to hold back or store a portion of peak flows for release during low-flow periods.

**Flow Rate** - Measure of the amount of fluid passing through the filter. This is always a variable of filter area, porosity, contamination, and differential pressure.

**Flue Gas Desulfurization** - The removal of sulfur oxides from exhaust gases of a boiler or industrial process; usually a wet scrubbing operation which concentrates hazardous materials in a slurry, requiring proper disposal.

**Fluoridation** - The addition of small quantities of a fluoride to potable water to bring the maximum fluoride content to the usually recommended level of 1.0 to 11 mg/l. Fluoridation is for the reduction of dental cavities in children.

**FOG** - Fats, Oils, and Grease. Includes hydrocarbons, fatty acids, soaps, fats and waxes whose content is determined by freon extraction of the sample and infrared analysis of the extract. The method includes both suspended and dissolved substances. Usually the dissolved substances cannot be removed by mechanical means.

**Food Chain** - Very simple pathway of nutrient flow, e.g., carnivore herbivore plant.

**Frazier Test** - Measures the amount of air transmitted through a filter under selected differential pressures. Historically used for textile products.

**Frequency** - Number of complete cycles of current per second, expressed in Hertz (Hz). 1 megahertz (MHz) is $10^6$ Hz.

**Fuel Oil** - Generic term for hydrocarbon fuels.

**Fugitive Emissions** - Air pollutants released to the air other than those from stacks or vents; typically small releases from leaks in plant equipment such as valves, pump seals, flanges, or sampling connections.

**Fungi** - Small, non-chlorophyll-bearing plants which may play a useful role in trickling filter treatment operations.

**Fungicide** - A pesticide used to control or destroy fungi on food or grain crops.

**FWPCA** - Federal Water Pollution Control Act.

## G

**Galvanic Couple** - The connection of two dissimilar metals in an electrolyte that results in current flow through the circuit.

**Gang Mixer**- Multiple unit stirrer.

**Garbage** - Food waste (animal and vegetable) resulting from the handling, storage, packaging, sale, preparation, cooking, and serving of foods.

**Gasification** - The conversion of soluble and suspended materials into gas during anaerobic decomposition. In clarifiers the resulting gas bubbles can become attached to the settled sludge and cause large clumps of sludge to rise and float on the water surface. In anaerobic sludge digesters, this gas is collected for fuel or disposed of using a waste gas burner.

**General Reporting Facility** - A facility having one or more hazardous chemicals above the 10,000-pound Threshold Planning Quantity. These facilities must file Material Safety Data Sheets and emergency inventory information with the SERC, LEPC, and local fire departments.

**Generation Time** - The time required for a given population to double in size. This time can be as short as 20 minutes or as long as a week.

**Generator** - A facility or mobile source that emits pollutants into the air; any person who produces a hazardous waste that is listed by EPA and therefore subject to regulation.

**Genetic Engineering** - A process of inserting new genetic information into existing cells in order to modify an organism for the purpose of changing particular characteristics.

**Giardia** - Giardia is a parasite, in cyst form, found in the feces of warm-blooded animals, including livestock, wildlife, and humans. Giardia causes giardiasis, also known as *beaver fever*. The symptoms of giardiasis include nausea and diarrhea. When sampling for Giardia, it takes at least three days to complete the analysis, due to the time-consuming (and expensive) analytical procedure involved. Therefore, it is not possible to monitor for Giardia on a continuous or even daily basis. As well, the results cannot be used to control water treatment processes because, by the time the results are available, the water has already been consumed.

**Global Warming** - See definition for climate change.

**Glyoxylate Cycle** - A modification of the Krebs cycle, which occurs in some bacteria. Acetyl coenzyme A is generated directly from oxidation of fatty acids or other lipid compounds.

**GMPs** - Good Manufacturing Practices. Food and Drug Administration regulations governing the manufacture of drugs and medical devices (Ref. Code of Federal

Regulations 21CFR).

**GPM** - Gallons per minute of a flowing stream.

**Grab Sample** - A single sample of soil or of water taken without regard to time or flow.

**Grains per Gallon** - A unit of concentration. 1 gr/gal = 17.1 mg/l.

**Gram Negative** - Bacteria cells which lose the crystal violet during the decolorizing step and are then colored by the counterstain. *Pseudomonas* and *Thiobacillus* are examples of Gram-negative strains.

**Gram Positive** - Bacterial cells which retain the crystal violet stain during a staining procedure. Most strains of bacilli are gram positive.

**Grease** - Compounded solid lubricant - contains petroleum base oil, animal fats, soaps (usually sodium, calcium, lithium), special chemicals.

**Greenhouse Effect** - See definition for climate change.

**Grit** - The heavy material present in wastewater, such as sand, coffee grounds, eggshells, gravel, and cinders.

**Grit, Grit Chamber** - In waste treatment, a chamber ahead of primary settling to remove sand, gravel, and larger inorganic matter. They are desirable on all waste treatment plants and almost a necessity where there are cross-connections between storm and sanitary sewers.

**Groundwater** - Water found below the surface of the land, usually in porous rock formations. Groundwater is the source of water found in wells and springs and is used frequently for drinking.

## H

**Halophilic or Halotolerant** - Bacteria which thrive in a highly salt environment, up to 25% NaCl.

**Hard Water** - The measurement of the amount of divalent metallic ions contained by a water. Soft 0 to 75 mg/l. Moderate 75 to 150 mg/l. Hard 150 to 300 mg/l. Very Hard over 300 mg/L.

**Hardness** - The concentration of calcium and magnesium salts in water. Hardness is a term originally referring to the soap-consuming power of water; as such it is sometimes also taken to include iron and manganese. A looser definition is any cation or anion that is capable of reacting with soap to form precipitates, curds, or scale.

**Hazard Communication Standard** - An OSHA regulation that requires chemical manufacturers, suppliers, and importers to assess the hazards of the chemicals they make, supply, or import, and to inform employers, customers, and workers of these hazards through a Material Safety Data Sheet.

**Hazardous Chemical** - EPA's designation for any hazardous material that requires a Material Safety Data Sheet. Such substances are capable of producing adverse physical effects (fire, explosion, etc.) or adverse health effects (cancer, dermatitis, etc.)

**Hazardous Waste** - Waste which is listed by the EPA as being a danger to human health or the environment. Also includes waste which may not be listed but has one or more of the following characteristics: it is ignitable, it is corrosive, or it reacts violently with water or other materials.

**Hazardous Waste Label** - Labeling a waste containment showing content and date collected.

**Hazardous Waste Landfill** - A specially permitted, excavated, or engineered area in which hazardous waste is deposited and covered. Proper protection of the environment from the materials to be deposited in such a landfill requires careful site selection, the cataloging of types of wastes, good design (including a liner and a leachate collection and treatment system), proper operation, and thorough final closure.

**Headworks** - The facilities where wastewater enters a wastewater treatment plant. The headworks may consist of bar screens, comminutors, a wet well, and pumps.

**Health Assessment** - An evaluation of available data on existing or potential risks posed by a Superfund site. Every site on the National Priorities List has a health assessment prepared by the Agency for Toxic Substances and Disease Registry.

**Heavy Metal** - A common hazardous waste; can damage organisms at low concentrations and tends to accumulate in the food chain.

**Herbicide** - A pesticide designed to control or kill plants, weeds, or grasses. Almost 70% of all pesticides used by farmers and ranchers are herbicides. These chemicals have wide-ranging effects on nontarget species (other than those the pesticide is meant to control).

**Heterotroph** - A microorganism which uses organic matter for energy and growth.

**High-Rate Treatment** - Removes heavier particles and floatables but at a lower efficiency than primary or enhanced primary treatment.

**House Sewer** - The pipeline connecting the house and drain and the septic tank.

**Household or Domestic Waste** - Solid waste, composed of garbage and rubbish, which normally originates from residential, private households, or apartment buildings. Domestic waste may contain a significant amount of toxic or hazardous waste from improperly discarded pesticides, paints, batteries, and cleaners.

**HRT** - Hours of Retention Time.

**Humidification** - The addition of water vapor to air.

**Humus** - The dark organic material in soils, produced by the decomposition of plant matter. The matter that remains after the bulk of detritus has been consumed (leaves, roots). Humus mixes with top layers of soil (rock particles), supplies some of the nutrients needed by plants, and increases acidity of soil; inorganic nutrients more soluble under acidic conditions, become more available, e.g., wheat grows best at pH 5.5 to 7.0. Humus modifies soil texture, creating a loose, crumbly texture that allows water to soak in and nutrients to be retained; it permits air to be incorporated into soil.

**Hydraulic Conductivity** - The ease of movement of water through the soil relative to a potential gradient.

**Hydraulic Gradient** - The direction of ground water flow due to changes in the depth of the water table.

**Hydraulic Load** - The gallons of flow per day per square foot of filter surface area. The use of metric measurement is also accepted.

**Hydraulic Loading** - Hydraulic loading refers to the flows (MGD or $m^3$/day) to a treatment plant or treatment process.

**Hydrocarbons** - Chemicals that consist entirely of hydrogen and carbon. Hydrocarbons contribute to air pollution problems, such as smog.

**Hydrogen Sulfide Gas** - Hydrogen sulfide is a gas with a rotten egg odor. This gas is produced under anaerobic conditions. Hydrogen sulfide is particularly dangerous because it dulls the sense of smell so that the odor is not noticeable after a period of exposure or in high concentrations. The gas is very poisonous to the respiratory system, explosive, flammable, and colorless.

**Hydrolysis** - The process in which carbohydrates and starches are simplified into organic soluble organics, usually by facultative anaerobes.

**Hydrophilic** - Having an affinity for water and aqueous solutions.

**Hygroscopic** - Absorbing or attracting moisture from the air.

**Hypolimion** - That region of a body of water that extends from the bottom up to the thermocline. This region is the most removed from surface influence and is likely to have chemical reducing conditions and to concentrate nuisance materials such as manganese and taste.

## I

**Identification Code or EPA I.D. Number** - The unique code assigned to each generator, transporter, and treatment, storage, or disposal facility by EPA to facilitate identification and tracking of hazardous waste. Superfund sites also have assigned I.D. numbers.

**Ignitable Waste** - Combustible or flammable materials; paints, solvents, oils, etc.

**Imhoff Tank** - A tank used to treat sewage, in which digestion and settlement take place in separate compartments one below the other. Anaerobic biological processes have been applied for many years to the treatment of organic wastes (sewage) of human origin. The first anaerobic process applied to human wastes was the "septic tank," beginning in 1895. In 1912, a new anaerobic process called the "two-story" septic tank was developed and applied to the wastewaters from municipal sources. The two-story septic tank was a modification of the original septic tank and was patented by Karl Imhoff in Germany. This modification was called the Imhoff tank. Later, in about 1918, the two-story septic tank, or Imhoff tank, was modified to provide for separation of the solids settling and anaerobic digestion functions of the process. The digestion of the solids in a separate tank was then referred to as "separate-sludge digestion". The first separate-sludge anaerobic digesters were built at Antigo, Wisconsin, in 1918. Considerable research and development on the anaerobic digestion process has occurred and the process is now widely applied to organic sludges generated at wastewater treatment plants. In contrast to aerobic biological processes that convert organic wastes to carbon dioxide ($CO_2$) and water ($H_2O$), anaerobic biological processes make use of microorganisms that thrive in the complete absence of molecular oxygen and convert the organics to methane ($CH_4$) and $CO_2$. Anaerobic processes have been recognized for some time as being much less energy intensive than aerobic processes and capable of stabilizing organic sludges and liquids at a high rate. However, the recognition by scientists and engineers of these desirable characteristics has been slow in coming.

**Impoundment** - A body of water or sludge confined by a dam, dike, floodgate, or other barrier.

**Incident Command System (ICS)** - An organizational scheme wherein one person, normally the Fire Chief, takes charge of an integrated, comprehensive emergency response. This commander is backed by an Emergency Operations Center which provides support, resources, communications, and advice.

**Incineration** - The destruction of solid, liquid, or gaseous wastes by controlled burning at high temperatures. Hazardous organic compounds are converted to ash, carbon dioxide, and water. Burning destroys organics, reduces the volume of waste, and vaporizes water and other liquids the wastes may contain. The residue ash produced may contain some hazardous material, such as noncombustible heavy metals, concentrated from the original waste.

**Incinerator** - A furnace for the routine burning of waste materials using controlled flame combustion. locations.

**Incompatible Waste** - Waste that reacts with other materials or water.

**Incorporation** - Incorporation means mixing biosolids with the soil. Incorporation includes injection, moldboard plowing, rototilling, chisel or disc plowing, and tandem disc harrowing.

**Indicator Organisms** - An organism found only under certain conditions (usually used regarding pollution), or in the absence of certain conditions. Equating pollution to specific organisms is useful, although a better correlation is made by observation of the ecological balance.

**Indirect Discharge** - The introduction of pollutants from a non-domestic source into a publicly owned wastewater treatment system. Indirect dischargers can be commercial or industrial facilities who must pre-treat their wastes before discharge into local sewers.

**Indoor Air** - Breathing air inside a habitable structure, often highly polluted because of lack of exchange with fresh oxygen from outdoors. Solvents, smoke, paints, furniture glues, carpet padding, and other synthetic chemicals trapped inside contribute to an often unhealthy environment.

**Industrial Sludge** - Any sludge that is not domestic wastewater sludge is industrial sludge. This includes wastewater sludge from manufacturing or processing of raw materials, intermediate products, final products or other activities that include pollutants from non-domestic wastewater sources.

**Industrial Waste** - Unwanted materials produced in or eliminated from an industrial operation and categorized under a variety of headings, such as liquid wastes, sludge, solid wastes, and hazardous wastes.

**Industrial Wastewater** - Water containing any type of industrial contaminants as well as sanitary sewage.

**Inert ingredients** - Substances that are not "active," such as water, petroleum distillates, talc, corn meal, or soaps. When discussing pesticides, inert ingredients do not attack a particular pest, but some are chemically or biologically active, causing health and environmental problems.

