CHAPTER 11

DISPOSAL OF SOLID WASTES AND RESIDUAL MATTER

The safe and reliable long-term disposal of solid waste residues is an important component of integrated waste management. Solid waste residues are waste components that are not recycled, that remain after processing at a materials recovery facility, or that remain after the recovery of conversion products and/or energy. Historically, solid waste has been placed in the soil in the earth's crust or deposited in the oceans. Although ocean dumping of municipal solid waste was officially abandoned in the United States in 1933, it is now argued that many of the wastes now placed in landfills or on land could be used as fertilizers to increase productivity of the ocean or the land. It is also argued that the placement of wastes in ocean trenches where tectonic folding is occurring is an effective method of waste disposal. Nevertheless, landfilling or land disposal is today the most commonly used method for waste disposal by far. Disposal of solid waste residues in landfills is the primary subject of this chapter.

The planning, design, and operation of modern landfills involve the application of a variety of scientific, engineering, and economic principles. The major topics covered in this chapter include: (1) a description of the landfill method of solid waste disposal, including environmental concerns and regulatory requirements; (2) a description of types of landfills and landfilling methods; (3) landfill siting considerations; (4) landfill gas management; (5) landfill leachate control; (6) surface water control; (7) landfill structural characteristics and settlement;

(8) environmental quality monitoring; (9) the layout and preliminary design of landfills; (10) development of landfill operation plan; (11) landfill closure and post-closure care; and (12) landfill design computations. Example design computations for landfills have been grouped together in the final section of this chapter. Reference is made to specific example problems as appropriate. Management policies and regulations for landfill closure and postclosure maintenance are discussed in Chapter 16.

11-1 THE LANDFILL METHOD OF SOLID WASTE DISPOSAL

Historically, landfills have been the most economical and environmentally acceptable method for the disposal of solid wastes, both in the United States and throughout the world. Even with implementation of waste reduction, recycling, and transformation technologies, disposal of residual solid waste in landfills still remains an important component of an integrated solid waste management strategy. Landfill management incorporates the planning, design, operation, closure, and postclosure control of landfills. The purposes of this section are (1) to introduce the reader to the landfilling process, (2) to review the principal reactions occurring in landfills, (3) to identify environmental concerns associated with landfills, and (4) to review briefly some federal and state regulations governing the disposal of solid waste in landfills. Many of the subjects introduced in this section are examined in greater detail later in this chapter.

The Landfilling Process

The purpose of the following discussion is to introduce the reader to the landfilling of solid waste by (1) defining some terms that are commonly used when discussing the landfilling of solid waste, (2) reviewing landfill operations and processes, (3) describing the life of a landfill, and (4) reviewing some of the reactions occurring in landfills.

Definition of Terms. *Landfills* are the physical facilities used for the disposal of residual solid wastes in the surface soils of the earth. In the past, the term sanitary landfill was used to denote a landfill in which the waste placed in the landfill was covered at the end of each day's operation. Today, *sanitary landfill* refers to an engineered facility for the disposal of MSW designed and operated to minimize public health and environmental impacts (see Fig. 11-1). Landfills for the disposal of hazardous wastes are called *secure landfills*. A sanitary landfill is also sometimes identified as a *solid waste management unit*. *Landfilling* is the process by which residual solid waste is placed in a landfill. Landfilling includes monitoring of the incoming waste stream, placement and compaction of the waste, and installation of landfill environmental monitoring and control facilities.

The term *cell* is used to describe the volume of material placed in a landfill during one operating period, usually one day (see Fig. 11-2). A cell includes

FIGURE 11-1
Views of operating landfills.

the solid waste deposited and the daily cover material surrounding it. *Daily cover* usually consists of 6 to 12 in of native soil or alternative materials such as compost that are applied to the working faces of the landfill at the end of each operating period. The purposes of daily cover are to control the blowing of waste materials; to prevent rats, flies, and other disease vectors from entering or exiting the landfill; and to control the entry of water into the landfill during operation.

A *lift* is a complete layer of cells over the active area of the landfill (see Fig. 11-2). Typically, landfills are comprised of a series of lifts. A *bench* (or *terrace*) is commonly used where the height of the landfill will exceed 50 to 75 ft. Benches are used to maintain the slope stability of the landfill, for the placement of surface water drainage channels, and for the location of landfill gas

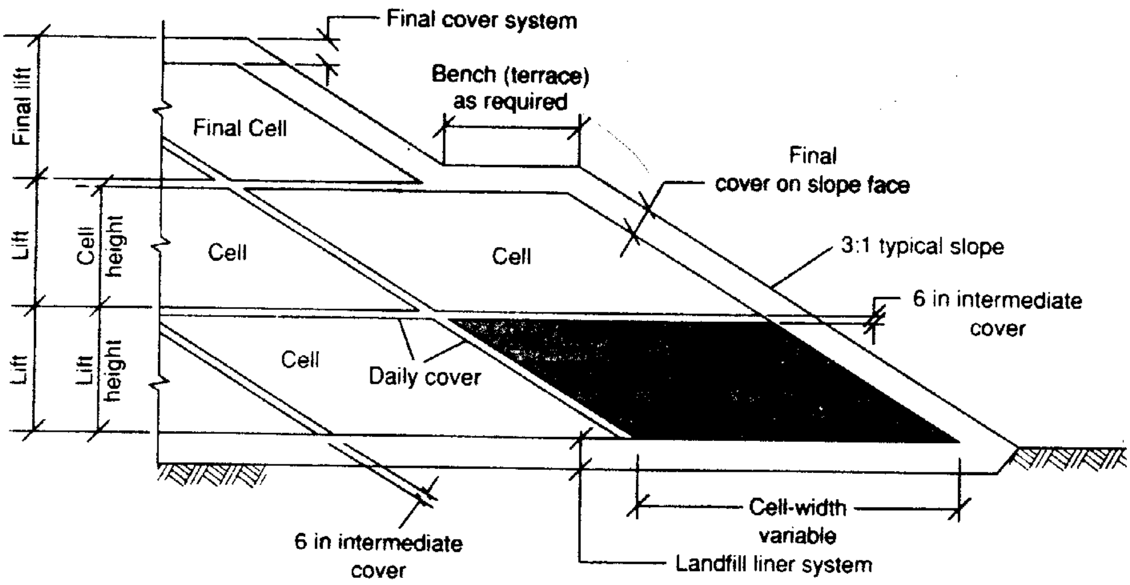


FIGURE 11-2
Sectional view through a sanitary landfill.

recovery piping. The *final lift* includes the cover layer. The ***final cover layer*** is applied to the entire landfill surface after all landfilling operations are complete. The final cover usually consists of multiple layers of soil and/or geomembrane materials designed to enhance surface drainage, intercept percolating water, and support surface vegetation.

The liquid that collects at the bottom of a landfill is known as *leachate*. In deep landfills, leachate is often collected at intermediate points. In general, leachate is a result of the percolation of precipitation, uncontrolled runoff, and irrigation water into the landfill. Leachate can also include water initially contained in the waste as well as infiltrating groundwater. Leachate contains a variety of chemical constituents derived from the solubilization of the materials deposited in the landfill and from the products of the chemical and biochemical reactions occurring within the landfill.

Landfill gas is the mixture of gases found within a landfill. The bulk of landfill gas consists of methane (CH_4) and carbon dioxide (CO_2), the principal products of the anaerobic decomposition of the biodegradable organic fraction of the MSW in the landfill. Other components of landfill gas include atmospheric nitrogen and oxygen, ammonia, and trace organic compounds.

Landfill liners are materials (both natural and manufactured) that are used to line the bottom area and below-grade sides of a landfill. Liners usually consist of layers of compacted clay and/or geomembrane material designed to prevent migration of landfill leachate and landfill gas. *Landfill control facilities* include liners, landfill leachate collection and extraction systems, landfill gas collection and extraction systems, and daily and final cover layers.

Environmental monitoring involves the activities, associated with collection and analysis of water and air samples, that are used to monitor the movement of landfill gases and leachate at the landfill site. *Landfill closure* is the term used to describe the steps that must be taken to close and secure a landfill site once the filling operation has been completed. *Postclosure* care refers to the activities associated with the long-term monitoring and maintenance of the completed landfill (typically 30 to 50 years).

Overview of Landfill Planning, Design, and Operation. The principal elements that must be considered in the planning, design, and operation of landfills are identified in Fig. 11-3, and include (1) landfill layout and design; (2) landfill operations and management; (3) the reactions occurring in landfills; (4) the management of landfill gases; (5) the management of leachate; (6) environmental monitoring; and (7) landfill closure and postclosure care. Each of the elements is considered in greater detail in this chapter.

The Life of a Modern Landfill. The following description of the life of a modern landfill is generic. Specific details of the operation will vary with the type of material being landfilled and the configuration of the landfill. Landfill types and configurations are described in Section 11-2, where significant departures from the generic operation scheme are noted. The development of a modern landfill is illustrated in Fig. 11-4.

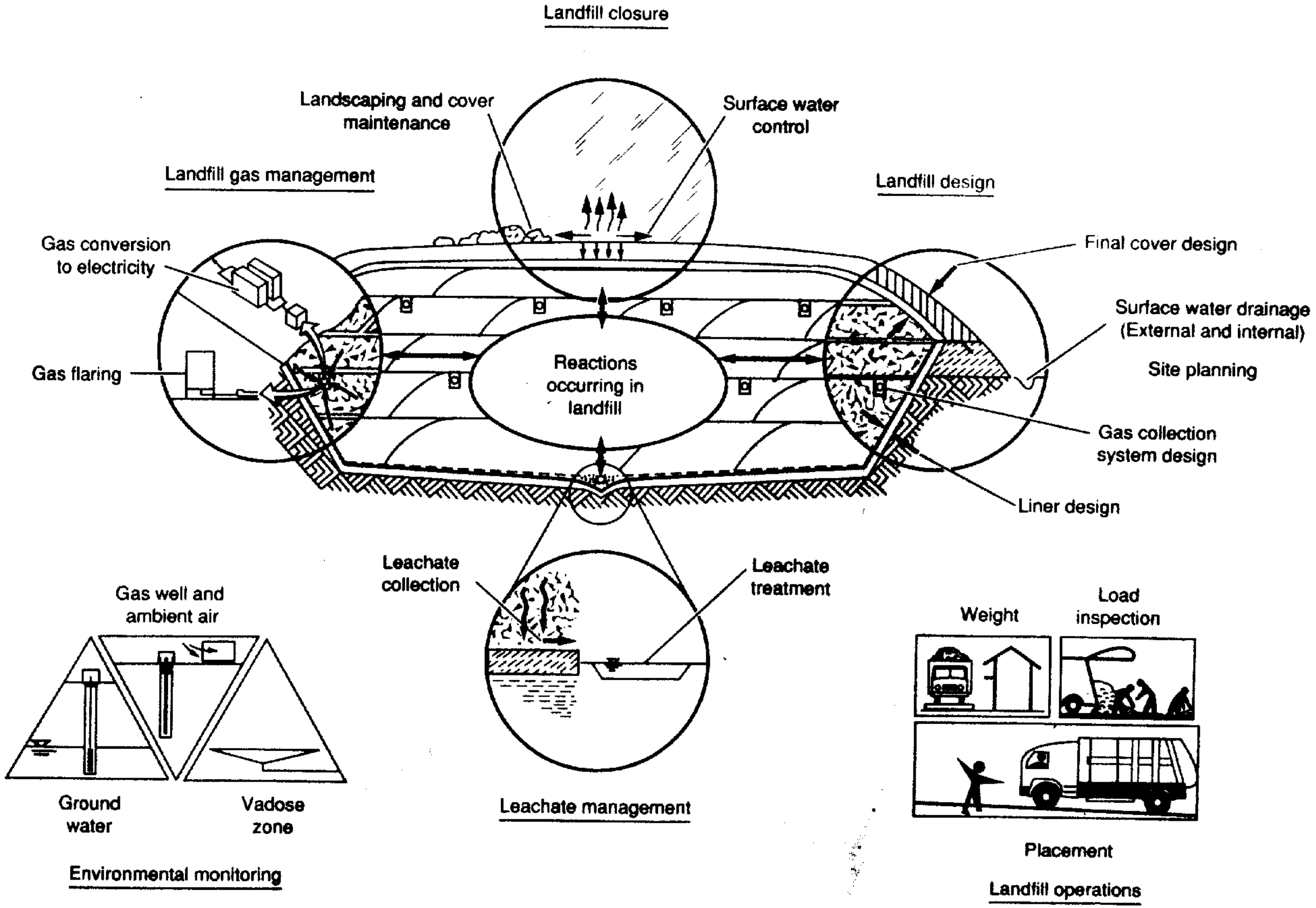


FIGURE 11-3
Definition sketch for landfill operations and processes.