**Infectious Waste** - See definition for medical waste.

**Infiltration** - The seepage of groundwater into a sewer system, including service connections. Seepage frequently occurs through defective or cracked pipes, pipe joints, connections, or manhole walls.

**Influent** - The liquid - raw (untreated) or partially treated - flowing into a reservoir, basin, treatment process or treatment plant.

**Inorganic Waste** - Waste material such as sand, salt, iron, calcium, and other mineral materials which are only slightly affected by the action of organisms. Inorganic wastes are chemical substances of mineral origin; whereas organic wastes are chemical substances usually of animal, or plant origin.

**Integrated Pest Management (IPM)** - A combination of biological, cultural, and genetic pest control methods with use of pesticides as the last resort. IPM considers a targeted species' life cycle and intervenes in reproduction, growth, or development to reduce the population. Land use practices are examined for possible change; other animals, birds, or reptiles in the ecosystem are used as natural predators.

**Interceptor Sewer** - A sewer designed to convey dry-weather flow (and a minor component of wet-weather flow) from the combined sewer system to the treatment plant. When wet-weather flows exceed the capacity of the interceptor sewer, the excess flows are discharged to the environment as combined sewer overflow (CSO).

**Interconnection** - A location within the sewer systems where the flow may pass from one sewer system to another. Interconnections generally provide overflow relief to combined sewers in the event of sewer backup, thus minimizing basement flooding. These interconnections generally discharge excess flows to storm sewers.

**Interface** - The common boundary layer between two substances such as between water and a solid (metal) or between water and a gas (air) or between a liquid (water) and another liquid (oil).

**Intermittent Stream** - A body of water flowing in a channel or bed composed primarily of substrates associated with flowing water which, during periods of the year, is below the local water table and obtains its flow from both surface runoff and groundwater discharges.

**Interspecies** - Between two different species, such as tomato and weeds.

**Interstate Commerce** - A clause of the United States Constitution which reserves to the federal government the right to regulate the conduct of business across state lines. Under this clause, the U.S. Supreme Court has ruled that states may not restrict the disposal of wastes originating out-of-state more than that of waste originating in-state.

**Inversion** - An atmospheric condition caused by increasing temperature with elevation, resulting in a layer of warm air preventing the rise of cooler air trapped beneath. This condition prevents the rise of pollutants that might otherwise be dispersed. Trapping pollutants near the ground increases ozone to harmful levels.

**Ion** - An electrically charged atom or group of atoms which can be drawn from wastewater during the electrodialysis process.

**Ion Exchange** - A process by which certain undesired ions of given charge are absorbed from solution within an ion-permeable absorbent, being replaced in the solution by desirable ions of similar charge from the absorbent.

**Ionic Strength** - A measure of the strength of a solution based on both the concentrations and valences of the ions present.

**Ionization** - The dissociation of a molecule into atoms or groups of atoms. This occurs when salts are dissolved in water. As an example, when copper sulfate is dissolved in water, the solution contains positive copper ions and negative sulfate ions.

**Irradiated Food** - Food that has been briefly exposed to radioactivity (usually gamma rays) to kill insects, bacteria, and mold. Irradiated food can be stored without refrigeration or chemical preservatives and has a long "shelf life."

**Irrigation** - Land application for disposal of effluents.

**Irritant** - A substance that can cause irritation of the skin, eyes, or respiratory system. An irritant can cause an acute effect from a single high-level exposure, or chronic effects from repeated, low-level exposures. Some examples of irritants are chlorine, nitric acid, and various pesticides.

## K

**Karst** - A geologic formation of irregular limestone deposits with sinks, underground streams, and caverns.

**Kick Net** - 500 micron white mesh net is designed to meet the requirements of groups performing U.S.EPA Rapid Bioassessment Protocols for Benthic Invertebrates. (Benthic = bottom dwelling.)

**Knit Fabric** - A fabric structure made by interlooping yarns.

**Krebs Cycle** - The oxidative process in respiration by which pyruvate (via acetyl coenzyme A) is completely decarboxylated to $CO_2$.

## L

**Lagoon** - A shallow, artificial treatment pond where sunlight, bacterial action, and oxygen work to purify wastewater; a stabilization pond. An aerated lagoon is a treatment pond that uses oxygen to speed up the natural process of biological decomposition of organic wastes. A lagoon is regulated as a point source under the Clean Water Act if there is a direct surface water discharge. Some lagoons that discharge into groundwater also are regulated if they have a direct hydrogeologic connection to surface water. In other areas, lagoons were historically used to dump various liquid, solid, and hazardous wastes from manufacturing or industrial processes. These wastes typically flooded and polluted surrounding environs or seeped underground. Such lagoons are now regulated under RCRA but some must be cleaned up under Superfund.

**Land Application** - The beneficial use of biosolids applied to land based upon crop needs and the composition of biosolids.

**Land Disposal Restrictions (Land Ban)** - Mandated by the 1984 amendments to RCRA; prohibits the disposal of hazardous wastes into or on the land.

**Landfill** - A method for final disposal of solid waste on land. The refuse is spread and compacted and a cover of soil applied so that effects on the environment (including public health and safety) are minimized. Under current regulations, landfills are required to have liners and leachate treatment systems to prevent contamination of groundwater and surface waters. An industrial landfill disposes of nonhazardous industrial wastes. A municipal landfill disposes of domestic waste including garbage, paper, etc. This waste may include toxins that are used in the home, such as insect sprays and powders, engine oil, paints, solvents, and weed killers.

**Large Quantity Generator** - Person or facility which generates more than 2200 pounds of hazardous waste per month. In 1989, only 1% of more than 20,000 generators fell into this category. Those generators produced nearly 97% of the nation's hazardous waste. These generators are subject to all requirements of RCRA.

**Lateral Sewers** - The pipes that run under the streets of a city and into which empty the sewers from homes or businesses.

**Leachate** - Liquid (mainly water) that percolates through a landfill and has picked up dissolved, suspended, and/or microbial contaminants from the waste. Leachate can be compared to coffee: water that has percolated down through the ground coffee.

**Leaching** - Leaching refers to the movement of soluble components in solution from the soil by water.

**Lethal Concentration 50 (LC 50)** - A concentration of a pollutant or effluent at which 50% of the test organisms die; a common measure of acute toxicity.

**Lethal Dose 50 (LD 50)** - The dose of a toxicant that will kill 50% of test organisms within a designated period of time. The lower the LD 50, the more toxic the compound.

**Lime** - A common water treatment chemical. Limestone is burned to product quicklime, which is mixed with water to produce slaked, or hydrated lime.

**Limited Degradation** - A policy that allows for some lowering of natural environmental quality to a given level beneath an established health standard.

**Limestone** - A rock containing mainly calcium carbonate and impurities.

**Limestone, Dolomitic** - Limestone containing both calcium carbonate and magnesium carbonate.

**Liner** - Structure of natural clay or manufactured material (plastic) which serves as a barrier to restrict leachate from reaching or mixing with groundwater in landfills, lagoons, etc.

**Liquefaction** - The conversion of large solid particles of sludge into very fine particles which either dissolve or remain suspended in wastewater.

**Litter** - The highly visible portion of solid waste (usually packaging material) which is generated by the consumer and carelessly discarded outside of the regular garbage disposal system, as on the highways or in streets.

**Loaded (Plugged)** - A filter element that has collected a sufficient quantity of insoluble contaminants such that it can no longer pass rated flow without excessive differential pressure.

**Local Emergency Planning Committee (LEPC)** - The body appointed by the State Emergency Response Commission (SERC), as required by EPCRA, which develops comprehensive emergency plans for Local Emergency Planning Districts, collects MSDS forms and chemical release reports, and provides this information to the public. Each county and some large city governments participate in an LEPC.

**Log Growth** - A growth phase in which cell production is maximum.

**Lube Oil** - Special crude fraction for viscosity - contains up to 50% chemical blending materials.

## M

**MacConkey Streak** - Laboratory test for the presence of gram-negative bacteria. We use this test to detect contamination of *Bacillus* products such as CF 1000, 1002, 4002, and some of the Enz-Odor® products.

**Macrofloc** - The stage of flocculation when the floc grows large enough to be seen.

**Macronutrient** - An element required in large proportion by plants and other life forms for survival and growth. Macronutrients include nitrogen (N), potassium (K), and phosphorus (P).

**Macroscopic** - Large enough to be seen by the unaided eye.

**Manifest System** - Tracking of hazardous waste from "cradle to grave" (generation through disposal), with accompanying documents known as "manifests."

**Market Grade (Wire Cloth)** - Screens that meet general industrial specifications and have a low percentage of open area.

**Masking Agent** - Substance used to cover up or disguise unpleasant odors. Liquid masking agents are dripped into wastewater, sprayed into the air, or evaporated (using heat) with the unpleasant fumes or odors and then discharged into the air by blowers to make an undesirable odor less noticeable.

**Material Safety Data Sheet (MSDS)** - Printed material concerning a hazardous chemical, or Extremely Hazardous Substance, including its physical properties, hazards to personnel, fire and explosion potential, safe handling recommendations, health effects, firefighting techniques, reactivity, and proper disposal. Originally established for employee safety by OSHA.

**Maximum Achievable Control Technology (MACT)** - Generally, the best available control technology, taking into account cost and technical feasibility.

**Maximum Contaminant Level (MCL)** - The maximum level of certain contaminants permitted in drinking water supplied by a public water system as set by EPA under the federal Safe Drinking Water Act.

**Maximum Contaminant Level Goal (MCLG)** - The maximum level of a contaminant that is associated with no adverse health effects from drinking water containing that contaminant over a lifetime. For chemicals believed to cause cancer, the MCLGs are set at zero. MCLGs are not enforceable, but are ideal, health-based goals which are set in the National Primary Drinking Water Standards developed by EPA. MCLs are set as close to MCLGs as possible, considering costs and technology.

**MCL** - Maximum Contaminant Level of pollution in drinking water.

**MCRT** - Mean Cell Retention Time (days). An expression of the average time that a microorganism will spend in an activated sludge process.

**Mean Filtration Rating** - Derived from Bubble Point test method. This data should be used as a guide only to compare overall retention capabilities between fabrics and should not be considered a guarantee of the particle size that the fabric will retain.

**Mechanical Aeration** - The use of machinery to mix air and water so that oxygen can be absorbed into the water. Some examples are paddle wheels, mixers, rotating brushes to agitate the surface of an aeration tank; pumps to create fountains; and pumps to discharge water down a series of steps forming falls or cascades.

**Medical Waste** - All wastes from hospitals, clinics, or other health care facilities ("Red Bag Waste") that contain or have come into contact with diseased tissues or infectious microorganisms. Also referred to as infectious waste which is hazardous waste with infectious characteristics, including: contaminated animal waste, human blood and blood products, pathological waste, and discarded sharps (needles, scalpels, or broken medical instruments).

**Medium** - The material in the trickling filter on which slime accumulates and organisms grow. As settled wastewater trickles over the media, organisms in the slime remove certain types of wastes thereby partially treating the wastewater. Also the material in a rotating biological contactor (RBC) or in a gravity or pressure filter.

**MEK** - Methyl ethyl ketone.

**Membrane** - A thin polymeric film with pores.

**Membrane Biological Reactor (MBR)** - This system is particularly well suited to wastewater or groundwater streams with recalcitrant organics, highly contaminated concentrations, or highly variable influent composition, or for streams where system footprint is a concern. The MBR system's applications have included batch chemical plant effluents, MTBE in groundwater, landfill leachate, chlorinated solvents in manufacturing plant wastewaters, oily wastes, POTWs with space restrictions, phosphorous control, and pharmaceutical intermediates. The system combines the benefits of a suspended growth reactor with the solids separation capability of an ultrafilter or microfilter membrane unit. The membrane provides a long solids retention time which can greatly enhance the biological degradation of influent organics. The MBR system can be operated in either an aerobic or anaerobic mode, increasing the spectrum of chemicals suitable for biological treatment. The ultrafiltration membrane solids/liquids separation unit provides highly efficient biomass separation allowing the biomass concentration within the upstream reactor to be up to 10 times greater that the concentration normally attainable in a conventional suspended growth system. The MBR system offers an excellent solution for in-process, at-source treatment applications. Benefits include: Cost-effectiveness - low life-cycle costs; Difficult contaminants degraded; High-quality effluent produced; Small footprint; Faster system start-ups; Long solids retention times; Minimal operating labor required; Minimal generation of biosludge.

**Mercaptans** - Compounds containing sulfur which have an extremely offensive skunk-like odor. Also sometimes described as smelling like garlic or onions.

**Mesh Count**- The number of threads in a linear inch of fabric/wire cloth.

**Mesh Opening** - See *pore size.*

**Mesophilic Bacteria** - A group of bacteria that grow and thrive in a moderate temperature range between 68°F (20°C) and 113°F (45°C).

**Metabolism** - All of the processes or chemical changes in an organism or a single cell by which food is built up (anabolism) into living protoplasm and by which protoplasm is broken down (catabolism) into simpler compounds with the exchange of energy.

**Metalized Screens** - Screens that have been metalized with nickel. These screens will bleed off static charges, promote EMC and reflect electromagnetic energy.

**Metals** - Limitations have been placed on the quantities of metals that can be discharged from treating plants. Specification are not always consistent nor are they the same for every operation. A processor must analyze his process for compliance. List of metals with restrictions: aluminum; cadmium; manganese; arsenic; nickel; ammonia copper nitrates; antimony cyanide phosphorus; barium chlorides; selenium; beryllium fluoride; silver; bromide; iron sulfide; bromates; lead; zinc; boron; mercury.

**mg/l** - Milligrams per liter = ppm (parts per million). Expresses a measure of the concentration by weight of a substance per unit volume.

**MGD** - Million gallons daily - refers to the flow through a waste treatment plant.

**Microbes** - Minute plant or animal life. Some microbes which may cause disease exist in sewage.

**Microorganisms** - Bacteria, yeasts, simple fungi, algae, protozoans, and a number of other organisms that are microscopic in size. Most are beneficial but some produce disease. Others are involved in composting and sewage treatment.

**Micron** - A unit of length. One millionth of a meter or one thousandth of a millimeter. One micron equals 0.00004 of an inch.

**Micronutrient** - An element required by plants and bacteria, in proportionately smaller amounts, for survival and growth. Micronutrients include: iron (Fe), manganese (MN), zinc (Zn), boron (B), and molybdenum (Mo).

**Microorganisms** - small organisms which require a microscope to be seen.

**MIK** - Methyl isobutyl ketone.

**Mill Grade (Wire Cloth)** - Stainless steel screens that have moderate open area and good strength.

**Milligrams/liter (mg/l)** - A measure of concentration used in the measurement of fluids. Mg/l is the most common way to present a concentration in water and is roughly equivalent to parts per million.

**Minimization** - Measures or techniques that reduce the amount of wastes generated during industrial production processes; this term also is applied to recycling and other efforts to reduce the volume of waste going to landfills. This term is interchangeable with waste reduction and waste minimization.

**Mitigation** - Measures taken to reduce adverse effects on the environment.

**Mixed Liquor** - A mixture of activated sludge and waters containing organic matter undergoing activated sludge treatment in the aeration tank.

**MLSS** - Mixed liquor suspended solids, the volume of suspended solids (see SS) in the mixed liquor (see ML) of an aeration tank.

**MLVSS** - Mixed liquor volatile suspended solids, the volume of organic solids that can evaporate at relatively low temperatures (55°C) from the mixed liquor of an aeration tank. This volatile portion is used as a measure or indication of microorganisms present. Volatile substances can also be partially removed by air stripping.

**Molecule** - The smallest division of a compound that still retains or exhibits all the properties of the substance.

**Monitoring Well** - A well used to take water quality samples or to measure ground water levels.

**Monoculture** - Aquaculture in which one species is grown.

**Morbidity** - Rate of incidence of disease.

**Mortality** - Death rate.

**Motile** - Motile organisms exhibit or are capable of movement.

**MPN Index** - Most Probable Number of coliform-group organisms per unit volume of sample water. Expressed as a density or population of organisms per 100 mL of sample water.

**MSDS** - Material Safety Data Sheet. A document that provides pertinent information and a profile of a particular hazardous substance or mixture. An MSDS is normally developed by the manufacturer or formulator of the hazardous substance or mixture. The MSDS is required to be made available to employees and operators whenever there is the likelihood of the hazardous substance or mixture being introduced into the workplace. Some manufacturers prepare MSDS for products that are not considered to be hazardous to show that the product or substance is not hazardous.

**Mutagenicity** - The property of a chemical that causes the genetic characteristics of an organism to change in such a way that future generations are permanently affected.

**Mutualism** - Two species living together in a relationship in which both benefit from the association.

## N

***N*-Acetylglucosamine and *N*-Acetylmuramic Acid** - Sugar derivatives in the peptidoglycan layer of bacterial cell walls.

**National Ambient Air Quality Standards (NAAQS)** - Maximum air pollutant standards that EPA set under the Clean Air Act for attainment by each state. The standards were to be achieved by 1975, along with state implementation plans to control industrial sources in each state.

**National Emissions Standards for Hazardous Air Pollutants (NESHAP)** - Emission standards set by EPA for an air pollutant not covered by NAAQS that may cause an increase in deaths or serious, irreversible, or incapacitating illness. Primary standards are designed to protect human health, secondary standards to protect public welfare.

**National Pollutant Discharge Elimination System (NPDES)** - The primary permitting program under the Clean Water Act which regulates all discharges to surface water.

**National Priorities List (NPL)** - A list of sites, many nominated by the states, for hazardous waste cleanup under Superfund.

**National Response Center (NRC)** - The primary communications center operated by the U.S. Coast Guard to receive reports of major chemical and oil spills and other hazardous substances into the environment. The NRC immediately relays reports to a predesignated federal On-Scene Coordinator.

**National Response Team (NRT)** - Representatives from 15 federal agencies with interests and expertise in various aspects of emergency response to pollution incidents. EPA serves as chair and the U.S. Coast Guard serves as vice-chair. The NRT is primarily a national planning, policy, and coordinating body and does not respond directly to incidents. The NRT provides policy guidance prior to an incident and assistance as requested by a federal On-Scene Coordinator via a Regional Response Team during an incident. NRT assistance usually takes the form of technical advice, access to additional resources or equipment, or coordination with other RRTs.

**National Strike Force (NSF)** - Operated by the U.S. Coast Guard, the NSF is composed of three strategically located teams (Atlantic, Pacific, and Gulf coasts) who back up the federal On-Scene Coordinator. These teams are extensively trained and equipped to respond to major oil spills and chemical releases. These capabilities are especially suited to incidents in a marine environment but also include site assessment, safety, action plan development, and documentation for both inland and coastal zone incidents. The NSF Coordination Center is at Elizabeth City, NC.

**Natural Treatments** - In eastern and southeastern Europe, and indeed in most non-Western countries, sewage is regarded as a resource rather than a problem. It is composted with animal waste, straw, seaweed, or any natural organic material to provide a totally safe, valuable, moisture-retaining agricultural product. Pathogen destruction is brought about by the heating provided in the composting cycle. On the proviso that no toxic chemical or industrial contents are present, the product makes a remarkably good fertilizer. For small nonrural communities with the required land space available, the sewage can be trickled through reed-beds, which take out most of the organics and nutrients while the oxygen in the air and the ultra-violet light from the sun kills the pathogens. Although excellent, such treatment is not really viable for large urban communities with considerable loadings and high land costs. Individual 'dry' toilets work well as pollution preventers, as indeed do the cesspools still used in many country areas. It could be said that the flush toilet, though once claimed to be the very height of hygiene, has in fact been the basic cause of most of the fecal pollution and eutrophication of our rivers and seas that we have today.

**Neutralization** - The chemical process in which the acidic or basic characteristics of a fluid are changed to those of water ($\mathrm{pH} = 7$).

**Nitrate Sensitive Area** - A defined area, designated by statutory order, within which measures are taken to minimize the leaching of nitrates from agriculture into groundwater.

**Nitrification** - An aerobic process in which bacteria change the ammonia and organic nitrogen in wastewater into oxidized nitrogen (usually nitrate). The second-stage BOD is sometimes referred to as the "nitrification stage" (first-stage BOD is called the "carbonaceous stage").

**Nitrifying Bacteria** - Bacteria that change the ammonia and organic nitrogen in wastewater into oxidized nitrogen (usually nitrate).

**Nitrogen Fixation** - Conversion of atmospheric nitrogen into organic nitrogen compounds available to green plants; a process that can be carried out only by certain strains of soil bacteria.

**Non-attainment** - Refers to areas of the United States that have not met air standards for human health by deadlines set in the Clean Air Act.

**Non-contact Cooling Water** - Water used for cooling which does not come into direct contact with any raw material, product, by-product, or waste.

**Nondegradation** - A policy that forbids any lowering of naturally occurring environmental quality regardless of established health standards.

**Nonpoint Source** - Any source of pollution not associated with a distinct discharge point. Includes sources such as rainwater, runoff from agricultural lands, industrial sites, parking lots, and timber operations, as well as escaping gases from pipes and fittings.

**No Observed Adverse Effect Level** or **No Observed Effect Level (NOAEL** or **NOEL)** - A level of exposure which does not cause observable harm.

**Nonwoven** - A porous web or sheet produced by mechanically, chemically or thermally bonding together polymers, fibers or filaments.

**NPDES Permit** - A National Pollutant Discharge Elimination System permit is the regulatory agency document issued by either a federal or state agency which is designated to control all discharges of pollutants from point sources into U.S. waterways. NPDES permits regulate discharges into navigable waters from all point sources of pollution, including industries, municipal wastewater treatment plants, sanitary landfills, large agricultural feed lots, and return irrigation flows.

**Nucleic Acid** - An organic acid consisting of joined nuceleotide complexes; the principal types are deoxyribonucleic acid (DNA) and ribonucleic acid (RNA).

**Nutrients** - Nutrients, such as nitrogen (N) and phosphorus (P), can lead to excessive growth of algae and higher aquatic plants (macrophytes), resulting in unpleasant conditions for swimming, release of toxins (from some blue-green algae), and depletion of the oxygen needed by fish.

**Nutrient Management** - Identifying how the major plant nutrients (nitrogen, phosphorus, and potassium) are to be annually managed for expected crop production and for the protection of water quality.

**Nutrient Management Plan** - A written site-specific plan which describes how the major plant nutrients (nitrogen, phosphorus and potassium) are to be managed annually. The goal of farm nutrient management planning is to minimize adverse environmental effects, primarily upon water quality, and avoid unnecessary nutrient applications above the point where long-run net farm financial returns are optimized.

## O

**Obligate Aerobe** - Bacteria which require the presence of oxygen, such as *Pseudomonas fluorescens*. A few strains of this species are capable of utilizing nitrate to allow anaerobic respiration.

**Odor Threshold** - The lowest concentration of a substance in air that can be smelled. Odor thresholds are highly variable because of the differing ability of individuals to detect odors.

**Oil Retention Boom** - A floating baffle used to contain and prevent the spread of floating oil on a water surface.

**On-Scene Coordinator (OSC)** - The federal official responsible for the coordination of a hazardous materials response action, as specified in individual Regional Contingency Plans. OSCs are predesignated by EPA for inland areas and by the U.S. Coast Guard for coastal areas. The OSC coordinates all federal containment, removal, and disposal efforts and resources during a pollution incident. The OSC is the point of contact for the coordination of federal efforts with those of the local response community. The OSC has access to extensive federal resources, including the National Strike Force, the Environmental Response Team, and Scientific Support Coordinators. The OSC can be a source of valuable support and information to the community.

**On Site** - On the same, or adjacent, property.

**Open Area** - The proportion of total screen area that is open space. Expressed as a percent.

**Organically Grown** - Food, feed crops, and livestock grown within an intentionally diversified, self-sustaining agro-ecosystem. In practice, farmers build up nutrients in the soil using compost, agricultural wastes, and cover crops instead of synthetically derived fertilizers to increase productivity, rotate crops, weed mechanically, and reduce dramatically their dependence on the entire family of pesticides. Farmers must be certified to characterize crops as organically grown and can only use approved natural and synthetic biochemicals, agents, and materials for 3 consecutive years prior to harvest. Livestock must be fed a diet that includes grains and forages that have been organically grown and cannot receive hormones, sub-therapeutic antibiotics, or other growth promoters.

**Organic Matter** - The carbonaceous waste contained in plant or animal matter and originating from domestic or industrial sources.

**Organic Nitrogen** - The nitrogen combined in organic molecules such as proteins, amines, and amino acids.

**Organism** - Any form of animal or plant life.

**ORP** - Oxidation Reduction Potential - the degree of completion of a chemical reaction by detecting the ratio of ions in the reduced form to those in the oxidized form as a variation in electrical potential measured by an ORP electrode assembly.

**OSHA** - The Williams-Steiger Occupational Safety and Health Act of 1970 (OSHA) is a law designed to protect the health and safety of industrial workers and treatment plant operators. It regulates the design, construction, operation and maintenance of industrial plants and wastewater treatment plants. The Act does not apply directly to municipalities, except in those states that have approved plans and have asserted jurisdiction under Section 18 of the OSHA Act. Wastewater treatment plants have come under stricter regulation in all phases of activity as a result of OSHA standards, which also refers to the federal and state agencies which administer OSHA.

**Oxidant** - A substance containing oxygen that reacts chemically with other materials to produce new substances. Oxidants are the primary ingredients in smog.

**Oxidation** - Combining elemental compounds with oxygen to form a new compound. A part of the metabolic reaction.

**Oxidation Pond** - A man-made lake or body of water in which wastes are consumed by bacteria. It is used most frequently with other waste treatment processes. An oxidation pond is basically the same as a sewage lagoon.

**Oxidizing Agent** - Any substance, such as oxygen ($O_2$) and chlorine ($Cl_2$), that can accept electrons. When oxygen or chlorine is added to wastewater, organic substances are oxidized. These oxidized organic substances are more stable and less likely to give off odors or to contain disease bacteria.

**Oxygen System** - Injects oxygen into liquid effluent; increases aerobic microbial activity and the rate of removal of BOD, COD, and ammoniacal nitrogen.

**Oxy-ozo synthesis** - Here the sewage is acidified and injected with ozone created by passing oxygen through an electric arc. It not only sterilizes the sludge, but bleaches it too, permitting its reuse as insulation material, for newsprint, as packaging, or as fuel. The supernatant liquid, too, can be ozonized in the outgoing pipeline to render it free of all pathogens prior to discharge to water. An excellent process although possibly more expensive than some. It was successfully used for the treatment of New York's and New Jersey's sewage until the Union bosses objected to the loss of employment of those who took the sludge out in barges to dump in the Atlantic Ocean.

**Ozonation** - The application of ozone to water, wastewater, or air, generally for the purposes of disinfection or odor control.

**Ozone ($O_3$)** - A naturally occurring unstable form of oxygen; attenuates harmful ultraviolet light in the stratosphere; a pollutant in the atmosphere at ground level; a powerful oxidizing agent and disinfectant.

**Ozonizer** - Equipment that generates ozone from oxygen or air by electrical discharge; used in the treatment and disinfection of water and wastewater

## P

**PAH** - Polycyclic aromatic hydrocarbons. (rarely used as abbreviation for polyaluminum hydroxide).

**Packed Tower Scrubber** - Cleans gases with a scrubbing liquor as they pass through inert media; removes soluble and noxious gases and mist droplets larger than 5 μm.