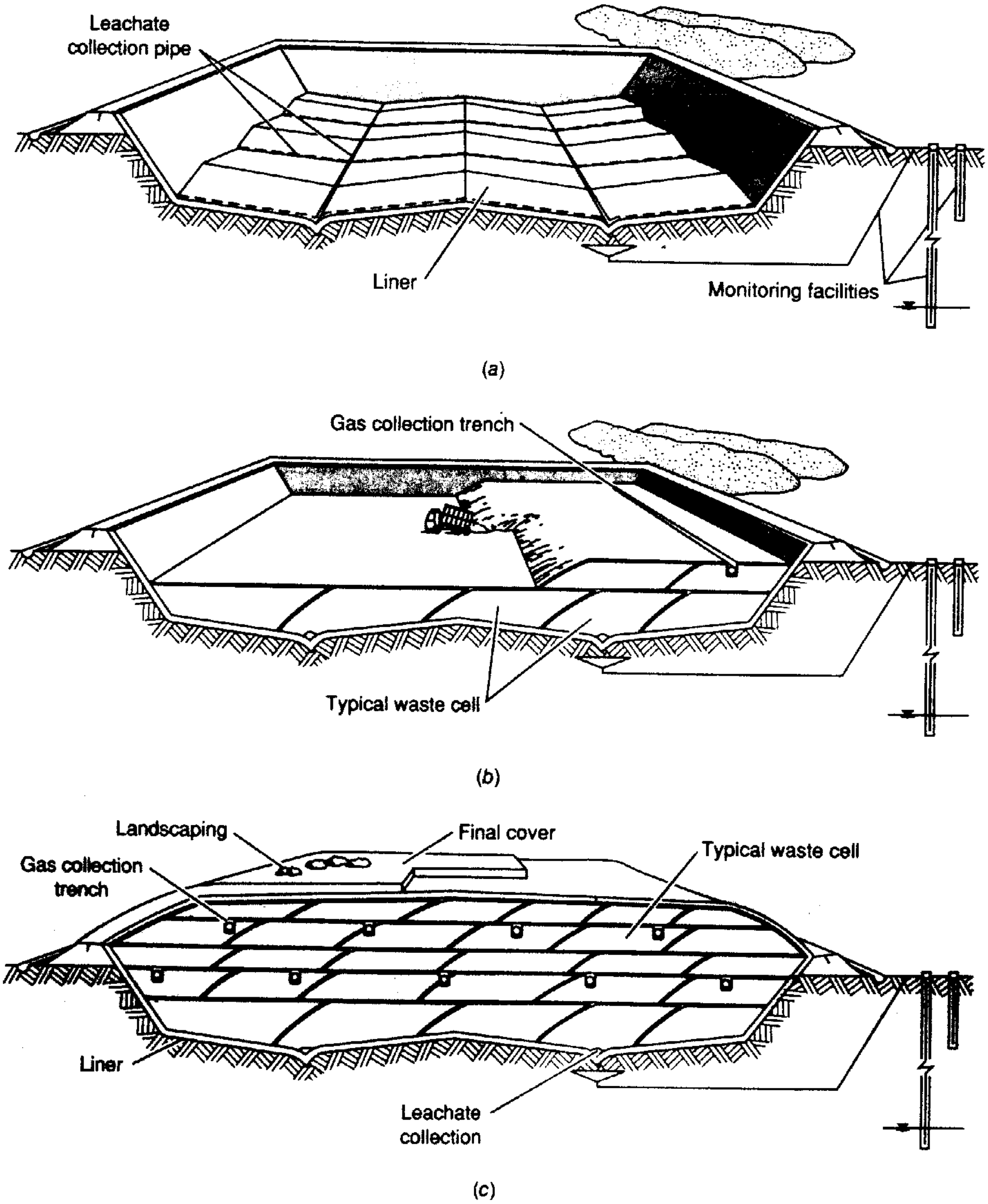


FIGURE 11-4
Development and completion of a solid waste landfill: (*a*) excavation and installation of landfill liner, (*b*) placement of solid waste in landfill, and (*c*) cutaway through completed landfill.

Preparation of the site for landfilling. The first step in the process involves the preparation of the site for landfill construction. Existing site drainage must be modified to route any runoff away from the intended landfill area. Rerouting of drainage is particularly important for ravine landfills where a significant watershed may drain through the site. In addition, drainage of the landfill area itself must be modified to route water away from the initial fill area. Other site preparation tasks include construction of access roads and weighing facilities, and installation of fences.

The next step in the development of a landfill is the excavation and preparation of the landfill bottom and subsurface sides. Modern landfills typically are constructed in sections. Working by sections allows only a small part of the unprotected landfill surface to be exposed to precipitation at any time. In addition, excavations are carried out over time, rather than preparing the entire landfill bottom at once. Excavated material can be stockpiled on unexcavated soil near the active area and the problem of precipitation collecting in the excavation is minimized. Where the entire bottom of the landfill is lined at once, provision must be made to remove stormwater runoff from the portion of the landfill that is not being used.

To minimize costs, it is desirable to obtain cover materials from the landfill site whenever possible. The initial working area of the landfill is excavated to the design depth, and the excavated material stockpiled for later use. Vadose zone (zone between ground surface and permanent groundwater) and groundwater monitoring equipment is installed before the landfill liner is laid down. The landfill bottom is shaped to provide drainage of leachate, and a low-permeability liner is installed (see Fig. 11-5). Leachate collection and extraction facilities are placed within or on top of the liner. Typically, the liner extends up the excavated walls of the landfill.

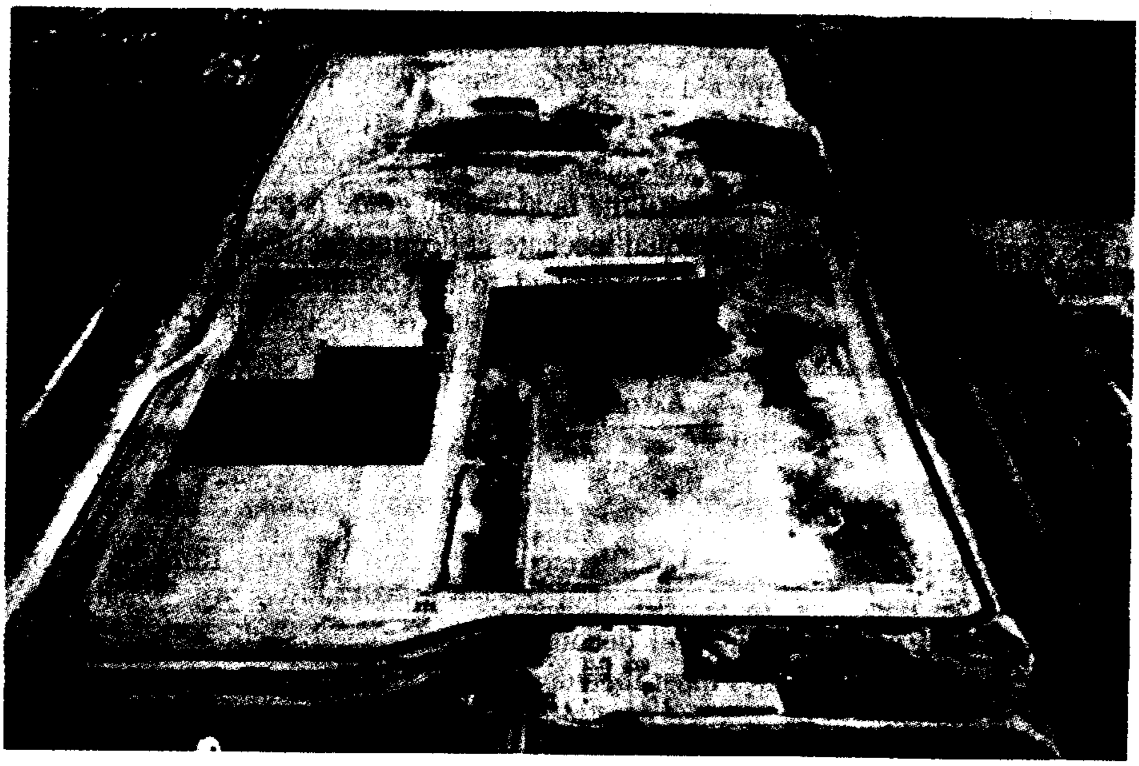


FIGURE 11-5
Aerial view of area type landfill. Geomembrane liner is being placed in front part of the landfill site (foreground). (Courtesy of Brown and Caldwell Consultants.)

Horizontal gas recovery trenches may be installed at the bottom of the landfill, particularly if emissions of volatile organic compounds (VOCs) from the newly placed waste is expected to be a problem. To minimize the release of VOCs, a vacuum is applied and air is drawn through the completed portions of the landfill. The gas that is removed must be burned under controlled conditions to destroy the VOCs. Before the fill operation begins, a soil berm is constructed at the downwind side of the planned fill area. The berm serves as a windbreak to control blowing materials and as a face against which the waste can be compacted. For excavated landfills, the wall of the excavation usually serves as the initial compaction face.

The placement of wastes. Once the landfill site has been prepared, the next step in the process involves the actual placement of waste material. As shown in Fig. 11-4*b*, the waste is placed in cells beginning along the compaction face, continuing outward and upward from the face. The waste deposited in each operating period, usually one day, forms an individual cell. Wastes deposited by the collection and transfer vehicles are spread out in 18- to 24-in layers and compacted. Typical cell heights vary from 8 to 12 ft. The length of the working face varies with the site conditions and the size of the operation (see Fig. 11-1). The working *face* is the area of a landfill where solid waste is being unloaded, placed and compacted during a given operating period. The width of a cell varies from 10 to 30 ft, again depending on the design and capacity of the landfill. All exposed faces of the cell are covered with a thin layer of soil (6 to 12 in) or other suitable material at the end of each operating period.

After one or more lifts have been placed, horizontal gas recovery trenches can be excavated in the completed surface (see Fig. 11-3). The excavated trenches are filled with gravel, and perforated plastic pipes are installed in the trenches. Landfill gas is extracted through the pipes as the gas is produced. Successive lifts are placed on top of one another until the final design grade is reached. Depending on the depth of the landfill, additional leachate collection facilities may be placed in successive lifts. A cover layer is applied to the completed landfill section. The final cover is designed to minimize infiltration of precipitation and to route drainage away from the active section of the landfill. The cover is landscaped to control erosion. Vertical gas extraction wells may be installed at this time through the completed landfill surface. The gas extraction system is tied together and the extracted gas may be flared or routed to energy recovery facilities as appropriate.

Additional sections of the landfill are constructed outward from the completed sections, repeating the construction steps outlined above. As organic materials deposited within the landfill decompose, completed sections may settle. Landfill construction activities must include refilling and repairing of settled landfill surfaces to maintain the desired final grade and drainage. The gas and leachate control systems also must be extended and maintained. Upon completion of all fill activities, the landfill surface is repaired and upgraded with the installation of a final cover. The site is landscaped appropriately and prepared for other uses.