**Parisitism** - One organism living on or in another to obtain nourishment, without providing any benefit to the host organism.

**Particle** - A relatively small subdivision of matter ranging in diameter from a few angstroms (as with gas molecules) to a few millimeters (as with large raindrops). The particle can have various shapes and dimensions.

**Particulate** - Free suspended solids.

**Parts per Billion (ppb)** - One ppb is comparable to one kernel of corn in a filled, 45-foot silo, 16 feet in diameter.

**Parts per Million (ppm)** - One ppm is comparable to one drop of gasoline in a tankful of gas (full-size car).

**Parts per Trillion (ppt)** - One ppt is comparable to one drop in a swimming pool covering the area of a football field 43 ft. deep.

**Pathogen** - An organism capable of causing a susceptible host to develop a disease or infection.

**Pathogen Reduction** - Decreasing the presence of disease-causing organisms through sewage sludge processing and site management practices.

**Pathogenic Organisms** - Bacteria, viruses or cysts which cause disease (typhoid, cholera, dysentery) in a host (such as a person). There are many types of bacteria (non-pathogenic) which do not cause disease. Many beneficial bacteria are found in wastewater treatment processes actively cleaning up organic wastes.

**PCB** - Polychlorinated biphenyls. Aka polychloro-biphenyls. Difficult to remediate chemical used in old-style transformers. Concentrated PCBs used to be referred to as "1268."

**Pelletization** - In this process biosolids are first stabilized (see definition), then completely dried and pressed into small pellets. The pellets are then used as fertilizer since they are high in nitrogen.

**Pentachlorophenol (PCP)** - A powerful biocide, used to preserve cotton and wood; toxic and persistent; release to the environment now heavily restricted.

**Peracetic Acid** - As used by the Oxymaster system, this process relies on the addition of acetic acid and hydrogen peroxide to the sewage. Although this effectively kills off the coliform indicator bacteria, it may be seen as merely cosmetic, as it is far less effective against other bacterial pathogens and viruses. It can also oxidize the urea in urine to give rise to free chlorine.

**Percolation** - The movement or flow of water through soil or rocks.

**Perennial Stream** - A body of water flowing in a channel or bed composed of substrates associated with flowing waters and capable, in the absence of pollution or other man-made disturbances, of supporting a benthic macroinvertebrate community which is composed of two or more recognizable taxonomic groups of organisms which are large enough to be seen by the unaided eye and can be obtained by United States Standard No. 30 sieve (28 meshes per inch, 0.595 mm openings) and live at least part of their life cycles within or upon available substrates in a body of water or water transport system.

**Performance Bond** - Cash or securities, deposited before a landfill operating permit is issued, which are held to ensure that all requirements for operating a landfill are performed. The money is returned to the owner after proper closure of the landfill is complete. If contamination or other problems appear at any time during operation, or upon closure, and are not addressed, the owner must forfeit all or part of the performance bond which is then used to cover costs of cleanup.

**Peristaltic Pump** - A type of positive displacement pump.

**Permeability** - Ability of a membrane or other material to permit a substance to pass through it.

**Permissible Exposure Limit (PEL)** - Workplace exposure limits for contaminants established by OSHA.

**Permit** - A legal document issued by state and/or federal authorities containing a detailed description of the proposed activity and operating procedures as well as appropriate requirements and regulations. The permitting process includes provisions for public comment.

**Pesticide** - Substances intended to repel, kill, or control any species designated a "pest" including weeds, insects, rodents, fungi, bacteria, or other organisms. The family of pesticides includes herbicides, insecticides, rodenticides, fungicides, and bactericides.

**pH** - pH is an expression of the intensity of the basic or acidic condition of a liquid. Mathematically, pH is the logarithm (base 10) of the reciprocal of the hydrogen ion concentration. The pH may range from 0 to 14, where 0 is most acidic, 14 most basic, and 7 is neutral. Natural waters usually have a pH between 6.5 and 8.5.

**Phenol** - An organic compound that is an alcohol derivative of benzene.

**Phototroph** - A microorganism which gains energy from sunlight (radiant energy).

**PIB** - Product Information Bulletin. General information on a product.

**Pin Floc** - Excessive solids carryover. May occur from time to time as small suspended sludge particles in the supernatant. There are two kinds: grey-ashlike, inert, has low BOD - indicates old sludge; and brown, but a portion neither settles nor rises, has high BOD - indicates young sludge.

**Plane Wave** - An electromagnetic wave with electric and magnetic components perpendicular to, and in phase with, each other.

**Plant Available Nitrogen (PAN)** - Plant available nitrogen is a calculated quantity of nitrogen made available during the growing season after application of biosolids. PAN includes a percentage of the organic nitrogen (20% in year 1), a percentage of the ammonium N (depends on pH and incorporation) and all the nitrate nitrogen in the biosolids.

**Plume** - A concentration of contaminants in air, soil, or water usually extending from a distinct source.

**Point Source** - A stationary location or fixed facility such as an industry or municipality that discharges pollutants into air or surface water through pipes, ditches, lagoons, wells, or stacks; a single identifiable source such as a ship or a mine.

**Pollution** - The impairment (reduction) of water quality by agriculture, domestic or industrial wastes (including thermal and radioactive wastes) to such a degree as to hinder any beneficial use of the water or render it offensive to the senses of sight, taste, or smell or when sufficient amounts of waste creates or poses a potential threat to human health or the environment.

**Pollution Prevention** - Actively identifying equipment, processes, and activities which generate excessive wastes or use toxic chemicals and then making substitutions, alterations, or product improvements. Conserving energy and minimizing wastes are pollution prevention concepts used in manufacturing, sustainable agriculture, recycling, and clean air/clean water technologies.

**Polychlorinated Biphenyls (PCBs)** - A group of toxic, persistent chemicals used in electrical transformers and capacitors for insulating purposes, and in gas pipeline systems as a lubricant. The sale and new use of PCBs were banned by law in 1979.

**Polyculture** - Fish farming in which two or more compatible or symbiotic species of fish are grown together. Also known as *multiculture*.

**Polyelectrolytes** - Synthetic chemicals used to speed the removal of solids from sewage. The chemicals cause the solids to flocculate or clump together more rapidly than chemicals such as alum or lime.

**Polymer** - A chemical formed by the union of many monomers (a molecule of low molecular weight). Polymers are used with other chemical coagulants to aid in binding small suspended particles to form larger chemical flocs for easier removal from water. All polyelectrolytes are polymers, but not all polymers are polyelectrolytes.

**Pore Size** - The distance between two adjacent warp or weft threads, measured in the projected plane. Only applies to fabrics above 10 microns.

**Porosity** - The porosity of a soil is the percentage of the soil volume not occupied by soil solids.

**Potable Water** - Water that does not contain objectionable pollution, contamination, minerals, or infective agents and is considered satisfactory for drinking.

**Potentially Responsible Party (PRP)** - Any individual or company that is potentially responsible for or has contributed to a spill or other contamination at a Superfund site. Whenever possible, EPA requires PRPs to clean up sites they have contaminated.

**POTW** - Publicly Owned Treatment Works, as opposed to an industrially owned facility or pipe system.

**ppm** - parts per million. The unit commonly used to designate the concentration of a substance in a wastewater in terms of weight, i.e., one pound per million pounds, etc. ppm is synonymous with the more commonly used term mg/l (milligrams per liter).

**PRD** - Plain Reverse Dutch weave.

**Predation** - One species benefits at the expense of another.

**Pretreatment** - Methods used by industry and other nonhousehold sources of wastewater to remove, reduce, or alter the pollutants in wastewater before discharge to a POTW.

**Pretreatment Facility** - Industrial wastewater treatment plant consisting of one or more treatment devices designed to remove sufficient pollutants from wastewaters to allow an industry to comply with effluent limits established by the U.S. EPA General and Categorical Pretreatment Regulations or locally derived prohibited discharge requirements and local effluent limits. Compliance with effluent limits allows for a legal discharge to a POTW.

**Primary Treatment** - This treatment removes the sludge, the solid content of sewage. It may take the form of either filtration or by settling the sludge by sinking it in large holding tanks. The bacterial reduction is normally 90%, and the viral reduction even greater, as the viruses mainly attach to the solids. As it is mainly the sludge that demands the oxygen and is also responsible for the turbidity, any following secondary treatment then becomes effective. The sludge removed by the primary process may be digested, sterilized, or otherwise treated, and if free of heavy metals or other toxic content, may be safely used as a soil conditioner and fertilizer or other uses. When dried by the heat sterilization process it is known as 'Basic Sludge' and widely used as compost.

**Process Wastewater** - Any water which comes into contact with any raw material, product, by-product, or waste.

**Prokaryotic Organism** - Microorganisms which do not have an organized nucleus surrounded by a nuclear membrane. Bacteria and blue-green algae fit in this category.

**Protozoa** - A group of motile microscopic animals (usually single-celled and aerobic) that sometimes cluster into colonies and often consume bacteria as an energy source.

**Psychrophilic Bacteria** - Bacteria whose optimum temperature range is between 0 and 20°C (32 to 68°F).

**Public Comment Period** - The time allowed for the members of an affected community to express views and concerns regarding an action proposed to be taken by EPA, such as a rulemaking, permit, or Superfund remedy selection.

**Public Contact or Public Use Sites** - Land with a potential for use or contact by the public. This includes parks, ball fields, cemeteries, plant nurseries, turf farms, golf courses, schools, lawns, home gardens, road banks, residential land or other similar areas. It does not include agricultural land.

**Public Water System** - Any water system that regularly supplies piped water to the public for consumption, serving at least an average of 25 individuals per day for at least 60 days per year, or has at least 15 service connections.

**Publicly Owned Treatment Works (POTW)** - A municipal or public service district sewage treatment system.

**Putrefaction** - Biological decomposition of organic matter with the production of ill-smelling products associated with anaerobic conditions.

**Pyrogen** - A fever-producing substance. The presence of these substances is determined by the Limulus Amebocyte Lysate (LAL) test and measured in EU/ml (endotoxin units per milliliter).

## R

**Rack** - Evenly spaced parallel metal bars or rods located in the influent channel to remove rags, rocks, and cans from wastewater.

**Radio Frequency Interference (RFI)** - EMI in electronic equipment caused by radio frequencies, ranging typically from 10 kHz ($10^4$ Hz) to 1000 MHz ($10^9$ Hz or 1 GHz).

**Radioactive Waste** - Any waste that emits energy as rays, waves, or streams of energetic particles. Radioactive materials are often mixed with hazardous waste, usually from nuclear reactors, research institutions, or hospitals.

**Radon** - A colorless, naturally occurring gas formed by radioactive decay of radium atoms. Radon accumulating in basements and other areas of buildings without proper ventilation has been identified as a leading cause of lung cancer.

**RAS** - Return activated sludge. Settled activated sludge that is collected in the secondary clarifier and returned to the aeration basin to mix with incoming raw settled wastewater.

**RASVSS** - Return Activated Sludge Volatile Suspended Solids.

**Raw Water** - Intake water prior to any treatment or use.

**RBC** - Rotating biological contactor. An attached culture wastewater treatment system.

**Reactivity** - Refers to those hazardous wastes that are normally unstable and readily undergo violent chemical change but do not explode.

**Reagent** - A pure chemical substance that is used to make new products or is used in chemical tests to measure, detect, or examine other substances.

**Receiving Waters** - A river, lake, ocean, stream, or other body of water into which wastewater or treated effluent is discharged.

**Recharge Area** - An area of land where there is a net annual transfer of water from the surface to ground water; where rainwater soaks through the earth to reach an aquifer.

**Record of Decision (ROD)** - A public document that explains which cleanup alternative was selected for a Superfund site.

**Recycle** - The use of water or wastewater within (internally) a facility before it is discharged to a treatment system.

**Recycled Water** - Treated wastewater that undergoes additional, advanced treatment to make it safe for nonpotable uses such as landscape irrigation.

**Recycling** - Reusing materials and objects in original or changed forms rather than discarding them as wastes.

**Red Bag Waste** - see definition for medical waste.

**REDOX Reactions** - Biological reductions/oxidations. These reactions usually require enzymes to mediate the electron transfer. The sediment in the bottom of a lake, sludge in a sewerage works or septic tank will have a very low redox potential and will likely be devoid of any oxygen. This sludge or wastewater will have a very high concentration of reductive anaerobic bacteria, indeed the bulk of the organic matter may in fact be bacteria. As the concentration of oxygen increases the oxidation potential of the water will increase. A low redox potential or small amount of oxygen is toxic to anaerobic bacteria, therefore, as the concentration of oxygen and redox potential increases the bacterial population changes from reductive anaerobic bacteria to oxidative aerobic bacteria. Measurement of redox potential is also referred to as ORP.

**Reducing Agent** - Any substance, such as a base metal (iron) or the sulfide ion that will readily donate (give up) electrons. The opposite of an oxidizing agent.

**Reference Dose (RfD)** - The particular concentration of a chemical that is known to cause health problems. A standard that also may be referred to as the acceptable daily intake.

**Refine** - To remove impurities.

**Refractory Materials** - Material difficult to remove entirely from wastewater such as nutrients, color, taste, and odor-producing substances and some toxic materials.

**Regional Response Team (RRT)** - There are 13 RRTs, one for each of 10 federal regions, plus one for Alaska, one for the Caribbean, and one for the Pacific Basin. Each RRT maintains a Regional Contingency Plan and has state and federal government representation. EPA and the U.S. Coast Guard cochair the RRTs. Like the NRT, RRTs are planning, policy, and coordinating bodies and do not respond directly to pollution incidents but do provide assistance when requested by the federal On-Scene Coordinator. RRTs also provide assistance to SERCs and LEPCs in local preparedness, planning, and training for emergency response.

**Registration** - Formal listing with EPA of a new pesticide before sale or distribution. EPA is responsible for premarket licensing of pesticides on the basis of data demonstrating no unreasonable adverse health or environmental effects when applied according to approved label directions.