Postclosure management. Monitoring and maintenance of the completed landfill must continue by law for some time after closure (30 to 50 years). It is particularly important that the landfill surface be maintained and repaired to enhance drainage, that gas and leachate control systems be maintained and operated, and that the pollution detection system be monitored (see Chapter 16).

Reactions Occurring in Landfills. Solid wastes placed in a sanitary landfill undergo a number of simultaneous and interrelated biological, chemical, and physical changes, which are introduced in this section. The various reactions are considered in greater detail in subsequent sections of this chapter.

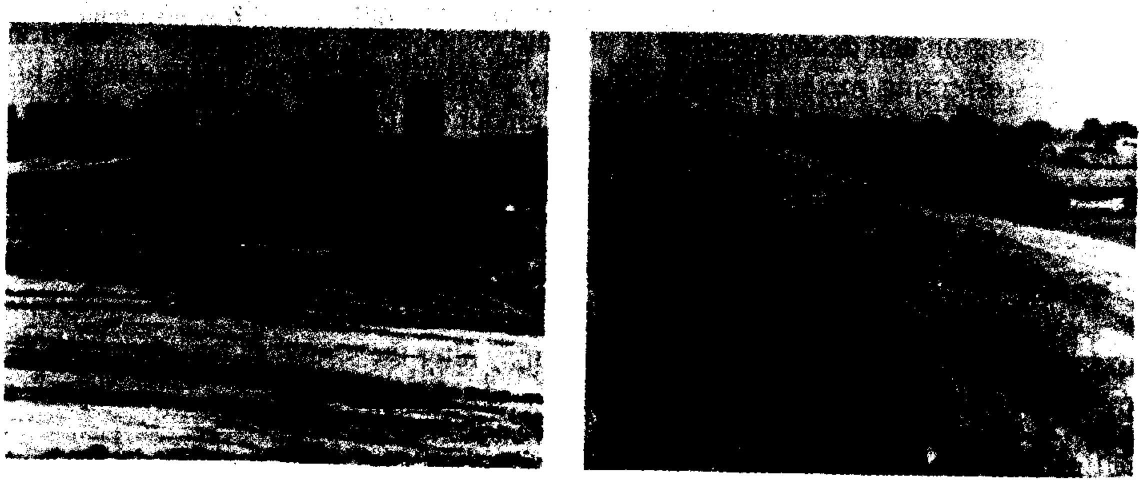
Biological reactions. The most important biological reactions occurring in landfills are those involving the organic material in MSW that lead to the evolution of landfill gases and, eventually, liquids. The biological decomposition process usually proceeds aerobically for some short period immediately after deposition of the waste until the oxygen initially present is depleted. During aerobic decomposition CO_2 is the principal gas produced. Once the available oxygen has been consumed, the decomposition becomes anaerobic and the organic matter is converted to CO_2, CH_4, and trace amounts of ammonia and hydrogen sulfide. Many other chemical reactions are biologically mediated as well. Because of the number of interrelated influences, it is difficult to define the conditions that will exist in any landfill or portion of a landfill at any stated time.

Chemical reactions. Important chemical reactions that occur within the landfill include dissolution and suspension of landfill materials and biological conversion products in the liquid percolating through the waste, evaporation and vaporization of chemical compounds and water into the evolving landfill gas, sorption of volatile and semivolatile organic compounds into the landfilled material, dehalogenation and decomposition of organic compounds, and oxidation-reduction reactions affecting metals and the solubility of metal salts. The dissolution of biological conversion products and other compounds, particularly of organic compounds, into the leachate is of special importance because these materials can be transported out of the landfill with the leachate. These organic compounds can subsequently be released into the atmosphere either through the soil (where leachate has move away from an unlined landfill) or from uncovered leachate treatment facilities. Other important chemical reactions include those between certain organic compounds and clay liners, which may alter the structure and permeability of the liner material. The interrelationships of these chemical reactions within a landfill are not well understood.

Physical reactions. Among the more important physical changes in landfills are the lateral diffusion of gases in the landfill and emission of landfill gases to the surrounding environment, movement of leachate within the landfill and into underlying soils, and settlement caused by consolidation and decomposition of landfilled material. Landfill gas movement and emissions are particularly important considerations in landfill management. As gas is evolved within a landfill, internal pressure may build, causing the landfill cover to crack and leak. Water entering the landfill through the leaking cover may enhance the gas production rate, causing still more cracking. Escaping landfill gas may carry trace carcinogenic and teratogenic compounds into the surrounding environment. Because landfill gas usually has a high methane content, there may be a combustion and/or explosion hazard. Leachate migration is another concern. As leachate migrates downward in the landfill, it may transfer compounds and materials to new locations where they may react more readily. Leachate occupies pore spaces in the landfill and in doing so may interfere with the migration of landfill gas.

Concerns with the Landfilling of Solid Wastes

Concerns with the landfilling of solid waste are related to (1) the uncontrolled release of landfill gases that might migrate off-site and cause odor and other potentially dangerous conditions, (2) the impact of the uncontrolled discharge of landfill gases on the greenhouse effect in the atmosphere, (3) the uncontrolled release of leachate that might migrate down to underlying groundwater or to surface waters, (4) the breeding and harboring of disease vectors in improperly managed landfills, and (5) the health and environmental impacts associated with the release of the trace gases arising from the hazardous materials that were often placed in landfills in the past. The goal for the design and operation of a modern landfill is to eliminate or minimize the impacts associated with these concerns (see Fig. 11-6).



(a) (b)

FIGURE 11-6
Views taken from completed landfills: (*a*) city of Sacramento, CA, skyline in background, about 30 blocks away and (*b*) area-type landfill next to housing area.

Federal and State Regulations for Landfills

In planning for the implementation of a new landfill, attention must be paid to the many federal and state regulations that have been enacted to improve the performance of sanitary landfills. The principal federal requirements for municipal solid waste landfills are contained in Subtitle D of the Resource Conservation and Recovery Act (RCRA) and in EPA Regulations on Criteria for Classification of Solid Waste Disposal Facilities and Practices (40 CFR 258). The final version of Part 258—Criteria for Municipal Solid Waste Landfills (MSWLFs) was signed on September 11, 1991. The subparts of Part 258 deal with the following issues:

Subpart A	General
Subpart B	Location restrictions
Subpart C	Operating criteria
Subpart D	Design criteria
Subpart E	Groundwater monitoring and corrective action
Subpart F	Closure and postclosure care
Subpart G	Financial assurance criteria

The Clean Air Act also contains provisions dealing with gas emissions from landfills. In addition to the federal regulations, many states have adopted regulations governing the design, operation, closure and long-term maintenance of landfills. In many cases, the regulations that have been adopted by the individual states have been more restrictive than the federal requirements. Permitting of landfills is considered in Chapter 20.

11-2 LANDFILL CLASSIFICATION, TYPES, AND METHODS

The purpose of this section is to introduce the reader to (1) a commonly used landfill classification system, (2) the different types of landfills that are now used, and (3) the different landfilling methods that are used in various parts of the country.

Classification of Landfills

Although a number of landfill classification systems have been proposed over the years, the classification system adopted by the state of California in 1984 is perhaps the most widely accepted classification system for landfills. In the California system, reported below, three classifications are used:

Classification	Type of waste
I	Hazardous waste
II	Designated waste
III	Municipal solid waste (MSW)

Designated wastes are nonhazardous wastes that may release constituents in concentrations that exceed applicable water quality objectives or those wastes which have been granted a variance by the State Department of Health Services (DOHS). Note that this classification system focuses primarily on the protection of surface and groundwater rather than landfill gas migration or air quality.

Types of Landfills

The principal types of landfills can be classified as (1) conventional landfills for commingled MSW, (2) landfills for milled solid wastes, and (3) monofills for designated or specialized wastes. Other types of landfills and landfill operations, including the recycle of leachate, are also discussed.

Landfills for Commingled MSW. The majority of the landfills throughout the United States are designed for commingled MSW. In many of these Class III landfills, limited amounts of nonhazardous industrial wastes and sludge from water and wastewater treatment plants are also accepted. In many states, treatment plant sludges are accepted if they are dewatered to a solids content of 51 percent or greater. For example, in California the deposition of sludge in MSW landfills is restricted to a ratio of five parts solid waste to one part sludge by weight. Many municipalities have adopted even more restrictive limitations on the amount of sludge that can be accepted.

In most cases, native soil is used as the intermediate and final cover material. However, in locations such as Florida and New Jersey where the amount of native soil available for use as intermediate cover material is limited, alternative materials such as compost produced from yard wastes and MSW, foam, old rugs and carpeting, dredging spoils, and demolition wastes have been used for the purpose. To obtain additional landfill capacity, abandoned and or closed landfills in some locations are being reused by excavating the decomposed material to recover the metals and using the decomposed residue as daily cover for the new wastes. In some cases, the decomposed wastes are excavated and stockpiled, and a liner is installed before the landfill is reactivated.

Landfills for Shredded Solid Wastes. An alternative method of landfilling that is being tried in several U.S. locations involves shredding of the solid wastes before placement in a landfill. Shredded (or milled) waste can be placed at up to 35 percent greater density than unshredded waste, and without daily cover in some state regulations. Blowing litter, odors, flies, and rats have not been significant problems. Because shredded waste can be compacted to a tighter and more uniform surface, a reduced amount of soil cover or some other cover material may be sufficient to control infiltration of water during the fill operation.

Disadvantages of the method include the need for a shredding facility and the need to operate a conventional landfill section for wastes that cannot be easily shredded. The shredded waste method has potential application in areas where landfill capacity is very expensive (because of the greater compaction obtainable), where suitable cover material is not readily available, and where precipitation is very low or highly seasonal. Shredded waste can also be used to produce compost that can be used as intermediate cover material.

Landfills for Individual Waste Constituents. Landfills for individual waste constituents are known as *monofills*. Combustion ash, asbestos, and other similar wastes, often identified as designated wastes, are typically placed in monofills to isolate them from materials placed in MSW landfills. Because combustion ash contains small amounts of unburned organic material, the production of odors from the reduction of sulfate (see Eq. 4-12) has been a problem in monofills used for combustion ash. In monofills used for combustion ash, the installation of a gas recovery system is recommended to control odor problems.

Other Types of Landfills. In addition to the conventional methods of landfilling already described, other specialized methods of landfilling designed to enhance different goals of landfill management are being developed. Alternative operational methods that are being used include (1) landfills designed to maximize the rate of landfill gas generation and (2) landfills operated as integrated solid waste treatment units. The practice of landfilling in wetland areas, now prohibited, is also described.

Landfills designed to maximize gas production. If the quantity of landfill gas that is produced and recovered from the anaerobic decomposition of solid wastes is to be maximized, specialized landfill designs will be required. For example, the use of deep, individually lined cells, in which the wastes are placed without intermediate layers of cover material and leachate is recycled to enhance the biological decomposition process, is a viable option. A possible disadvantage of such a landfill is that excess leachate must ultimately be disposed of.

Landfills as integrated treatment units. In this method of operation, the organic constituents would be separated out and placed in a separate landfill where the biodegradation rates would be enhanced by increasing the moisture content of the waste, either by recycling leachate or by seeding with digested wastewater treatment plant sludge or animal manure. The degraded material would be excavated and used as cover material for new fill areas, and the excavated cell would be filled with new waste.

Landfills in wetland areas. In the past, landfilling in wetland areas, such as swamps, marshes, and tidal areas, was considered acceptable if adequate drainage was provided and if nuisance conditions did not develop. Under current federal regulations, such destruction of wetland areas is prohibited, although the expansion of an existing landfill may be allowed under special conditions. Because many landfills already exist in these areas, a brief description of the methods typically used in these fills is presented.

The usual practice in filling wetlands was to divide the area into cells or lagoons and schedule the filling operations so that one individual cell or lagoon would be filled each year. Often, solid wastes were placed directly in the water.