**Release** - Any spilling, leaking, pumping, pouring, emitting, emptying, discharging, injecting, escaping, leaching, dumping, or disposing into the environment of a hazardous or toxic chemical, or extremely hazardous substance.

**Remedial Action** - The actual construction or cleanup phase of a Superfund site cleanup.

**Reportable Quantity (RQ)** - Amount of a hazardous or extremely hazardous substance that, if released into the environment, must be reported to the NRC, the SERC, and the LEPC under Section 304 of EPCRA.

**Residual Risk** - The risk associated with pollutants after the application of maximum achievable control technology or MACT.

**Residual Shrinkage** - The amount of shrinkage remaining in a fabric after it has undergone all fabric weaving, washing, and heat setting steps.

**Resource Recovery** - The extraction of useful materials or energy from solid waste.

Such materials can include paper, glass, and metals that can be reprocessed for re-use. Resource recovery also is employed in pollution prevention.

**Respiration** - The energy producing process of breathing, by which an organism supplies its cells with oxygen and relieves itself of carbon dioxide. A type of heterotrophic metabolism that uses oxygen in which 38 mol of ATP are derived from the oxidation of 1 mol of glucose, yielding 380,000 cal. (An additional 308,000 cal is lost as heat.)

**Responsiveness Summary** - A summary of oral and written comments received by EPA during a public comment period on key documents or actions proposed to be taken, and EPA's response to those comments.

**Retentate** - Substance retained in the upstream side of a filter.

**Reverse Osmosis** - A high-pressure filtration system that uses selectively permeable membranes with extremely small pores to separate ions and particles.

**RF (Radio Frequency) Welding** - Utilizes specific bands of radio frequency waves which are directed through specially constructed tooling to form localized melting/joining of certain dielectric thermoplastic materials. Can be used to form hermetic seals. Also known as *high frequency* or *dielectric welding*.

**Rhizosphere** - Soil surrounding plant roots.

**Risk** - A measure of the chance that damage to life, health, property, or the environment will occur.

**Risk Assessment** - A process to determine the increased risk from exposure to environmental pollutants together with an estimate of the severity of impact. Risk assessments use specific chemical information plus risk factors.

**Risk Communication** - The process of exchanging information about levels or significance of health or environmental risk.

**Risk Factor** - A characteristic (e.g., race, sex, age, obesity) or variable (e.g., smoking, exposure) associated with increased chance of toxic effects. Some standard risk factors used in general risk assessment calculations include average breathing rates, average weight, and average human life span.

**R/O Unit** - Reverse osmosis unit for water purification in small aquariums and miniature yard ponds, utilizes a membrane under pressure to filter dissolved solids and pollutants from the water. Two different filter membranes can be used: the CTA (cellulose triacetate) membrane is less expensive, but only works with chlorinated water and removes 50 to 70% of nitrates, and the TFC membrane, which is more expensive, removes 95% of nitrates, but is ruined by chlorine. R/O wastes water and a system that cleans 100 gallons a day will cost from $400 to $600 with membrane replacement adding to the cost. A unit that handles 140 gallons a day will cost above $700.

**Rodenticide** - A pesticide or other agent used to kill rats and other rodents or to prevent them from damaging food, crops, or forage.

**Roof Leader** - The roof leader (or downspout) conveys runoff that has been collected in eavestroughs from roof tops, down to the ground surface or to a receiving sewer service.

**Rotary Scrubber** - A device that separates particulate contamination from a gas stream by impaction onto a wet rotor or into a fine spray of scrubbing liquor.

**Rotating Biological Contactor** - An aerobic treatment system that rotates plastic media with fixed microbial film alternately through liquid effluent and air to reduce the BOD value.

**Routine Storage** - The storage of biosolids (for extended periods of time) until the land is in a condition to receive the biosolids.

**RR** - Respiration rate - the weight of oxygen utilized by the total weight of MLSS in a given time.

**Runoff** - Water running down slopes rather than sinking in (again, result of poor humus content), e.g., erosion due to deforestation.

## S

**Salts** - The minerals that water picks up as it passes through the air, over and under the ground, and through household and industrial uses.

**Sand Filters** - Devices that remove some suspended solids from sewage. Air and bacteria decompose additional wastes filtering through the sand. Cleaner water drains from the bed. The sludge accumulating at the surface must be removed from the bed periodically.

**Sanitary Sewers** - In a separate system, pipes in a city that carry only domestic wastewater. The stormwater runoff is taken care of by a separate system of pipes.

**Saprophytic Bacteria**- Bacteria that break down bodies of dead plants and animals (non-living organic material), returning organic materials to the food chain. Saprophytic bacteria are usually non-pathogenic, too.

**SAR** - Sodium adsorption ratio. This ratio expresses the relative activity of sodium ions in the exchange reactions with the soil.

**Satellite Treatment** - Any form of treatment located at a facility located away from the wastewater treatment plant.

**SCFM** - Cubic feet of air per minute at standard conditions of temperature, pressure and humidity (0°C, 14.7 psi, and 50% relative humidity).

**Screens** - Equipment that separates solid material from liquid by allowing the liquid to pass through constrictions (the screen) of chosen size.

**Scrubbing** - A common method of reducing stack air emissions; removal of impurities by spraying a liquid that concentrates the impurities into waste.

**Seasonal High Water Table** - The minimum depth from the soil surface at which redoximorphic features are present in the soil.

**Secondary Treatment** - This involves aeration of the clear effluent produced following primary treatment solids removal. The liquid phase may be aerated in daylight in large storage tanks, or it may be trickled or sprayed over banks of stones open to the air and daylight. Both are effective. The pathogen reduction is a further 90%, giving now 99% total reduction in infectivity. As the biological oxygen demand is now substantially reduced and the transparency to natural UV light penetration much enhanced, if now placed into the sea, a further rapid die-off of organisms will come about.

**Sediment** - Topsoil, sand, and minerals washed from the land into water, usually after rain or snowmelt. Sediments collecting in rivers, reservoirs, and harbors can destroy fish and wildlife habitat and cloud the water so that sunlight cannot reach aquatic plants. Loss of topsoil from farming, mining, or building activities can be prevented through a variety of erosion-control techniques.

**Sedimentation** - The process of subsidence and deposition of suspended matter from a wastewater by gravity.

**Sedimentation Tanks** - Helps remove solids from sewage. The wastewater is pumped to the tanks where the solids settle to the bottom or float on the top as scum. The scum is skimmed off the top, and solids on the bottom are pumped to incineration, digestion, filtration, or other means of final disposal.

**Seeding** - Introduction of microorganisms into a biological oxidation unit to minimize the time required to build a biological sludge. Also referred to as inoculation with cultured organisms.

**Seine Net** - A net designed to collect aquatic organisms inhabiting natural waters from the shoreline to 3 ft depths is called a seine net. Most often a plankton seine.

**Selvage** - A loom-finished edge that prevents cloth unravelling.

**Septage** - The biodegradable waste from septic tanks and similar treatment works. Septage includes the sediments, water, grease, and scum pumped from a septic tank.

**Septic** - A condition produced by anaerobic bacteria. If severe, the wastewater turns black, gives off foul odors, contains little or no dissolved oxygen and creates a high oxygen demand.

**Septic Tanks/Soil Absorption Systems** - The most common form of on-site wastewater treatment is a septic tank/soil absorption system. In this system, wastewater flows from the household sewage lines into an underground septic tank. The following then occurs: (1) The waste components separate, with the heavier solids (sludge) settling to the bottom and the grease and fatty solids (scum) floating to the top. (2) Bacteria partially decompose and liquefy the solids. (3) Baffles in the tank provide maximum retention time of solids to prevent inlet and outlet plugging, and to prevent rapid flow of wastewater through the tank. (4) The liquid portion (effluent) flows through an outlet on the septic tank to the soil absorption field. (5) The absorption field is usually a series of parallel trenches, each containing a distribution pipe or tile line embedded in drain field gravel or rock. (6) The effluent drains out through holes in the pipe or seams between tile sections, then through the drain field gravel or rock and into the soil. (7) The soil filters remaining minute solids, some dissolved solids, and pathogens (disease-producing microorganisms). Water and dissolved substances slowly percolate outward into the soil and down toward groundwater or restrictive layers. A portion of the water evaporates into the air, and plants growing over the drain field lines utilize some of the water.

**Settleable Solids** - Those solids in suspension which will pass through a 2000-micron sieve and settle in 1 hr under the influence of gravity.

**Sewage** - The used water and water-carried solids from homes that flow in sewers to a wastewater treatment plant. The preferred term is wastewater.

**Sewage Sludge** - A solid, semisolid, or liquid residue generated during the treatment of domestic sewage in a treatment works.

**Sewers** - A system of pipes that collect and deliver wastewater to treatment plants or receiving streams.

**Shock Load** - The arrival at a plant of a waste which is toxic to organisms in sufficient quantity or strength to cause operating problems. Possible problems include odors and sloughing off of the growth or slime on a trickling-filter medium. Organic or hydraulic overloads also can cause a shock load.

**Sieve** - A screen with apertures of uniform size used for sizing granular materials.

**Single-loop Controllers** - A self-contained unit composed of microprocessor-based sequencers, timers, and programmable logic controllers all dedicated to controlling a single loop or specific system.

**Sink Hole** - A naturally occurring basin which has no visible external or surface drainage, and in which ponding may occur during or following periods of rainfall.

**Siphon** - A closed conduit that lies above the hydraulic grade line, resulting in a pressure less than atmospheric and requiring a vacuum within the conduit to start flow. A siphon utilizes atmospheric pressure to effect or increase flow through the conduit.

**Siting** - Choosing a location for a facility.

**Skimming** - (1) The process of diverting water from the surface of a stream or conduit by means of a shallow overflow. (2) The process of removing grease or scum from the surface of wastewater in a tank.

**Skimmings** - Grease, solids, liquids, and scum skimmed from wastewater settling tanks.

**Slake** - To become mixed with water so that a true chemical combination takes place, as in the slaking of lime.

**Sleeve Bearing** - Also known as *journal bearing*. A metal jacket fully or partially enclosing a rotating inner shaft.

**Slimes** - (1) Substances of a viscous organic nature, typically formed from microbiological growth, that attach themselves to other objects, forming a coating. (2) The coating of biomass that accumulates in trickling filters or sand filters and periodically sloughs away to be collected in clarifiers.

**Sloughings** - Trickling-filter slimes that have been washed off the filter media. They are generally quite high in BOD and will lower effluent quality unless removed.

**Sludge** - (1) Accumulated solids separated from liquids during the treatment process that have not undergone a stabilization process. (2) Removed material resulting from chemical treatment, coagulation, flocculation, sedimentation, flotation, or biological oxidation of water or wastewater. (3) Any solid material containing large amounts of entrained water collected during water or wastewater treatment.

**Sludge Age** - Average residence time of suspended solids in a biological treatment system equal to the total weight of suspended solids in the system divided by the total weight of suspended solids leaving the systems.

**Sludge Blanket** - Accumulation of sludge hydrodynamically suspended within an enclosed body of water or wastewater.

**Sludge Blanket Depth** - Also referred to as depth of blanket and is a measurement of the depth of solids in a vessel. The measurement may be performed using a sonic meter, density meter, or Secchi disc.

**Sludge Boil** - An upwelling of water and sludge deposits caused by release of decomposition gases in the sludge deposits.

**Sludge Concentration** - Any process of reducing the water content of sludge while leaving the sludge in a fluid condition.

**Sludge Collector** - A mechanical device for scraping the sludge on the bottom of a settling tank to a sump from which it can be drawn.

**Sludge Density Index** - A measure of the degree of compaction of a sludge after settling in a graduated container, expressed in milliliters per gram (ml/g). The sludge density index is the reciprocal of the sludge volume index (SVI).

**Sludge Holding Tank** - A tank, typically constructed of steel or concrete, that is used for liquid sludge storage.

**Sludge Lagoon** - An earthen basin that receives only sludge that has been removed from a wastewater treatment facility. It does not include a wastewater treatment lagoon or sludge treatment units that are a part of a mechanical treatment.

**Sludge Solids** - Dissolved and suspended solids in sludge.

**Sludge Thickening** - The increase in solids concentration of sludge resulting from gravitational force in a sedimentation or digestion tank.

**Sludge Volume Index (SVI)** - The ratio of the volume (in milliliters) of sludge settled from a 1000-ml sample in 30 minutes to the concentration of mixed liquor (in milligrams per liter (mg/l)) multiplied by 1000. The SVI is the reciprocal of the sludge density index.

**Slugs** - Intermittent releases or discharges of industrial wastes.

**Slurry** - A watery mixture of insoluble matter, such as lime slurry.

**Small Quantity Generator (SQG)** - Persons or facilities that produce 220 to 2,200 pounds per month of hazardous waste. SQGs are required to keep more records than conditionally exempt generators. SQGs may include automotive shops, dry cleaners, photographic developers, and a host of other small enterprises. SQGs comprise by far the vast majority of hazardous waste generators.

**Smog** - Dust, smoke, or chemical fumes that pollute the air and make hazy, unhealthy conditions (literally, the word is a blend of smoke and fog). Automobile, truck, bus, and other vehicle exhausts and particulates are usually trapped close to the ground, obscuring visibility and contributing to a number of respiratory problems.

**Soda Ash** - A common name for commercial sodium carbonate ($Na_2CO_3$).

**Sodium Bisulfite ($NaHSO_3$)** - A salt used for reducing chlorine residuals. A strong reducing agent; typically found in white powder or granular form in strengths up to 44%. At a strength of 38%, 1.46 parts sodium bisulfite will consume 1 part of chlorine residual.

**Sodium Carbonate ($Na_2CO_3$)** - A salt used in water treatment to increase the alkalinity or pH of water or to neutralize acidity. Also called *soda ash.*

**Sodium Hydroxide (NaOH)** - A strong caustic chemical used in treatment processes to neutralize acidity, increase alkalinity, or raise the pH value. Also known as caustic soda, sodium hydrate, lye, and white caustic.

**Sodium Hypochlorite (NaOCl)** - A water solution of sodium hydroxide and chlorine in which sodium hypochlorite is the essential ingredient.

**Sodium Metabisulfite ($Na_2S_2O_5$)** - A cream-colored powder used to consume chlorine residual. 1.34 parts of sodium metabisulfite will consume 1 part of chlorine residual.

**Soil** - A natural body synthesized over time from a mixture of inorganic and organic parent materials, now supporting living plants. Soils with depth have natural horizons (layers) that give them their properties. Such properties include texture, color, structure, and bulk density.

**Soil pH** - An index of the acidity or alkalinity of a suspension of soil in a liquid such as distilled water or dilute salt solution. The index is the logarithmic expression of the activity of H-ions in the liquid surrounding the soil particles. A pH $>7.0$ is alkaline and $<7.0$ is acid. A soil pH is not a measure of total acidity in a soil. It is a measure of the acidity or alkalinity of the soil.

**Soil Profile** - A two-dimensional view of the soil from the earth's surface down to and including the parent material.

**Soil Saturation** - The water content of a soil beyond which no more water is absorbed.

**Soil Structure** - The arrangement of soil particles into larger particles or clumps. This arrangement modifies the bulk density and porosity of the soil.

**Soil Washing** - Water-based volume reduction process in which contaminated soil or dredgings are separated into a small contaminated fraction, for further treatment or disposal, and a larger cleaned fraction.

**Solid Waste** - As defined under RCRA, any solid, semisolid, liquid, or contained gaseous materials discarded from industrial, commercial, mining, or agricultural operations, and from community activities. Solid waste includes garbage, construction debris, commercial refuse, sludge from water supply or waste treatment plants or air pollution control facilities, and other discarded materials.

**Solid Waste Management Facility** - Any disposal or resource recovery system; any system, program, or facility for resource conservation; any facility for the treatment of solid wastes.

**Solidification** - Solidification methods result in a solid, low-permeable block of contaminated soil or sludge. To accomplish this, solidifying admixtures which mechanically lock contaminants within the solidified matrix are incorporated into the sludge or contaminated soil. This may or may not involve chemical bonding between the toxic contaminant and the additive. By decreasing the exposed surface area and/or encapsulating the waste, contaminant migration can be significantly decreased.

**Solids Inventory** - Mass of sludge in the treatment system. Inventory of plant solids should be tracked through the use of mass balance set of calculations.

**Solids Loading** - Amount of solids applied to a treatment process per unit time per unit volume.

**Solids Retention Time (SRT)** - The average time of retention of suspended solids in a biological wastewater treatment system. Equals the total weight of suspended solids leaving the system per unit time.

**Soluble** - Matter or compounds capable of dissolving into a solution.

**Soluble BOD** - The BOD of water that has been filtered in the standard suspended solids test.

**Solution** - A liquid mixture of dissolved substances, displaying no phase separation.

**Solvent** - Typically a liquid substance capable of dissolving or dispersing one or more other substances.

**Source Reduction** - The design, manufacture, purchase, or use of materials (such as products and packaging) to reduce the amount or toxicity of garbage generated. Source reduction can help reduce waste disposal and handling charges because the costs of recycling, municipal composting, landfilling, and combustion are avoided. Source reduction conserves resources and reduces pollution.

**Source Separation** - Organizing materials by type (such as paper, metal, plastic, and glass) so that these items can be recycled instead of thrown away. For example, many of us separate these items from the rest of our household and office wastes. Industries also organize materials in this fashion.

**Sparger** - An air diffuser designed to give large bubbles. Used singly or in combination with mechanical aeration devices.

**Spec. Sheet** - Specification Sheet. Detailed information on a product, including tests, color, odor, specific gravity, bacterial strains, other major ingredients, etc.

**Species** - A subdivision of a genus having members differing from other members of the same genus in minor details.

**Specific Gravity** - The ratio of the mass of a body to the mass of an equal volume of water at a specific temperature.

**Specific Oxygen Uptake Rate (SOUR)** - A measure of the microbial activity in a biological system expressed in milligrams of oxygen per hour per gram of volatile suspended solids. Also called *respiration rate.*

**Spiral Air Flow Diffusion** - A method of diffusing air in the grit chamber or aeration tank of the activated-sludge process where, by means of properly designed baffles and the proper location of diffusers, a spiral helical movement is given to the air and the reactor liquor.

**Split Bearing Cover** - A bearing cover plate that is made up of two halves that can be easily removed to access the bearing for maintenance or inspection.

**Split Case Pump** - A pump with a casing that is split parallel to the drive shaft.

**Split Rigid Coupling** - An inflexible coupling that is split in half parallel to the pump shaft. This coupling is very useful when the pump impeller needs to be positioned further away or closer to the motor.

**Splitter Box** - (1) A division box that splits the incoming flow into two or more streams. (2) A device for splitting and directing discharge from the head box to two separate points of application.

**Spray Aerator** - An aerator consisting of a pressure nozzle through which water is propelled into the air in a fine spray.

**Squirrel Cage Motor** - A polyphase motor that is widely used in water and wastewater treatment applications and can be purchased in many configurations. Enclosures for these motors include open drip-proof, totally enclosed non-ventilated, and totally enclosed fan cooled.

**Stabilization** - Stabilization techniques limit the solubility or mobility of contaminants in sludge, even though the physical characteristics of the waste may not be changed or improved. To accomplish this, reagents are added or other specialized materials and blended with the sludge or contaminated soil. Stabilization ensures that the hazardous components are maintained in their least mobile or toxic form.

**Staged Treatment** - (1) Any treatment in which similar processes are used in series or stages. (2) In the activated-sludge process, two or more stages consisting of a clarifying stage and a biological stage, or two biological stages. (3) In anaerobic digestion, an operation in which sludge is completely mixed in the first tank and pumped to a second tank for separation of the supernatant liquor from the solids.

**Standard Industrial Classification Code (SIC Code)** - A method of grouping industries with similar products or services and assigning codes to these groups.

**Standard Methods** - An assembly of analytical techniques and descriptions commonly accepted in water and wastewater treatment (i.e., Standard Methods for the Examination of Water and Wastewater) published jointly by the American Public Health Association, the American Water Works Association, and the Water Environment Federation.

**Standard Pressure** - Atmospheric pressure at sea level under standard conditions.

**Standby Motor** - An identical motor that is maintained in case of breakdown or malfunction of a pump's prime driver.

**State Emergency Response Commission (SERC)** - The agency appointed by the governor of a state to oversee the administration of EPCRA at the state level. This commission designates and appoints members to LEPCs and reviews emergency response plans for cities and counties.

**Static Head** - Vertical distance between the free level of the source of supply and the point of free discharge or the level of the free surface.

**Static Level** - (1) The elevation of the water table or pressure surface when it is not influenced by pumping or other forms of extraction. (2) The level of elevation to which the top of a column of water would rise, if afforded the opportunity to do so, from an artesian aquifer, basin, or conduit under pressure. Also called *hydrostatic level.*

**Static Suction Head** - The vertical distance from the source of supply when its level is above the pump to the center line of the pump.

**Static Suction Lift** - The vertical distance between the center of the suction end of a pump and the free surface of the liquid being pumped. Static lift does not include friction losses in the suction pipes. Static suction head includes lift and friction losses.

**Static Tubular Aerator** - A system in which air is blown into vertical tubes submerged in a liquid, promoting mixing and oxygen transfer.

**Stator** - The stationary member of an electric motor or generator.

**Steady Flow** - (1) A flow in which the rate or quantity of water passing a given point per unit of time, remains constant. (2) Flow in which the velocity vector does not change in either magnitude or direction with respect to time at any point or section.

**Steady Nonuniform Flow** - A flow in which the quantity of water flowing per unit of time remains constant at every point along the conduit but the velocity varies along the conduit because of a change in the hydraulic characteristics.

**Step Aeration** - A procedure for adding increments of settled wastewater along the line of flow in the aeration tanks of an activated-sludge plant.

**Step-feed Process** - A procedure for adding increments of settled wastewater along the line of flow in biological reactors of an activated-sludge process.

**Sterilization** - The destruction of all living organisms. In contrast, *disinfection* is the destruction of most of the living organisms.

**Stiff White Foam** - A collection of minute bubbles that are formed on the surface of biological reactors when incomplete digestion of surfactants occurs.

**Stoichiometric** - Pertaining to or involving substances that are in the exact proportions required for a given reaction.

**Storm Sewers** - A separate system of pipes that carry only runoffs from buildings and land during a storm.

**Stormwater** - That portion of rainfall that does not infiltrate into the soil.

**Stormwater Management** - The management of runoff to provide controlled release rates to receiving systems, typically through the use of detention/retention facilities such as lakes.

**Straggler Floc** - Large (6 mm or larger) floc particles that have poor settling characteristics.

**Strain Gauge** - A device that converts a movement, such as a coil of wire as it is loaded, into a change in electrical properties. This results in a very sensitive measurement of the strain. Strain gauges are often used in pressure sensors and weight scales.

**Submerged Aerated Filter** - A device in which highly aerated effluent flows through inert medium that is completely submerged; fixed microbial film reduces the BOD and ammoniacal content of the effluent.

**Submerged Biological Contactor** - An aerobic treatment system in which plastic medium that is largely submerged in effluent is rotated by rising air, the fixed microbial film on the medium reducing the BOD value.

**Submersible Pump** - A motor and pump combination designed to be placed entirely below the liquid surface. Submersible pumps are typically constructed as pumps vertically closed-coupled to a submersible motor. They are used for domestic and industrial treatment applications and for pumping groundwater from wells.

**Submicron Particles** - Particles of less than 1μm in size, present in smoke and fumes.

**Subsoil** - The part of the soil profile beneath the surface soil that has been altered from its original geologic characteristics. In many instances, it is called a "B horizon."

**Substrate** - (1) Substances used by organisms in liquid suspension. (2) The liquor in which activated sludge or other matter is kept in suspension.

**Suction Gauge** - A pressure gauge placed on suction piping near the point where the pump connection is made. The gauge reading gives a good approximation of the suction head conditions.

**Suction Head** - (1) The head at the inlet to a pump. (2) The head below atmospheric pressure in a piping system.

**Suction Lift** - The vertical distance from the liquid surface in an open tank or reservoir to the center line of a pump drawing from the tank or reservoir and set higher than the liquid surface.

**Suction Valve** - A valve that is located on the suction piping of a pump.

**Suctoreans** - Ciliates that are stalked in the adult stage and have rigid tentacles to catch prey.

**Sulfate-reducing Bacteria** - Bacteria capable of assimilating oxygen from sulfate compounds and reducing them to sulfides. See *sulfur bacteria.*

**Sulfur Bacteria** - Bacteria capable of using dissolved sulfur compounds in their growth.

**Sulfur Cycle** - A graphical presentation of the conservation of matter in nature showing the chemical transformation of sulfur through various stages of decomposition and assimilation. Various chemical forms of sulfur as it moves among living and nonliving matter are used to illustrate general biological principles that are applicable to wastewater and sludge treatment.

**Sulfur Dioxide ($SO_2$)** - Toxic gas produced during the combustion of sulfur compounds in fossil fuels; component of acid rain.

**Sump** - A tank or pit that receives drainage and stores it temporarily and from which the discharge is pumped or ejected.

**Sump Pump** - A sump (depression) and pump assembly that receives groundwater infiltration flows collected by weeping tiles located around the foundations of buildings, and pumps the flows up onto the outside ground surface.

**Supernatant** - (1) The liquid remaining above a sediment or precipitate after sedimentation. (2) The most liquid stratum in a sludge digester.

**Suppressed Weir** - A weir with one or both sides flush with the channel of approach. This prevents contraction of the nappe adjacent to the flush side. The suppression may occur on one end or both ends.

**Surface Aeration** - The absorption of air through the surface of a liquid.

**Surface Aerator** - Equipment in which blades or vanes rotate about a vertical or horizontal shaft and entrain air to mix and aerate wastewater.

**Surface Impoundment** - Treatment, storage, or disposal of liquid hazardous wastes in ponds.

**Surface Medium** - Captures particles on the upstream surface with efficiencies in excess of depth media, sometimes close to 100% with minimal or no off-loading. Commonly rated according to the smallest particle the media can repeatedly capture. Examples of surface media include ceramic media, microporous membranes, synthetic woven screening media and in certain cases, wire cloth. The medium characteristically has a narrow pore size distribution.

**Surface Overflow Rate** - A design criterion used for sizing clarifiers. Typically expressed as the flow volume per unit amount of clarifier space.

**Surface Resistivity** - Expressed in ohms/square. It is numerically equal to the resistance between two electrodes forming opposite sides of a square on the surface of a material. The size of the square is irrelevant. For conductive materials, surface resistivity is the ratio of the volume resistivity to the fabric thickness (r/t).

**Surface Runoff** - The portion of rainfall, irrigation water, or wastewater that does not infiltrate into the soil.

**Surface Soil** - Surface soil (A horizon) is the portion of the soil profile at the interface with the earth's atmosphere. It is normally the portion of the profile containing the greatest amount of organic matter. If the surface is plowed it is called a plow layer or Ap horizon.

**Surface Water** - All water naturally open to the atmosphere (rivers, lakes, reservoirs, ponds, streams, seas, estuaries) and all springs, wells, or other collectors directly influenced by surface water.

**Surfactant** - A surface-active agent that concentrates at interfaces, forms micelles, increases solution, lowers surface tension, increases adsorption, and may decrease flocculation.

**Surge** - (1) A momentary increase in flow (in an open conduit) or pressure (in a closed conduit) that passes longitudinally along the conduit, typically because of sudden changes in velocity or quantity. (2) Any periodic, typically abrupt, change in flow, temperature, pH, concentration, or similar factor.