Alternatively, clean fill material was added up to, or slightly above, the water level before waste filling operations were started. To withstand mud waves and to increase structural stability, dikes dividing the cells or lagoons were constructed with riprap, trees, tree limbs, lumber, demolition wastes, and similar materials in addition to clean fill material. In some cases, to prevent the movement of leachate and gases from completed cells or lagoons, clay and lightweight interlocking steel or wood-sheet piling has been used.

Landfilling Methods

The principal methods used for the landfilling of MSW are (1) excavated cell/trench, (2) area, and (3) canyon. The principal features of these types of landfills, illustrated in Figs. 11-7 and 11-8, are described below. Landfill design details are presented later in the chapter.

Excavated Cell/Trench Method. The excavated cell/trench method of landfilling (see Fig. 11-7*a*) is ideally suited to areas where an adequate depth of cover material is available at the site and where the water table is not near the surface. Typically, solid wastes are placed in cells or trenches excavated in the soil (see Fig. 11-8*a*). The soil excavated from the site is used for daily and final cover. The excavated cells or trenches are usually lined with synthetic membrane liners or low-permeability clay or a combination of the two to limit the movement of both landfill gases and leachate (see Fig. 11-8). Excavated cells are typically square, up to 1000 ft in width and length, with side slopes of 1.5:1 to 2:1. Trenches vary from 200 to 1000 ft in length, 3 to 10 ft in depth, and 15 to 50 ft in width.

In some states, landfills constructed below the high-groundwater level are allowed if special provisions are made to prevent groundwater from entering the landfill and to contain or eliminate the movement of leachate and gases from completed cells. Usually the site is dewatered, excavated, and then lined in compliance with local regulations. The dewatering facilities are operated until the site is filled to avoid the creation of uplift pressures that could cause the liner to heave and rupture. The use of clay and membrane liners is considered further in Section 11-5.

Area Method. The area method is used when the terrain is unsuitable for the excavation of cells or trenches in which to place the solid wastes (see Figs. 11-7*b* and 11-8*b*). High-groundwater conditions, which occur in many parts of Florida and elsewhere too, necessitate the use of area-type landfills. Site preparation includes the installation of a liner and leachate control system. Cover material must be hauled in by truck or earthmoving equipment from adjacent land or from borrow-pit areas. As noted above, in locations with limited availability of material that can be used as cover, compost produced from yard wastes and MSW has been used successfully as intermediate cover material. Other techniques that have been used include the use of movable temporary cover materials such as soil and geomembranes. Soil and geomembranes, placed temporarily over a completed cell, can be removed before the next lift is begun.

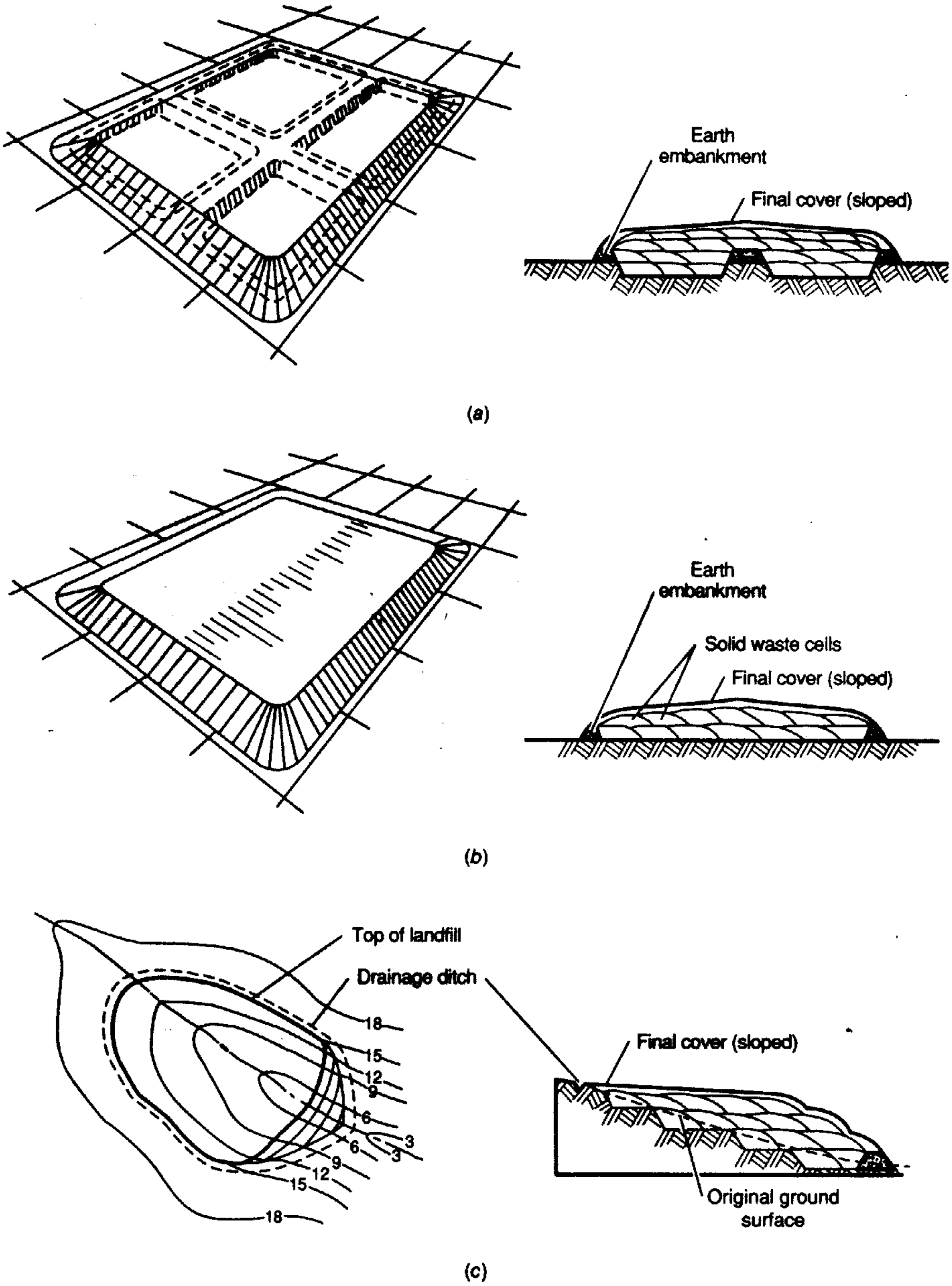
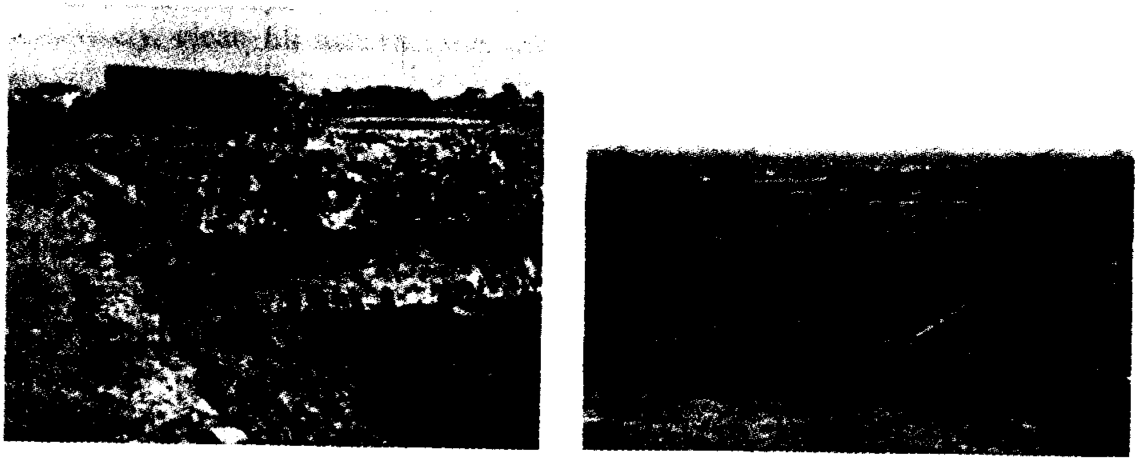


FIGURE 11-7
Commonly used landfilling methods: (*a*) excavated cell/trench, (*b*) area, and (*c*) canyon/depression.



(a) (b)

FIGURE 11-8
Pictorial views of the construction of different types of landfills: (*a*) excavated cell landfill and (*b*) area landfill.

Canyon/Depression Method. Canyons, ravines, dry borrow pits, and quarries have been used for landfills (see Figs. 11-7*c* and 11-9). The techniques to place and compact solid wastes in canyon/depression landfills vary with the geometry of the site, the characteristics of the available cover material, the hydrology and geology of the site, the type of leachate and gas control facilities to be used, and the access to the site.

Control of surface drainage often is a critical factor in the development of canyon/depression sites. Typically, filling for each lift starts at the head end of the canyon (see Fig. 11-7*c*) and ends at the mouth, so as to prevent the accumulation of water behind the landfill. Canyon/depression sites are filled in multiple lifts, and the method of operation is essentially the same as the area method described above. If a canyon floor is reasonably flat, the initial landfilling may be carried out using the excavated cell/trench method discussed previously.

FIGURE 11-9
Landfilling in a canyon site. Site is being prepared for placement of geomembrane landfill liner.

A key to the successful use of the canyon/depression method is the availability of adequate material to cover the individual lifts as they are completed and to provide a final cover over the entire landfill when the final height is reached. Cover material is excavated from the canyon walls or floor before the liner system is installed. Borrow pits and abandoned quarries may not contain sufficient soil for intermediate cover, so that cover material may have to be imported. Compost produced from yard waste and MSW can be used for the intermediate cover layers.

11-3 LANDFILL SITING CONSIDERATIONS

One of the most difficult tasks faced by most communities in implementing an integrated solid waste management program is the siting of new landfills. This section introduces the factors that must be considered in siting a new landfill. Greater detail in Chapter 20 is provided. Factors that must be considered in evaluating potential sites for the long-term disposal of solid waste include (1) haul distance, (2) location restrictions, (3) available land area, (4) site access, (5) soil conditions and topography, (6) climatological conditions, (7) surface water hydrology, (8) geologic and hydrogeologic conditions, (9) local environmental conditions, and (10) potential ultimate uses for the completed site. Final selection of a disposal site usually is based on the results of a detailed site survey, engineering design and cost studies, and an environmental impact assessment. It is interesting that the up-front development costs for new landfills in California now vary from $10 million to $20 million (1992) before the first load of waste is placed in the landfill.

Haul Distance

The haul distance is one of the important variables in the selection of a disposal site. From computations presented in Chapters 8 and 10, it is clear that the length of the haul can significantly affect the overall design and operation of the waste management system. Although minimum haul distances are desirable, other factors must also be considered. Because the siting of landfills is usually determined by environmental and political concerns, long-distance hauling, discussed in Chapter 10, is now becoming more routine.

Location Restrictions

Location restrictions refer to where landfills can be located. Restrictions now apply with respect to siting landfills near airports, in floodplains, in wetlands, in areas with known faults, in seismic impact zones, and in unstable areas (see Table 11-1). The specific federal requirements are contained in Subpart B—Location Restrictions of Part 258 of Subtitle D of the Resource Conservation and Recovery Act (RCRA). In addition, many states have adopted additional location restrictions. All current restrictions must be reviewed carefully during the preliminary siting process to avoid expending time and money evaluating a site that will not conform with the regulatory requirements.