**Surge Suppressor** - A device used in connection with automatic control of pumps to minimize surges in a pipeline.

**Suspended Growth Reactors** - The most commonly applied biological treatment system is a suspended growth approach, more commonly called the activated sludge process. In this process, effluent from the primary clarifier is introduced to an aeration tank and mixed with a mass of microorganisms comprised of bacteria, fungi, rotifers, and protozoa. This mixture of liquid, waste solids, and microorganisms is called the mixed liquor and the waste solids and microorganisms the mixed liquor suspended solids (MLSS, mg/L). The organisms absorb dissolved organics and break them down into carbon dioxide, water, and various stable compounds. Bacteria are primarily responsible for assimilating the organic matter in wastewater and the rotifers and protozoa are helpful in removing the dispersed bacteria which otherwise would not settle out. The energy derived from the decomposition process is used for cell maintenance and to produce more microorganisms. Once most of the dissolved organics have been used up, the MLSS is routed to the secondary (or final) clarifier for separation. As with primary settling, two streams are produced: a clarified effluent, which is sent to the next stage of treatment, and a liquid sludge composed largely of microorganisms. Lying at the bottom of the final clarifer, without a food source, these organisms become nutrient-starved or "activated." A portion of the sludge is then pumped to the head of the tank (return activated sludge) where the process starts all over again. The remainder of the sludge is processed for disposal (waste activated sludge). It is necessary to continuously waste sludge to balance the gain through microbial growth.

**Suspended Matter** - (1) Solids in suspension in water, wastewater, or effluent. (2) Solids in suspension that can be readily removed by standard filtering procedures in a laboratory.

**Suspended Solids** - (1) Insoluble solids that either float on the surface of, or are in suspension in, water, wastewater, or other liquid. (2) Solid organic or inorganic particles (colloidal, dispersed, coagulated, or flocculated) physically held in suspension by agitation or flow. (3) The quantity of material removed from wastewater in a laboratory test and referred to as nonfilterable residue.

**Sustainable Agriculture** - Environmentally friendly methods of farming that allow the production of crops or livestock without damage to the farm as an ecosystem, including effects on soil, water supplies, biodiversity, or other surrounding natural resources. The concept of sustainable agriculture is an "intergenerational" one in which we pass on a conserved or improved natural resource base instead of one which has been depleted or polluted. Terms often associated with farms or ranches that are self-sustaining include "low-input," "organic," "ecological," "biodynamic," and "permaculture."

**Synchronous Motor** - An electric motor having a speed strictly proportional to the frequency of the operating current.

**Synergism** - The cooperative action of two or more organisms producing a greater total result than the sum of their independent effects; chemicals or muscles in synergy enhance the effectiveness of one another beyond what an individual could have produced.

## T

**Tangential Crossflow Filtration** - Process where the feed stream "sweeps" the membrane surface and the particulate debris is expelled, thus extending filter life. The filtrate flows through the membrane. Most commonly used in the separation of high- and low-molecular weight matter such as in ultrapure reverse osmosis, ultrafiltration, and submicron microfiltration processes.

**Tapered Aeration** - The method of supplying varying quantities of air into the different parts of a biological reactor in the activated-sludge process, more at the inlet, less near the outlet, in approximate proportion to the oxygen demand of the mixed liquor under aeration.

**Taxonomy** - The classification, nomenclature, and laboratory identification of organisms.

**TDS** - Total dissolved solids is commonly estimated from the electrical conductivity of the water. Pure water is a poor conductor of electricity. Impurities dissolved in the water cause an increase in the ability of the water to conduct electricity. Conductivity, usually expressed in units of microsiemens, formerly micromhos or in mg/l, thus becomes an indirect measure of the level of impurities in the water.

**Technical Assistance Grant (TAG)** - EPA grants of up to $50,000 for citizens' groups to obtain assistance in interpreting information related to cleanups at Superfund sites. Grants are used by such groups to hire technical advisors to help them understand the site-related information for the duration of response activities.

**Ten-to-the-Minus-Sixth ($10^{-6}$)** - Used in risk assessments to refer to the probability of risk. Literally means a chance of one in a million. Similarly, ten-to-the-minus-fifth means a probability of one in 100,000, and so on.

**Teratogen** - A substance capable of causing birth defects.

**Tertiary Effluent** - The liquid portion of wastewater leaving tertiary treatment.

**Tertiary Treatment** - It may take the form of passing the primary and secondary treated liquid phase through clear quartz tubes exposed to intense ultraviolet light. With fully transparent and well-oxygenated liquid phase effluent, this can totally destroy all known pathogens, and so be employed to provide safe discharges to bathing waters and to shellfish areas. Tertiary treatment may also include chemically stripping off the phosphate and nitrate levels found in the outfall. The phosphates emanate from detergents and from human urine in the effluent, whilst the nitrates come from both sewage and agricultural sources. Such nutrient stripping treatment may be essential in waters where eutrophication is likely to produce dangerous levels of toxic algae.

**Thermal Oxidation** – High-temperature incineration of pollutants such as VOCs and odors in gas streams.

**Thermophilic Bacteria** - Hot temperature bacteria. a group of bacteria that grow and thrive in temperatures above 113°F (45°C), such as *bacillus licheniformis*. The optimum temperature range for these bacteria in anaerobic decomposition is 120° F (49°C) to 135°F (57°C).

**Threshold Limit Value (TLV)** - The concentration of an airborne substance that a healthy person can be exposed to for a 40-hour work week without adverse effect; a workplace exposure standard.

**Throughput** - The amount of solution which will pass through a filter prior to clogging.

**Titration** - The determination of a constituent in a known volume of solution by the measured addition of a solution of known strength to completion of the reaction as signaled by observation of an end point.

**Tolerance** - The ability of an organism to withstand exposure to a specific compound. A tolerance level may be defined as a period of exposure or a level of exposure (concentration) that is withstood.

**Tonnage** - The amount of waste that a landfill accepts, usually expressed as tons per month. The rate at which a landfill accepts waste is limited by the landfill's permit.

**Total Carbon** - A quantitative measure of both total inorganic and total organic carbon as determined instrumentally by chemical oxidation to carbon dioxide and subsequent infrared detection in a carbon analyzer. See total *organic carbon.*

**Total Dissolved Solids (TDS)** - The sum of all dissolved solids (volatile and nonvolatile).

**Total Dynamic Discharge Head** - Total dynamic head plus dynamic suction head or minus dynamic suction lift.

**Total Dynamic Head** - The difference between the elevation corresponding to the pressure at the discharge flange of a pump and the elevation corresponding to the vacuum or pressure at the suction flange of the pump, corrected to the same datum plane, plus the velocity head at the discharge flange of the pump minus the velocity head at the suction flange of the pump.

**Total Head** - (1) The sum of the pressure, velocity, and position heads above a datum. The height of the energy line above a datum. (2) The difference in elevation between the surface of the water at the source of supply and the elevation of the water at the outlet, plus velocity head and lost head. (3) In open channel flow, the depth plus the velocity head.

**Total Kjeldahl Nitrogen** - The combined amount of organic and ammonia nitrogen.

**Total Organic Carbon** - The amount of carbon bound in organic compounds in a sample. Because all organic compounds include carbon as the common element, total organic carbon measurements provide a fundamental means of assessing the degree of organic pollution.

**Total Oxygen Demand** - A quantitative measure of all oxidizable material in a sample water or wastewater as determined instrumentally by measuring the depletion of oxygen after high-temperature combustion.

**Total Pumping Head** - The measure of the energy increase imparted to each pound of liquid as it is pumped, which equals the algebraic difference between the total discharge head and the total suction head.

**Total Solid** - The sum of dissolved and suspended solid constituents in water or wastewater.

**Total Suspended Solids (TSS)** - The portion of solids in water that is retained by filter when the sample is filtered. High suspended solids can decrease light penetration and reduce photosynthesis.

**Toxic Release Inventory (TRI)** - A database of annual toxic releases from certain manufacturers compiled from EPCRA Section 313 reports. Manufacturers must report annually to EPA and the states the amounts of almost 350 toxic chemicals and 22 chemical categories that they release directly to air, water, or land, inject underground, or transfer to off-site facilities. EPA compiles these reports and makes the information available to the public under the "Community Right-to-Know" portion of the law.

**Toxic Substances** - A substance that kills or injures an organism through chemical, physical, or biological action.

**Toxic Wastes** - Wastes that can cause an adverse response when they come in contact with a biological entity.

**Toxicity** - The relative degree of being poisonous or toxic. A condition which may exist in wastes and will inhibit or destroy the growth or function of certain organisms.

**Toxicity Characteristic Leaching Procedure (TCLP)** - A test designed to determine whether a waste is hazardous or requires treatment to become less hazardous; also can be used to monitor treatment techniques for effectiveness.

**Toxicity Testing** - Biological testing (usually with an invertebrate, fish, or small mammal) to determine the adverse effects, if any, of a chemical, compound, or effluent.

**Trace Nutrients** - Substances vital to bacterial growth of organisms.

**Transpiration** - The process by which water vapor is released to the atmosphere by living plants, a process similar to people sweating.

**Trap** - (1) A device used to prevent a material flowing or carried through a conduit from reversing its direction of flow or movement, or from passing a given point. (2) A device to prevent the escape of air from sewers through a plumbing fixture or catch basin.

**Treatment Methodologies** - There are many specific ways of treating sewage to render it safe to human health and the environment.

**Treatment, Storage, and Disposal Facility (TSD)** - Refers to any facility which treats, stores, or disposes of hazardous wastes.

**Trickling Filter** - A support medium for bacterial growth, usually a bed of rocks or stones. The sewage is trickled over the bed so the bacteria can break down the organic wastes. The bacteria collect on the stones through repeated use of the filter.

**Trisodium Phosphate ($Na_3PO_4$)** - Trisodium phosphate has the property of softening water by precipitating metallic ions, as a gelatinous precipitate. It can also help in dispersing soil and in the saponification of fatty acids. It can cocrystallize with sodium hypochlorite (NaOCI), which then has the added advantage of being a bleaching agent.

**Trough** - A structure, typically with a length several times its transverse dimensions, used to hold or transport water or other liquids.

**TSS** - Total suspended solids.

**Tube Settler** - A series of tubes approximately 0.5 cm (2 in.) in diameter, placed in a sedimentation tank to improve the solids removal efficiency.

**Turbidimeter** - An instrument for measurement of turbidity in which a standard suspension is used for reference.

**Turbidity** - (1) A condition in water or wastewater caused by the presence of suspended matter and resulting in the scattering and absorption of light. (2) Any suspended solids imparting a visible haze or cloudiness to water that can be removed by filtration. (3) An analytical quantity typically reported in turbidity units determined by measurements of light scattering.

**Turbulence** - (1) The fluid property that is characterized by irregular variation in the speed and direction of movement of individual particles or elements of flow. (2) A state of flow of water in which the water is agitated by cross currents and eddies, as opposed to laminar, streamline, or viscous flow. See *turbulent flow.*

**Turbulent Flow** - (1) The flow of a liquid past an object such that the velocity at any fixed point in the fluid varies irregularly. (2) A type of fluid flow in which there is an unsteady motion of the particles and the motion at a fixed point varies in no definite manner. Also called *eddy flow* or *sinuous flow.*

## U

**Ultimate Biochemical Oxygen Demand** - (1) Commonly, the total quantity of oxygen required to completely satisfy the first-stage BOD. (2) More strictly, the quantity of oxygen required to completely satisfy both the first- and second-stage $BOD_5$.

**Ultrafiltration** - The separation from a liquid of particles of 0.005 to 0.1 m in size by pumping the liquid through a synthetic membrane at high pressure.

**Ultrapure Water** - Water from which most other materials have been removed, producing a resistivity of at least 18 Ohm-cm, and making it sufficiently pure for the most exacting microelectronic, pharmaceutical, and medical uses.

**Ultrasonic (Processes)** - Process which utilizes specially designed tooling usually vibrating at 15 to 80 Hz. Processes are designed to cause localized heating of thermoplastic materials which, in turn, will provide some type of welded or fused joint. Benefits are elimination of fillers and minimized heat stress on surrounding materials.

**Ultrasonic Sensor** - A device that transmits and then receives ultrasonic waves that bounce off a liquid surface to measure the liquid level. The elapsed time for the signal to leave and return to the sensor is a function of the distance to the liquid surface.

**Ultraviolet Light System** - A disinfection system in which light of 254 nm, produced by mercury lamps, damages microorganisms by disrupting their genetic material.

**Ultraviolet Treatment** - In UV treatment the clear effluent resulting following primary and secondary treatment is passed through transparent tubes and irradiated with powerful UV light. If treatment is fully efficient, the remaining viruses and bacteria can be killed to give an output that could virtually be drunk, even the undiluted output straight from the effluent pipe. This method is quite one of the very best methods possible and is much to be recommended. Unfortunately, it does not sterilize the sludge, as the UV is unable to penetrate the turbidity.

**Underdrain** - A drain that carries away groundwater or the drainage from prepared beds to which water or wastewater has been applied.

**Underground Injection Control (UIC)** - A program under the Safe Drinking Water Act that regulates the use of wells to pump fluids underground.

**Underground Storage Tank (UST)** - A tank and any underground piping connected to the tank that has 10% or more of its volume (including pipe volume) beneath the surface of the ground. USTs are designed to hold gasoline, other petroleum products, and hazardous materials.

**Unicellular** – Single-celled organisms, such as bacteria.

**Universal Joint** - A joint or coupling that permits limited motion in any direction and used to transmit rotary motion between shafts that are not collinear.

**Universal Motor** - An electric motor that is capable of running on alternating current or direct current.

**Unsteady Nonuniform Flow** - Flow in which the velocity and the quantity of water flowing per unit time at every point along the conduit varies with respect to time and position.