TABLE 11-1
Siting limitations contained in Subtitle D of the Resources Conservation and Recovery Act as adopted by the EPA

Location	Siting limitation
Airports	10,000 ft from an airport used by turbojet aircraft; 5000 ft from an airport used by piston-type aircraft. Any landfills closer will have to demonstrate that they do not pose a bird hazard to aircraft.
Flood plains	100-year flood plain. Landfill located within the 100-year floodplain will have to be designed so as not to restrict flood flow, reduce the temporary water storage capacity of the floodplain, or result in washout of solid waste, which would pose a hazard to human health and the environment.
Wetlands	New landfills will not be able to locate in wetlands unless the following conditions have been demonstrated: (1) No practical alternative with less environmental risk exists. (2) Violations of other state and local laws will not occur. (3) The unit would not cause or contribute to significant degradation of the wetland. (4) Appropriate and practicable steps have been taken to minimize potential adverse impacts. (5) Sufficient information to make determination is available.
Fault areas	New landfill units cannot be sited within 200 ft of a fault line that has had a displacement in Holocene time (past 10,000 years).
Seismic impact zone	New landfill unit located within a seismic impact zone will have to demonstrate that all contaminant structures (liners, leachate collection systems, and surface water control structures) are designed to resist the maximum horizontal acceleration in lithified materials (liquid or loose materials consolidated into solid rock) for the site.
Unstable areas	Landfill units located in unstable areas must demonstrate that the design ensures stability of structural components. The unstable areas include areas that are landslide prone, that are in karst geology susceptible to sinkhole formation, and that are undermined by subsurface mines. Existing facilities that cannot demonstrate the stability of the structural components will be required to close within five years of the regulation's effective date.

Available Land Area

In selecting potential land disposal sites, it is important to ensure that sufficient land area is available. Although there are no fixed rules concerning the area required, it is desirable to have sufficient area, including an adequate buffer zone, to operate for at least five years at a given site. For shorter periods, the disposal operation becomes considerably more expensive, especially with respect to site preparation, provision of auxiliary facilities such as platform scales and storage facilities, and completion of the final cover. In the initial assessment of potential disposal sites, it is important to project the extent of the waste diversion that is likely to occur in the future and determine the impact of that diversion on the quantity and condition of the residual materials to be disposed of. For preliminary planning purposes, the amount of land area required can be estimated as illustrated in Example 11-1.

Example 11-1 Estimation of required landfill area. Estimate the required landfill area for a community with a population of 31,000. Assume that the following conditions apply:

1. Solid waste generation = 6.4 lb/capita · d
2. Compacted specific weight of solid wastes in landfill = 800 lb/yd^3
3. Average depth of compacted solid wastes = 20 ft

Solution

1. Determine the daily solid wastes generation rate in tons per day.

$$\text{Generation rate} = \frac{(31{,}000 \text{ people})(6.4 \text{ lb/capita} \cdot \text{d})}{2000 \text{ lb/ton}}$$

$$= 99.2 \text{ ton/d } (89{,}994 \text{ kg/d})$$

2. Computationally, the required area is determined as follows:

$$\text{Volume required/d} = \frac{99.2 \text{ ton/d} \times 2000 \text{ lb/ton}}{800 \text{ lb/yd}^3}$$

$$= 248 \text{ yd}^3\text{/d } (190 \text{ m}^3\text{/d})$$

$$\text{Area required/yr} = \frac{(248 \text{ yd}^3\text{/d})(365 \text{ d/yr})(227 \text{ ft}^3\text{/yd}^3)}{(20 \text{ ft})(43{,}560 \text{ ft}^2\text{/acre})}$$

$$= 2.81 \text{ acre/yr } (1.14 \text{ hectare/yr})$$

Comment. The actual site requirements will be greater than the value computed because additional land is required for a buffer zone, office and service buildings, access roads, utility access, and so on. Typically, this allowance varies from 20 to 40 percent. A more rigorous approach to the determination of the required landfill area involves consideration of the contours of the completed landfill (see Example 11-7 in Section 11-12) and the effects of gas production and overburden compaction (see Example 11-13 in Section 11-12).

Site Access

As the number of operating landfills continues to decrease, new landfills that are being sited are increasing in size. Because land areas of suitable size are often not near existing developed roadways and cities, construction of access roadways and the use of long haul equipment has become a fact of life and an important part of landfill siting. Rail lines often pass nearby remote sites that are suitable for use as landfills; thus, there is renewed interest in the use of rail haul for transporting wastes to these remote sites.

Soil Conditions and Topography

Because it is necessary to cover the solid wastes placed in the landfill each day and to provide a final cover layer after the landfilling operation is completed, data must be obtained on the amounts and characteristics of the soils in the area. If the soil under the proposed landfill area is to be used for cover material, data must be developed on its geologic and hydrogeologic characteristics. If cover material is to be obtained from a borrow pit, test borings will be needed to characterize the material. The local topography must be considered because it will affect the type of landfill operation to be used, the equipment requirements, and the extent of work necessary to make the site usable. If suitable cover material is limited or an effort is being made to extend the useful life of the landfill, it may be necessary to consider the use of compost or other materials for intermediate cover.

Climatologic Conditions

Local weather conditions must also be considered in the evaluation of potential sites. In many locations, winter conditions will affect access to the site. Wet weather may necessitate the use of separate landfill areas. Where freezing is severe, landfill cover material must be available in stockpiles when excavation is impracticable. Wind strength and wind patterns must also be considered carefully. To avoid blowing or flying debris, windbreaks must be established. The specific form of windbreak depends on local conditions.

Surface Water Hydrology

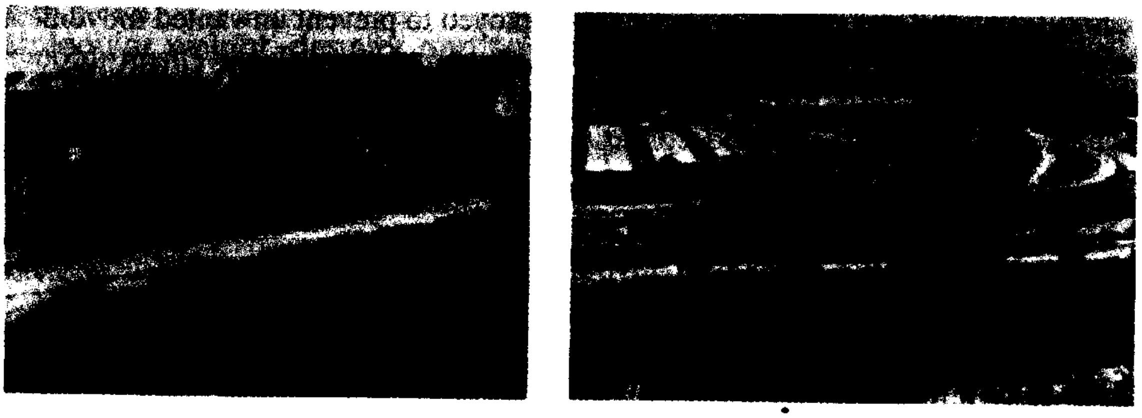
The local surface water hydrology of the area is important in establishing the existing natural drainage and runoff characteristics that must be considered. Other conditions of flooding (e.g., the limits of the 100-year flood) must also be identified. Because mitigation measures must be developed to divert surface runoff from the landfill site, planners must take great care in defining existing and intermittent flow channels and the area and characteristics of the contributing watershed.

Geologic and Hydrogeologic Conditions

Geologic and hydrogeologic conditions are perhaps the most important factors in establishing the environmental suitability of the area for a landfill site. Data on these factors are required to assess the pollution potential of the proposed site and to establish what must be done to the site to ensure that the movement of leachate or gases from the landfill will not impair the quality of local groundwater or contaminate other subsurface or bedrock aquifers. In the preliminary assessment of alternative sites, it may be possible to use U.S. Geological Survey maps and state or local geologic information. Geologic drilling logs of nearby wells can also be used for a preliminary assessment.

Local Environmental Conditions

Although it has been possible to build and operate landfill sites in close proximity to both residential and industrial developments, they must be operated very



(a) (b)

FIGURE 11-10
Views from well-managed completed landfills: (*a*) next to an expensive residential area and (*b*) adjacent to an industrial park.

carefully if they are to be environmentally acceptable with respect to traffic, noise, odor, dust, airborne debris, visual impact, vector control, hazards to health, and property values (see Fig. 11-10). To minimize the impact of landfilling operations, landfills are now sited in more remote locations where adequate buffer zones surrounding the landfill can be maintained.

Ultimate Use for Completed Landfills

One of the advantages of a landfill is that, once it is completed, a sizable area of land becomes available for other purposes. Because the ultimate use affects the design and operation of the landfill, this issue must be resolved before the layout and design of the landfill is begun. Choices for the ultimate use of completed landfills are becoming more limited by state and federal regulations dealing with landfill closure and postclosure maintenance. If the completed landfill is to be used for some municipal function, a staged planting program should be initiated and continued as portions of the landfill are completed. The ultimate use and long-term management of landfill sites are considered in Chapters 16 and 20.

11-4 COMPOSITION AND CHARACTERISTICS, GENERATION, MOVEMENT, AND CONTROL OF LANDFILL GASES

A solid waste landfill can be conceptualized as a biochemical reactor, with solid waste and water as the major inputs, and with *landfill gas* and *leachate* as the principal outputs. Material stored in the landfill includes partially biodegraded organic material and the other inorganic waste materials originally placed in the landfill. Landfill gas control systems are employed to prevent unwanted movement of landfill gas into the atmosphere or the lateral and vertical movement through the surrounding soil. Recovered landfill gas can be used to produce energy or can be flared under controlled conditions to eliminate the discharge of harmful constituents to the atmosphere.

Composition and Characteristics of Landfill Gas

Landfill gas is composed of a number of gases that are present in large amounts (the principal gases) and a number of gases that are present in very small amounts (the trace gases). The principal gases are produced from the decomposition of the organic fraction of MSW. Some of the trace gases, although present in small quantities, can be toxic and could present risks to public health.

Principal Landfill Gas Constituents. Gases found in landfills include ammonia (NH_3), carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), hydrogen sulfide (H_2S), methane (CH_4), nitrogen (N_2), and oxygen (O_2). The typical percentage distribution of gases found in a MSW landfill is reported in Table 11-2. Data on molecular weight and density are presented in Table 11-3. Data that can be used to determine the solubility of these gases in water (leachate) are presented in Appendix F. Methane and carbon dioxide are the principal gases produced from the anaerobic decomposition of the biodegradable organic waste components in MSW. When methane is present in the air in concentrations between 5 and 15

TABLE 11-2
Typical constituents found in MSW landfill gas[a]

Component	Percent (dry volume basis)[b]
Methane	45–60
Carbon dioxide	40–60
Nitrogen	2–5
Oxygen	0.1–1.0
Sulfides, disulfides, mercaptans, etc.	0–1.0
Ammonia	0.1–1.0
Hydrogen	0–0.2
Carbon monoxide	0–0.2
Trace constituents	0.01–0.6
Characteristic	**Value**
Temperature, °F	100–120
Specific gravity	1.02–1.06
Moisture content	Saturated
High heating value, Btu/sft^3	400–550

[a] Adapted from Refs. 16, 24, 34.

[b] Exact percentage distribution will vary with the age of the landfill.

TABLE 11-3
Molecular weight, density, and specific weight of gases found in sanitary landfill at standard conditions (0°C, 1 atm)

Gas	Formula	Molecular weight	Density, g/L	Specific weight, lb/ft^3
Air		28.97	1.2928	0.0808
Ammonia	NH_3	17.03	0.7708	0.0482
Carbon dioxide	CO_2	44.00	1.9768	0.1235
Carbon monoxide	CO	28.00	1.2501	0.0781
Hydrogen	H_2	2.016	0.0898	0.0056
Hydrogen sulfide	H_2S	34.08	1.5392	0.0961
Methane	CH_4	16.03	0.7167	0.0448
Nitrogen	N_2	28.02	1.2507	0.0782
Oxygen	O_2	32.00	1.4289	0.0892

[a] Adapted from Ref. 35.

Note: For ideal gas behavior, the density is equal to mp/RT where m is the molecular weight of the gas, p is the pressure, R is the *universal* gas constant, and T is the temperature using a consistent set of units.

percent, it is explosive. Because only limited amounts of oxygen are present in a landfill when methane concentrations reach this critical level, there is little danger that the landfill will explode. However, methane mixtures in the explosive range can form if landfill gas migrates off-site and mixes with air. The concentration of these gases that may be expected in the leachate will depend on their concentration in the gas phase in contact with the leachate, as estimated using Henry's law, given in Appendix F. Because carbon dioxide will affect the pH of the leachate, carbonate equilibrium data that can be used to estimate the pH of the leachate are given in Appendix G.

Trace Landfill Gas Constituents. The California Integrated Waste Management Board has performed an extensive landfill gas sampling program as part of its landfill gas characterization study. Summary data on the concentrations of trace compounds found in landfill gas samples from 66 landfills are reported in Table 11-4. In another study conducted in England, gas samples were collected from three different landfills and analyzed for 154 compounds. A total of 116 organic compounds were found in landfill gas [54]. Many of the compounds found would be classified as volatile organic compounds (VOCs). The data presented in Table 11-4 are representative of the trace compounds found at most MSW landfills. The presence of these gases in the leachate that is removed from the landfill will depend on their concentrations in the landfill gas in contact with the leachate. Expected concentrations of these constituents in the leachate can be estimated using Henry's law as outlined in Appendix F. Note that the occurrence of significant concentrations of VOCs in landfill gas is associated with older landfills that accepted industrial and commercial wastes containing VOCs. In newer landfills in which the disposal of hazardous waste has been banned, the concentrations of VOCs in the landfill gas have been extremely low.

TABLE 11-4
Typical concentrations of trace compounds found in landfill gas at 66 California MSW landfills[a]

Compound	Concentration, ppbV[b] Median	Mean	Maximum
Acetone	0	6,838	240,000
Benzene	932	2,057	39,000
Chlorobenzene	0	82	1,640
Chloroform	0	245	12,000
1,1-Dichloroethane	0	2,801	36,000
Dichloromethane	1,150	25,694	620,000
1,1-Dichloroethene	0	130	4,000
Diethylene chloride	0	2,835	20,000
trans-1,2-Dichloroethane	0	36	850
2,3-Dichloropropane	0	0	0
1,2-Dichloropropane	0	0	0
Ethylene bromide	0	0	0
Ethylene dichloride	0	59	2,100
Ethylene oxide	0	0	0
Ethyl benzene	0	7,334	87,500
Methyl ethyl ketone	0	3,092	130,000
1,1,2-Trichloroethane	0	0	0
1,1,1-Trichloroethane	0	615	14,500
Trichloroethylene	0	2,079	32,000
Toluene	8,125	34,907	280,000
1,1,2,2-Tetrachloroethane	0	246	16,000
Tetrachloroethylene	260	5,244	180,000
Vinyl chloride	1,150	3,508	32,000
Styrenes	0	1,517	87,000
Vinyl acetate	0	5,663	240,000
Xylenes	0	2,651	38,000

[a]Adapted from Ref. 5.
[b]ppbV = parts per billion by volume.

Generation of Landfill Gases

The generation of the principal landfill gases, the variation in their rate of generation with time, and the sources of trace gases in landfills is considered in the following discussion.

Generation of the Principal Landfill Gases. The generation of the principal landfill gases is thought to occur in five more or less sequential phases, as illustrated in Fig. 11-11. Each of these phases is described below; additional details may be found in Refs. 6, 12, 13, 34, 37, and 38. A more detailed description of the anaerobic digestion process, including the organisms and the principal reactions involved in the formation of methane is presented in Chapter 14.

Phase I—Initial adjustment. Phase I is the *initial adjustment phase*, in which the organic biodegradable components in MSW undergo microbial decom-

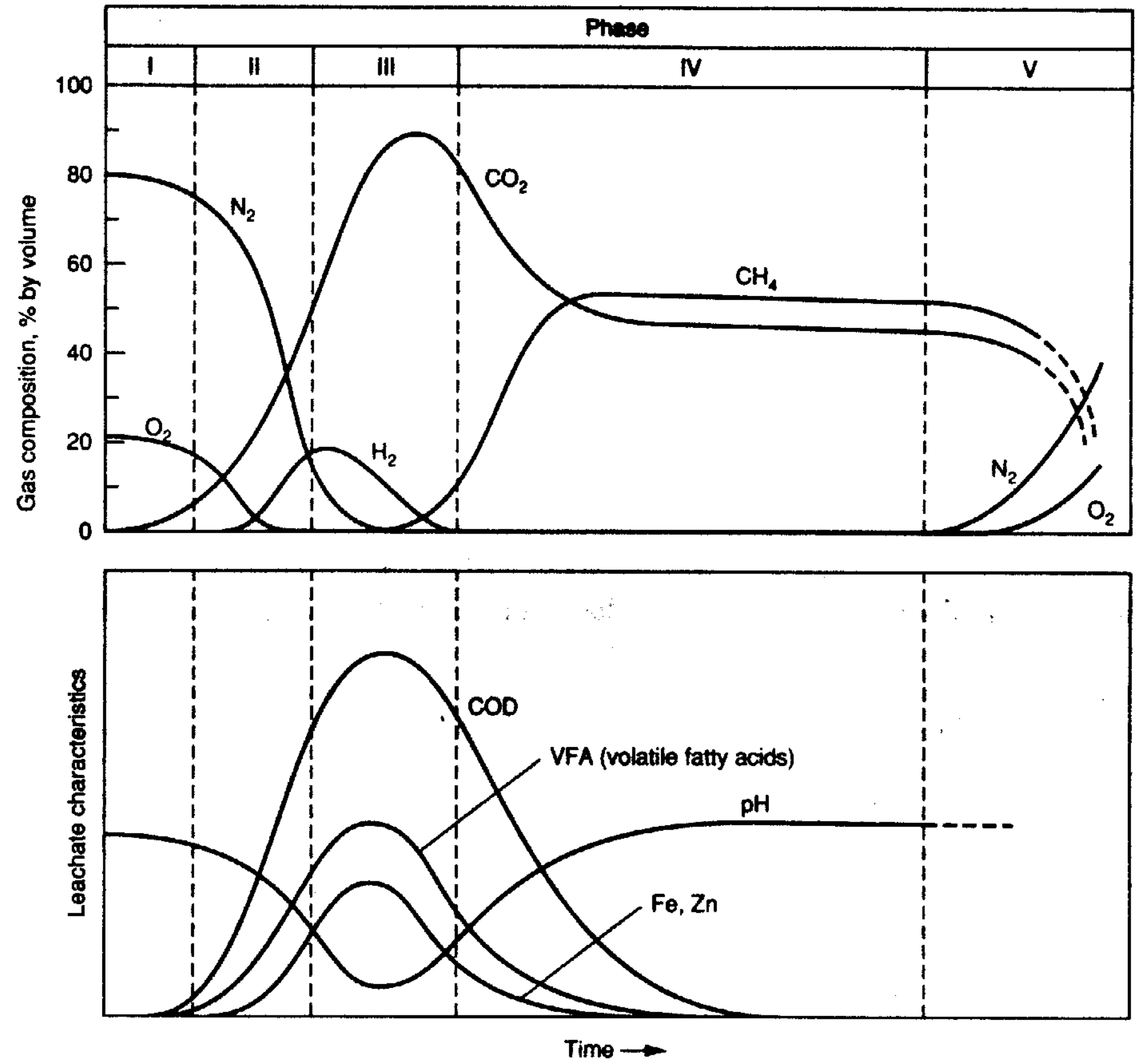


FIGURE 11-11
Generalized phases in the generation of landfill gases (I = initial adjustment, II = transition phase, III = acid phase, IV = methane fermentation, and V = maturation phase). (Adapted from Refs. 13, 34, 37, and 38.)

position as they are placed in a landfill and soon after. In Phase I, biological decomposition occurs under aerobic conditions, because a certain amount of air is trapped within the landfill. The principal source of both the aerobic and the anaerobic organisms responsible for waste decomposition is the soil material that is used as a daily and final cover. Digested wastewater treatment plant sludge, disposed of in many MSW landfills, and recycled leachate are other sources of organisms.

Phase II—transition phase. In Phase II, identified as the *transition phase*, oxygen is depleted and anaerobic conditions begin to develop. As the landfill becomes anaerobic, nitrate and sulfate, which can serve as electron acceptors (see Table 14-2) in biological conversion reactions, are often reduced to nitrogen gas and hydrogen sulfide (see Eqs. 4-12, 4-13, and 4-14). The onset of anaerobic conditions can be monitored by measuring the oxidation/reduction potential of the waste. Reducing conditions sufficient to bring about the reduction of nitrate and sulfate occur at about −50 to −100 millivolts. The production of methane occurs when the oxidation/reduction potential values are in the range from −150 to −300 millivolts. As the oxidation/reduction potential continues to decrease, members of the microbial community responsible for the conversion of the organic material in MSW to methane and carbon dioxide begin the three-step process (see Fig. 14-1), with conversion of the complex organic material to organic acids and other intermediate products as described in Phase III. In Phase II, the pH of the leachate, if any is formed, starts to drop due to the presence of organic acids and the effect of the elevated concentrations of CO_2 within the landfill (see Fig. 11-11).

Phase III—acid phase. In Phase III, the *acid phase*, the microbial activity initiated in Phase II accelerates with the production of significant amounts of organic acids and lesser amounts of hydrogen gas. The first step in the three-step process involves the enzyme-mediated transformation (hydrolysis) of higher-molecular mass compounds (e.g., lipids, polysaccharides, proteins, and nucleic acids) into compounds suitable for use by microorganisms as a source of energy and cell carbon. The second step in the process (acidogenesis) involves the microbial conversion of the compounds resulting from the first step into lower-molecular mass intermediate compounds as typified by acetic acid (CH_3COOH) and small concentrations of fulvic and other more complex organic acids. Carbon dioxide (CO_2) is the principal gas generated during Phase III. Smaller amounts of hydrogen gas (H_2) will also be produced. The microorganisms involved in this conversion, described collectively as nonmethanogenic, consist of facultative and obligate anaerobic bacteria. These microorganisms are often identified in the engineering literature as *acidogens* or *acid formers*.

The pH of the leachate, if formed, will often drop to a value of 5 or lower because of the presence of the organic acids and the elevated concentrations of CO_2 within the landfill. The biochemical oxygen demand (BOD_5), the chemical oxygen demand (COD), and the conductivity of the leachate will increase significantly during Phase III due to the dissolution of the organic acids in the leachate. Also, because of the low pH values in the leachate, a number of inorganic constituents, principally heavy metals, will be solubilized during Phase III. Many essential nutrients are also removed in the leachate in Phase III. If leachate is not recycled, the essential nutrients will be lost from the system. It is important to note that if leachate is not formed, the conversion products produced during Phase III will remain within the landfill as sorbed constituents and in the water held by the waste as defined by the field capacity (see Section 11-5).

Phase IV—methane fermentation phase. In Phase IV, the *methane fermentation phase*, a second group of microorganisms, which convert the acetic acid and hydrogen gas formed by the acid formers in the acid phase to CH_4 and CO_2, becomes more predominant. In some cases, these organisms will begin to develop toward the end of Phase III. The microorganisms responsible for this conversion are strict anaerobes and are called methanogenic. Collectively, they are identified in the literature as *methanogens* or *methane formers*. In Phase IV, both methane and acid formation proceed simultaneously, although the rate of acid formation is considerably reduced.

Because the acids and the hydrogen gas produced by the acid formers have been converted to CH_4 and CO_2 in Phase IV, the pH within the landfill will rise to more neutral values in the range of 6.8 to 8. In turn, the pH of the leachate, if formed, will rise, and the concentration of BOD_5 and COD and the conductivity value of the leachate will be reduced. With higher pH values, fewer inorganic constituents can remain in solution; as a result, the concentration of heavy metals present in the leachate will also be reduced.