**Upflow** - Term used to describe treatment units in which flow enters at the bottom and exits at the top.

**Upflow Clarifier** - A treatment unit in which liquid containing suspended solids is passed upward through a blanket of settling sludge. Mixing, flocculation, and solids removal are all accomplished in the same unit.

**Upflow Coagulation** - Coagulation achieved by passing liquid, to which coagulating chemicals may have been added, upward through a blanket of settling sludge.

**Upflow Tank** - (1) A sedimentation tank in which water or wastewater enters near the bottom and rises vertically, typically through a blanket of previously settled solids. The clarified liquid flows out at the top and settled sludge flows out the bottom. (2) A vertical-flow tank.

**Upset** - An upset digester does not decompose organic matter properly. The digester is characterized by low gas production, high volatile acid/alkalinity relationship, and poor liquid/solids separation. A digester in an upset condition is sometimes called a "sour" or "stuck" digester.

**Upstream Side** - The feed side of the filter.

**Uronic Acid** - Class of acidic compounds of the general formula $HOOC(CHOH)_nCHO$ that contain both carboxylic and aldehydic groups, are oxidation products of sugars, and occur in many polysaccharides; especially in the hemicelluloses.

**Useful Life** - Determined when contamination causes an adverse flow rate, low efficiency, or high differential pressure.

**UV Ozone** - A powerful wastewater treatment process employing ozone in solution and ultraviolet light; oxidizes COD and toxic substances, removes color, and disinfects.

## V

**Vacuum** - A space condition that is characterized by pressure lower than atmospheric. This condition is created when air is pumped out of an unvented space.

**Vacuum Breaker** - A device for relieving a vacuum or partial vacuum formed in a pipeline to prevent backsiphoning.

**Vacuum Filter** - A filter used to accomplish sludge dewatering and consisting of a cylindrical drum mounted on a horizontal axis, covered with filter medium, and revolving partially submerged in a dilute sludge mixture. See *vacuum filtration*.

**Vacuum Filtration** - A continuous filtration operation that is typically accomplished on a rotating cylindrical drum. As the drum rotates, part of its circumference is subject to an internal vacuum that draws sludge to the filter medium and removes water for subsequent treatment. The dewatered sludge cake is released by a scraper.

**Vacuum Gauge** - A gauge that indicates the pressure of the air or gas in a partial vacuum.

**Vadose Zone** - Unsaturated zone of soil above the groundwater, extending from the bottom of the capillary fringe all the way to the soil surface.

**Valence** - An integer representing the number of hydrogen atoms with which one atom of an element (or one radical) can combine (negative valence), or the number of hydrogen atoms the atom or radical can displace (positive valence).

**Valve** - A device installed in a pipeline to control the magnitude and direction of flow. It consists of a shell and a disc or plug fitted to the shell.

**Valve Seat** - The surface on which a valve rests.

**Valve Throttling** - To control or modulate flow through a system by manually or automatically opening or closing a valve to various degrees. In a pumped system, changing the discharge valve to various positions between full open and full closed regulates the amount of discharge head. Gate valves and plug valves are often used to throttle the discharge of centrifugal pumps.

**Vapor** - (1) The gaseous form of any substance. (2) A visible condensation such as fog, mist, or steam that is suspended in air.

**Vapor Dispersion** - The movement of vapor clouds or plumes in the air due to wind, gravity, spreading, and mixing.

**Vapor Extraction** - A technique that makes use of a partial vacuum to remove volatile and semi-volatile contamination, such as hydrocarbons, from soils.

**Vapor Pressure** - Pressure exerted by a vapor in a confined space. It is a function of the temperature.

**Vapor Recovery System** - A system by which the volatile gases from gasoline are captured instead of being released into the atmosphere. Recovery systems may be required for gasoline stations in some cities and other nonattainment areas.

**Vaporization** - The process by which a substance such as water changes from the liquid or solid state to the gaseous state.

**Variable-frequency Drive (VFD)** - An electronic controller that adjusts the speed of an electric motor by modulating the power being delivered. These drives provide continuous control, matching motor speed to the specific demands of the work being performed.

**V-belt Drive** - A type of pump coupling that consists of a belt of triangular shape running on sheaves or pulleys with similarly shaped grooves. The movement of the belt in the groove creates a wedging action that improves the traction of the system and therefore gives it more pulling power than a round or flat belt system.

**V-belt Drive Pulley** - A disc-shaped object that rotates around a fixed center. The outside edges of the disk are grooved to hold the belts. Also known as a *sheave*.

**Vector** - (i) Plasmid or virus used in genetic engineering to insert genes into a cell. (ii) Agent, usually an insect or other animal, able to carry pathogens from one host to another.

**Vector Attraction** - The characteristic of sewage sludge that attracts rodents, flies, mosquitoes or other organisms capable of transporting infectious agents.

**Vector Attraction Reduction** - Decreasing the characteristic of sewage sludge that attracts rodent, flies, mosquitoes, or other organisms capable of transmitting infectious agents.

**Vegetative** - Actually growing state.

**Vegetative Cell** - Growing or feeding form of a microbial cell, as opposed to a resting form such as a spore.

**Velocity Head** - (1) The vertical distance or height through which a body would have to fall freely, under the force of gravity, to acquire the velocity it possesses. It is equal to the square of the velocity divided by twice the acceleration of gravity. (2) The theoretical vertical height through which a liquid body may be raised by its kinetic energy.

**Velocity Meter** - A vaned water meter that operates on the principle that the vanes of the wheel move at approximately the same velocity as the flowing water.

**Venturi Aerator** - A submerged jet aeration device in which the liquid to be aerated is pumped through a nozzle within a larger diameter tube, causing air entrainment and vigorous liquid mixing.

**Venturi Meter** - A differential meter for measuring the flow of water or other fluid through closed conduits or pipes. It consists of a Venturi tube and one of several proprietary forms of flow-registering devices. The difference in velocity heads between the entrance and the contracted throat is an indication of the rate of flow.

**Venturi Scrubber** - A device that removes submicron particles and reactive trace gases from gas streams by passing the gas at high velocity through the scrubbing liquor, ensuring vigorous mixing.

**Vertical Pump** - (1) A reciprocating pump in which the piston or plunger moves in a vertical direction. (2) A centrifugal pump in which the pump shaft is in a vertical position.

**Vertical Screw Pump** - A pump, similar in shape, characteristics, and use to a horizontal screw pump, but which has the axis of its runner in a vertical position.

**Vesicles** - Spherical structures, formed intracellularly, by some arbuscular mycorrhizal fungi.

**Viable Count** - Measurement of the concentration of live cells in a microbial population.

**Vibration Sensor** - An on-line sensor to monitor trends in equipment vibration to detect problems before failure.

**Vibrio** - (1) Curved, rod-shaped bacterial cell. (2) Bacterium of the genus *Vibrio.*

**Virion** - Virus particle; the virus nucleic acid surrounded by protein coat and in some cases other material.

**Virulence** - Degree of pathogenicity of a parasite.

**Virus** - Any of a large group of submicroscopic infective agents that typically contain a protein coat surrounding a nucleic acid core and are capable of growth only in a living cell.

**Viscosity** - Molecular attractions with a fluid that makes it resist a tendency to deform under applied forces.

**V-notch Weir** - A triangular weir with the apex of the triangle submerged in fluid.

**Void** - A pore or open space in rock or granular material not occupied by solid matter. It may be occupied by air, water, or other gaseous or liquid material. Also called *interstice* or *void space*.

**Volatile** - A volatile substance is one that is capable of being evaporated or changed to a vapor at a relatively low temperature. Volatile substances also can be partially removed by air stripping.

**Volatile Acids** - Fatty acids containing six or fewer carbon atoms. They are soluble in water and can be steam distilled at atmospheric pressure. They have pungent odors and are often produced during anaerobic decomposition.

**Volatile Organic Compounds (VOCs)** - Substances such as solvents that are liquid at room temperature, but vaporize significantly and take part in the generation of ozone pollution in the lower atmosphere.

**Volatile Solids (VS)** - Materials, typically organic, that can be driven off from a sample by heating, typically to 550°C with nonvolatile inorganic solids (ash) remaining.

**Volatile Suspended Solids (VSS)** - That fraction of suspended solids, including organic matter and volatile inorganic salts, that will ignite and burn when placed in an electric muffle furnace at 550°C.

**Volume Resistivity** - Or specific resistivity of a material, expressed in W/cm. Resistance to electrical current flow through the bulk of an object.

**Volute** - One of the two main components of a centrifugal pump; the other is the impeller. The volute forces the liquid to discharge from the pump. This is accomplished by offsetting the impeller in the volute and by maintaining a close clearance between the impeller and the volute at the cutwater.

**Vortex** - A revolving mass of water in which the streamlines are concentric circles and the total head for each streamline is the same.

**VS/L** - Measure of volatile solids, usually expressed as g VS/l/day (grams volatile solids per liter per day).

## W

**Waste Activated Sludge (WAS)** - Solids removed from the activated-sludge process to prevent an excessive buildup in the system.

**Waste Incineration** - Incineration of waste at high temperatures in two stages to promote efficient combustion to an ash and carbon dioxide.

**Waste Minimization** - The analysis and revision of the use of materials, processes, equipment, and procedures in order to reduce the unnecessary use of energy and resources, to reduce the generation of effluents and wastes, and to recycle where practical.

**Wastewater** - The used water and solids from a community that flow to a treatment plant. Stormwater, surface water, and groundwater infiltration also may be included in the wastewater that enters a wastewater treatment plant. The term "sewage" usually refers to household wastes, but this word is being replaced by the term *wastewater*.

**Water-retention Curve** - Graph showing soil-water content as a function of increasingly negative soil water potential.

**Wastewater Treatment Plant (WWTP)** - A plant that treats urban wastewater and some of the runoff collected in the combined sewer system, and discharges the treated effluent to a receiving waterbody.

**Water Column** - (1) Water above the valve in a set of pumps. (2) A measure of head or pressure in a closed pipe or conduit.

**Water Content** - Water contained in a material expressed as the mass of water per unit mass of oven-dry material.

**Water Hammer** - The phenomenon of oscillations in the pressure of water about its normal pressure in a closed conduit, flowing full, which results from a too-rapid acceleration or retardation of flow. Momentary pressures greatly in excess of the normal static pressure may be produced in a closed conduit by this phenomenon.

**Water Treatment Plant (WTP)** - A plant that treats raw water for use as potable (drinkable) water.

**Watershed** - A topographically defined area or region of land drained by a river/stream or system of rivers/streams such that all outflows are discharged through a single outlet.

**Wearing Ring** - A replaceable metal ring that is incorporated in the pump at the point where the clearance between the pump casing and the impeller are the closest. The wear ring can be placed on the casing, on the impeller, or at both locations. When these rings reach their wear limits, they can be replaced. This restores the design clearance on the parts and keep the pump operating as efficiently as possible.

**Weathering** - All physical and chemical changes produced in rock by atmospheric agents.

**Weeping Tile** - A weeping tile (or foundation drain) is a perforated pipe that is located along the foundation of buildings to collect groundwater infiltration flows and route them to a sump pump for disposal on the surface, or a sewer service for disposal in a sewer.

**Weir** - A device that has a crest and some side containment of known geometric shape, such as a V, trapezoid, or rectangle, and is used to measure flow of liquid. The liquid surface is exposed to the atmosphere. Flow is related to the upstream height of water above the crest, position of crest with respect to downstream water surface, and geometry of the weir opening.

**Wet Air Oxidation** - A process that treats wastewater containing high strength or hazardous organic chemicals by a combination of high temperature and pressure that creates highly reactive hydroxyl radicals.

**Wet Well** - A component of a pumping station that creates a reservoir of the fluid from which the pumps draw their suction.

**Wetlands** - Areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, under normal circumstances, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs and similar areas. Constructed wetlands for wastewater treatment are not included.

**White Rot Fungus** - Fungus that attacks lignin, along with cellulose and hemicellulose, leading to a marked lightening of the infected wood.

**Wild Type** - Strain of microorganism isolated from nature. The usual or native form of a gene or organism.

**Winogradsky Column** - Glass column with an anaerobic lower zone and an aerobic upper zone, which allows growth of microorganisms under conditions similar to those found in nutrient-rich water and sediment.

**Wire-to-water Efficiency** - The ratio of mechanical output of a pump to the electrical input at the meter.

**Worm Gear Reducer** - A gear consisting of a short-rotating screw and a toothed wheel.

**Woronin Body** - Spherical structure associated with the simple pore in the septa separating hyphal compartments of fungi in the phylum *Ascomycota*.

## X

**Xenobiotic** - Compound foreign to biological systems. Often refers to human-made compounds that are resistant or recalcitrant to biodegradation and decomposition.

**Xerophile** - Organism adapted to grow at low water potential, i.e., very dry habitats.

## Y

**Yeast** - Fungus whose thallus consists of single cells that multiply by budding or fission.

## Z

**Z-list** - OSHA's Toxic and Hazardous Substances Tables (Z-1, Z-2, and Z-3) of air contaminants; any material found on these tables is considered hazardous.

**Zone of Saturation** - The layer beneath the surface of the land in which all openings are filled with water.

**Zoogleal Film** - A complex population of organisms that form a "slime growth" on a trickling-filter medium and break down the organic matter in wastewater.

**Zoogleal Mass** - Jelly-like masses of bacteria found in both the trickling-filter and activated sludge processes.

**Zoospore** - An asexual spore formed by some fungi that usually can move in an aqueous environment via one or more flagella.

**Zygospore** - Thick-walled resting spore resulting from fusion of two gametangia of fungi in the phylum Zygomycota.

**Zygote** - In eukaryotes, the single diploid cell resulting from the union (fusion) of two haploid gametes.

**Zymogenous Flora** - Refers to microorganisms, often transient or alien, that respond rapidly by enzyme production and growth when simple organic substrates become available. Also called *copiotrophs*.

# INDEX

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