Phase V—maturation phase. Phase V, the *maturation phase*, occurs after the readily available biodegradable organic material has been converted to CH_4 and CO_2 in Phase IV. As moisture continues to migrate through the waste, portions of the biodegradable material that were previously unavailable, will be converted. The rate of landfill gas generation diminishes significantly in Phase V, because most of the available nutrients have been removed with the leachate during the previous phases and the substrates that remain in the landfill are slowly biodegradable. The principal landfill gases evolved in Phase V are CH_4 and CO_2. Depending on the landfill closure measures, small amounts of nitrogen and oxygen may also be found in the landfill gas. During maturation phase, the leachate will often contain humic and fulvic acids, which are difficult to process further biologically.

Duration of phases. The duration of the individual phases in the production of landfill gas will vary depending on the distribution of the organic components in landfill, the availability of nutrients, the moisture content of waste, moisture routing through the fill, and the degree of initial compaction. For example, if several loads of brush are compacted together the carbon/nitrogen ratio and the nutrient balance may not be favorable for the production of landfill gas (see Chapter 14). Likewise, the generation of landfill gas will be retarded if sufficient moisture is not available. Increasing the density of the material placed in the landfill will decrease the possibility of moisture reaching all parts of the waste and, thus, reduce the rate of bioconversion and gas production. Typical data on the percentage distribution of principal gases found in a newly completed landfill as a function of time are reported in Table 11-5.

Volume of Gas Produced. The generalized chemical reaction for the anaerobic decomposition of solid waste can be written as

$$\underset{\text{(solid waste)}}{\underset{\text{matter}}{\text{Organic}}} + H_2O \xrightarrow{\text{bacteria}} \underset{\text{matter}}{\underset{\text{organic}}{\text{biodegraded}}} + CH_4 + CO_2 + \underset{\text{gases}}{\text{other}} \quad (11\text{-}1)$$

TABLE 11-5
Percentage distribution of landfill gases observed during the first 48 months after the closure of a landfill cell[a]

Time interval since cell completion, months	Average, percent by volume		
	Nitrogen, N_2	Carbon dioxide, CO_2	Methane, CH_4
0–3	5.2	88	5
3–6	3.8	76	21
6–12	0.4	65	29
12–18	1.1	52	40
18–24	0.4	53	47
24–30	0.2	52	48
30–36	1.3	46	51
36–42	0.9	50	47
42–48	0.4	51	48

[a] From Ref. 32.

Note that the reaction requires the presence of water. Landfills lacking sufficient moisture content have been found in a "mummified" condition, with decades-old newsprint still in readable condition. Hence, although the total amount of gas that will be produced from solid waste derives straightforwardly from the reaction stoichiometry, local hydrologic conditions affect significantly the rate and the period of time over which that gas production takes place.

The volume of the gases released during anaerobic decomposition can be estimated in a number of ways. For example, if the individual organic constituents found in MSW (with the exception of plastics) are represented with a generalized formula of the form $C_aH_bO_cN_d$, then the total volume of gas can be estimated using Eq. (11-2), assuming the complete conversion of the biodegradable organic waste to CO_2 and CH_4.

$$C_aH_bO_cN_d + \left(\frac{4a - b - 2c - 3d}{4}\right)H_2O \rightarrow$$

$$\left(\frac{4a - b - 2c - 3d}{8}\right)CH_4 + \left(\frac{4a - b + 2c + 3d}{8}\right)CO_2 + dNH_3 \qquad (11\text{-}2)$$

In general, the organic materials present in solid wastes can be divided into two classifications: (1) those materials that will decompose rapidly (three months to five years) and (2) those materials that will decompose slowly (up to 50 years or more). The rapidly and slowly decomposable components of the organic fraction of MSW are identified in Table 11-6. A procedure that can be used to estimate the amount of gas that can be generated from the biodegradable portion of the organic waste in MSW is illustrated in Example 11-2. Assuming the formula

TABLE 11-6
Rapidly and slowly biodegradable organic constituents in MSW

Organic waste component	Rapidly biodegradable	Slowly biodegradable
Food wastes	✓	
Newspaper	✓	
Office paper	✓	
Cardboard	✓	
Plastics[a]		
Textiles		✓
Rubber		✓
Leather		✓
Yard wastes	✓[b]	✓[c]
Wood		✓
Misc. organics	–	✓

[a] Plastics are generally considered nonbiodegradable.

[b] Leaves and grass trimmings. Typically, 60 percent of the yard wastes are considered rapidly biodegradable.

[c] Woody portions of yard wastes.

$C_{75}H_{122}O_{55}N$, as developed in Example 11-2 can be used to describe the rapidly biodegradable organic fraction of the MSW, then, as computed in Example 11-2, the maximum amount of gas that would be expected under optimum conditions is 14.0 ft^3/lb of biodegradable organic solids destroyed. The biodegradable fraction of the organic waste depends to a large extent on the lignin content of the waste (see Chapter 3). The biodegradability of various organic constituents, based on lignin content, is reported in Table 11-7. As shown, newspaper is only 22 percent biodegradable.

TABLE 11-7
Biodegradability of the organic constituents in MSW

Organic waste component	Lignin content, % of VS	Biodegradable fraction,[a] % of VS
Food wastes	0.4	0.82
Newspaper	21.9	0.22
Office paper	0.4	0.82
Cardboard	12.9	0.47
Yard wastes	4.1	0.72

[a] Biodegradable fraction = 0.83 − (0.028) × LC, where LC = % of VS (volatile solids).

Example 11-2 Estimate the chemical composition and the amount of gas that can be derived from the organic constituents in MSW. Determine the chemical composition and the amount of gas that can be derived from the rapidly and slowly decomposable organic constituents in MSW as given in Table 3-4. Assume 60 percent of the yard wastes will decompose rapidly.

Solution

1. Set up a computation table to determine the percentage distribution of the major elements composing the waste. The necessary computations for the rapidly and slowly decomposable organic constituents are presented below. The moisture content of the waste constituents is taken from Table 4-1.

Component	Wet weight,[a] lb	Dry weight,[b] lb	Composition,[c] lb					
			C	H	O	N	S	Ash
Rapidly decomposable organic constituents								
Food wastes	9.0	2.7	1.30	0.17	1.02	0.07	0.01	0.14
Paper	34.0	32.0	13.92	1.92	14.08	0.10	0.06	1.92
Cardboard	6.0	5.7	2.51	0.34	2.54	0.02	0.01	0.29
Yard wastes	11.1[d]	4.4	2.10	0.26	1.67	0.15	0.01	0.20
Total	60.1	44.8	19.83	2.69	19.31	0.34	0.09	2.55
Slowly decomposable organic constituents								
Textiles	2.0	1.8	0.99	0.12	0.56	0.08	—	0.05
Rubber	0.5	0.5	0.39	0.05	—	0.01	—	0.05
Leather	0.5	0.4	0.24	0.03	0.05	0.04	—	0.04
Yard wastes	7.4[e]	3.0	1.43	0.18	1.14	0.10	0.01	0.13
Wood	2.0	1.6	0.79	0.10	0.69	—	—	0.02
Total	12.4	7.3	3.84	0.48	2.44	0.23	0.01	0.29

[a] See Table 3-4.
[b] See Table 4-1.
[c] See Table 4-3.
[d] 11.1 = 18.5 × 0.60.
[e] 7.4 = 18.5 − 11.1.

2. Compute the molar composition of the elements neglecting the ash.

	C	H	O	N	S
lb/mole	12.01	1.01	16.00	14.01	32.06
Total moles					
Rapidly decomp.	1.6511	2.6634	1.2069	0.0241	0.0028
Slowly decomp.	0.3197	0.4752	0.1525	0.0164	0.0003

3. Determine an approximate chemical formula without sulfur. Set up a computation table to determine normalized mole ratios.

	Mol. ratio (nitrogen = 1)	
Component	**Rapidly decomposable**	**Slowly decomposable**
Carbon	68.5	19.5
Hydrogen	110.5	29.0
Oxygen	50.1	9.2
Nitrogen	1.0	1.0

The chemical formulas without sulfur are

$$\text{Rapidly decomposable} = C_{68.5}H_{110.5}O_{50.1}N \qquad (\text{use } C_{68}H_{111}O_{50}N)$$

$$\text{Slowly decomposable} = C_{19.5}H_{29}O_{9.2}N \qquad (\text{use } C_{20}H_{29}O_{9}N)$$

4. Estimate the amount of gas that can be derived from the rapidly and slowly decomposable organic constituents in MSW.
   (*a*) Using Eq. (11-2), the resulting equations are
      i. Rapidly decomposable

$$\underset{1741.0}{C_{68}H_{111}O_{50}N} + \underset{288.0}{16H_2O} \rightarrow \underset{560.0}{35CH_4} + \underset{1452.0}{33CO_2} + \underset{17}{NH_3}$$

      ii. Slowly decomposable

$$\underset{427}{C_{20}H_{29}O_{9}N} + \underset{162}{9H_2O} \rightarrow \underset{176}{11CH_4} + \underset{396}{9CO_2} + \underset{17}{NH_3}$$

   (*b*) Determine the volume of methane and carbon dioxide produced. The specific weights of methane and carbon dioxide are 0.0448 and 0.1235 lb/ft^3, respectively (see Table 11-3).
      i. Rapidly decomposable

$$\text{Methane} = \frac{(560.0)(44.8)}{(1741.0)(0.0448\ \text{lb/ft}^3)} = 321.7\ \text{ft}^3 \text{ at STP}$$

$$\text{Carbon dioxide} = \frac{(1452.0)(44.8\ \text{lb})}{(1741.0)(0.1235\ \text{lb/ft}^3)} = 302\ \text{ft}^3 \text{ at STP}$$

      ii. Slowly decomposable

$$\text{Methane} = \frac{(176)(7.3\ \text{lb})}{(427)(0.0448\ \text{lb/ft}^3)} = 67.2\ \text{ft}^3 \text{ at STP}$$

$$\text{Carbon dioxide} = \frac{(396)(7.3\ \text{lb})}{(427)(0.1235\ \text{lb/ft}^3)} = 54.8\ \text{ft}^3 \text{ at STP}$$

   (*c*) Determine the total theoretical amount of gas generated per unit dry weight of organic matter destroyed.
      i. Rapidly decomposable

$$\text{Vol/lb} = \frac{321.7\ \text{ft}^3 + 302.5\ \text{ft}^3}{44.8\ \text{lb}} = 13.9\ \text{ft}^3/\text{lb}$$

ii. Slowly decomposable

$$\text{Vol/lb} = \frac{67.2\ \text{ft}^3 + 54.8\ \text{ft}^3}{7.3\ \text{lb}} = 16.7\ \text{ft}^3/\text{lb}$$

Comment. The landfill gas generation values computed in this example represent the maximum amount of gas that could be produced under optimum conditions from the destruction of the biodegradable volatile solids (BVS) in the organic fraction of MSW. The range for the individual organic constituents varies from about 10 to 17 ft^3/lb BVS destroyed. Gas generation values of 12 ft^3/lb BVS destroyed have been reported in the literature for mixed organic waste. The actual quantities of gas generated will be lower because not all of the biodegradable organic matter is available for decomposition. For example, paper contained in plastic bags, while biodegradable, is typically not available for biological conversion. Biodegradable organic wastes that are not exposed to sufficient moisture to sustain biological activity will not be converted.

Variation in Gas Production with Time. Under normal conditions, the rate of decomposition, as measured by gas production, reaches a peak within the first two years and then slowly tapers off, continuing in many cases for periods up to 25 years or more. If moisture is not added to the wastes in a well-compacted landfill, it is not uncommon to find materials in their original form years after they were buried.

The variation in the rate of gas production from the anaerobic decomposition of the rapidly (five years or less—some highly biodegradable wastes are decomposed within days of being placed in a landfill) and slowly (5 to 50 years) biodegradable organic materials in MSW can be modeled as shown in Fig. 11-12. As shown in Fig. 11-12, the yearly rates of decomposition for rapidly and slowly decomposable material are based on a triangular gas production model in which

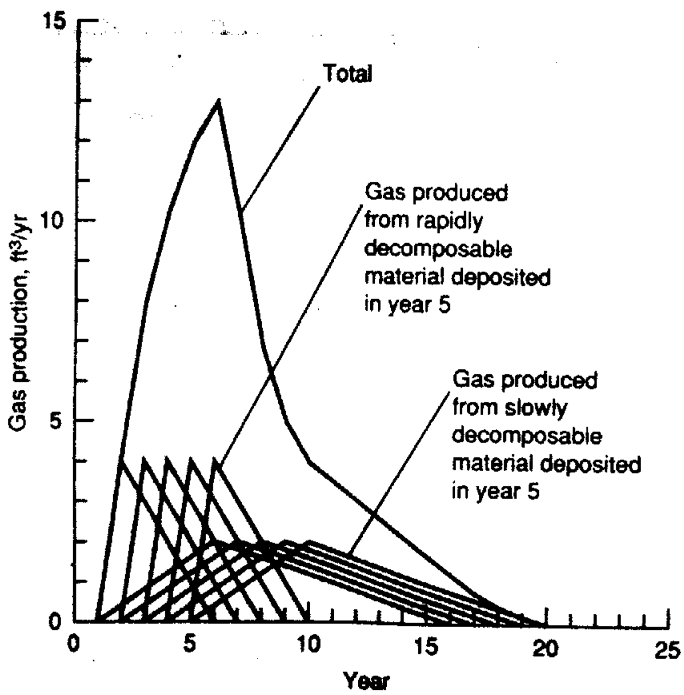


FIGURE 11-12
Graphical representation of gas production over a five-year period from the rapidly and slowly decomposable organic materials placed in a landfill.

the peak rate of gas production occurs one and five years, respectively, after gas production starts. Gas production is assumed to start at the end of the first full year of landfill operation. The area under the triangle is equal to one half the base times the altitude, therefore, the total amount of gas produced from the waste placed the first year of operation is equal to

Total gas produced, ft^3/lb

$$= 1/2 \text{ (base, yr)} \times \text{(altitude, peak rate of gas production, } ft^3/lb \cdot yr) \quad (11\text{-}3)$$

Using a triangular gas production model, the total rate of gas production from a landfill in which wastes were placed for a period of five years is obtained graphically by summing the gas produced from the rapidly and slowly biodegradable portions of the MSW deposited each year (see Fig. 11-12). The total amount of gas produced corresponds to the area under the rate curve. Determination of the total amount of gas produced in a landfill is illustrated in Example 11-8 in Section 11-12.

As noted previously, in many landfills the available moisture is insufficient to allow for the complete conversion of the biodegradable organic constituents in the MSW. The optimum moisture content for the conversion of the biodegradable organic matter in MSW is on the order of 50 to 60 percent. Also in many landfills, the moisture that is present is not uniformly distributed. When the moisture content of the landfill is limited, the gas production curve is more flattened out and is extended over a greater period of time. An example of the effect of reduced moisture content on the production of landfill gas is presented in Fig. 11-13. The production of landfill gas over extended periods of time is of great significance with respect to the management strategy to be adopted for postclosure maintenance.

Sources of Trace Gases. Trace constituents in landfill gases have two basic sources. They may be brought to the landfill with the incoming waste or they may

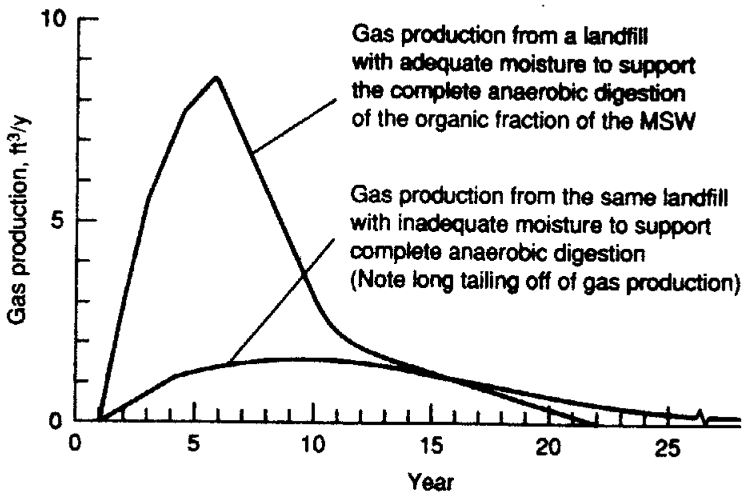


FIGURE 11-13
Effect of reduced moisture content on the production of landfill gas.

TABLE 11-8
Estimated times for the complete volatilization of selected volatile liquids found in landfills[a]

Compound	Evaporation time, d[b]
Chloroethene	0.0
Dichloromethane	1.2
Trichloromethane	4.4
Benzene	6.4
Tetrachloromethane	9.6
Trichloroethene	13.6
Toluene	23.4
Tetrachloroethene	62.6
Chlorobenzene	76.0
1,2-Dibromoethane	128.2
o-Dichlorobenzene	497.6

[a] Excerpted from Ref. 26.

[b] Based on a 10 mm sphere of volatile liquid at 25°C, in a landfill with a porosity of 0.5.

be produced by biotic and abiotic reactions occurring within the landfill [25]. Of the trace compounds found in landfill gases, many are mixed into the incoming waste in liquid form, but tend to volatilize. The tendency to volatilize can be shown to be approximately proportional to the vapor pressure of the liquid, and inversely proportional to the surface area of a sphere of the volatile liquid within the landfill [26]. The wide variation in volatilization times that are expected from some selected volatile liquids that may be found in landfills is illustrated in Table 11-8. In newer landfills where the disposal of hazardous waste has been banned, the concentrations of VOCs in the landfill gas have been reduced significantly.

Complex biochemical pathways can exist for the production or consumption of any of the trace constituents. For example, vinyl chloride is a byproduct of the degradation of di- and trichloroethene. Because of the organic nature of these gases they can be sorbed by waste constituents in the landfill. At present, very little can be stated definitively about the rates of biochemical transformation of the trace compounds. Half-lives varying from a fraction of a year to over a thousand years have been reported for various compounds.

Movement of Landfill Gas

Under normal conditions, gases produced in soils are released to the atmosphere by means of molecular diffusion. In the case of an active landfill, the internal pressure is usually greater than atmospheric pressure and landfill gas will be released by both convective (pressure-driven) flow and diffusion. Other factors influencing the movement of landfill gases include the sorption of the gases into liquid or solid components [47] and the generation or consumption of a gas component through chemical reactions or biological activity. The following general equation relates

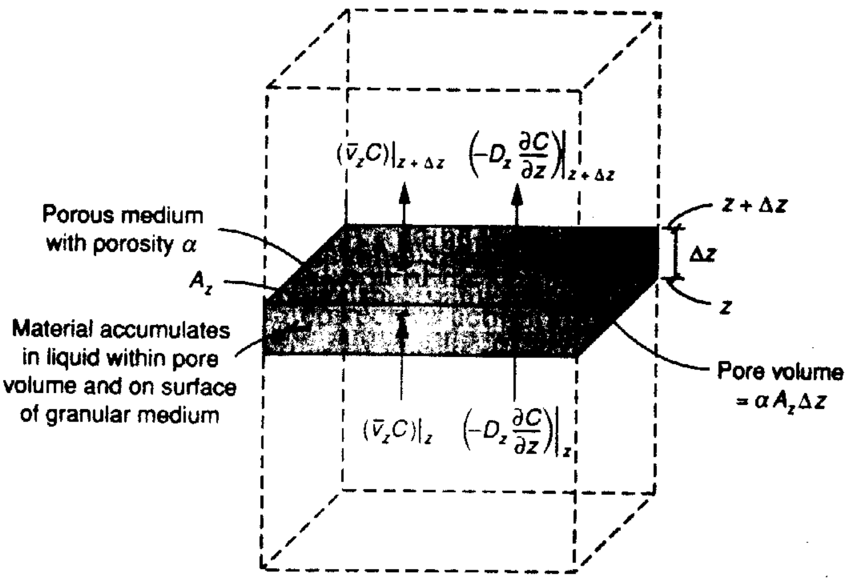


FIGURE 11-14
Control volume for the vertical movement of landfill gas.

these factors in a one-dimensional (vertical) control volume (see Fig. 11-14) [26]. Note that the following discussion of the movement of landfill gases is given in metric units with U.S. customary units in parentheses, as most of the available constants and coefficients for landfill gases are given in metric units.

$$\alpha(1 + \beta)\frac{\partial C_A}{\partial t} = -V_z\frac{\partial C_A}{\partial z} + D_z\frac{\partial^2 C_A}{\partial z^2} + G \qquad (11\text{-}4)$$

where α = total porosity, cm^3/cm^3 (ft^3/ft^3)
β = retardation factor accounting for sorption and phase change
C_A = concentration of compound A, g/cm^3 ($lb \cdot mole/ft^3$)
V_z = convective velocity in the vertical direction, cm/s (ft/d)
D_z = effective diffusion coefficient, cm^2/s (ft^2/d)
G = lumped parameter used to account for all generation terms, $g/cm^3 \cdot s$ ($lb \cdot mole/ft^3 \cdot d$)
z = depth, m (ft)

The convective velocity V_z in the vertical direction can be estimated using Darcy's law as follows:

$$V_z = -\frac{k}{\mu}\frac{dP}{dz} \qquad (11\text{-}5)$$

where V_z = convective velocity, m/s (ft/d)
k = intrinsic permeability, m^2 (ft^2)
μ = gas-mixture viscosity, $N \cdot s/m^2$ ($lb \cdot d/ft^2$)
P = pressure, N/m^2 (lb/ft^2)
z = depth, m (ft)

Typical values for the convective velocity for the principal gases in landfills are on the order of 1 to 15 cm/d. Solutions of Eq. (11-4) are generally accomplished using finite difference or finite element numerical methods in conjunction with high-speed computers. The numerical solution of Eq. (11-4) in two and three dimensions is discussed in Ref. 26.

Simplified forms of Eq. (11-4) can be helpful in estimating emissions without having to resort to complex numerical computer-based solution techniques. For example, if sorptive and generative effects are neglected, then Eq. (11-4) reduces under steady-state conditions to

$$0 = -V_z \frac{dC_A}{dz} + D_z \frac{d^2 C_A}{dz^2} \qquad (11\text{-}6)$$

If landfill gas is no longer being produced in significant quantities, only the diffusive portion of Eq. (11-6) remains, which can be integrated to yield the following expression:

$$N_A = -D_z \frac{dC_A}{dz} \qquad (11\text{-}7)$$

where N_A = gas flux, g/cm$^2 \cdot$ s (lb · mol/ft$^2 \cdot$ d)

The effective diffusion coefficient is a function of both the molecular diffusion and the porosity of the soil. The following relationship was determined empirically for Lindane vapor movement through soil:

$$D_z = D \frac{(\alpha_{\text{gas}})^{10/3}}{\alpha^2} \qquad (11\text{-}8)$$

where D_z = effective diffusion coefficient, cm^2/s (ft^2/d)
D = diffusion coefficient, cm^2/s (ft^2/d)
α_{gas} = gas-filled porosity, cm^3/cm^3 (ft^3/ft^3)
α = total porosity, cm^3/cm^3 (ft^3/ft^3)

Another approach used to determine the effective diffusion coefficient is as follows:

$$D_z = D\alpha\tau \qquad (11\text{-}9)$$

where τ = tortuosity factor (typical value = 0.67)

Movement of Principal Landfill Gases. Although most of the methane escapes to the atmosphere, both methane and carbon dioxide have been found at concentrations up to 40 percent at lateral distances of up to 400 ft from the edges of unlined landfills. For unvented landfills, the extent of this lateral movement varies with the characteristics of the cover material and the surrounding soil. If methane is vented in an uncontrolled manner, it can accumulate (because its specific gravity is less than that of air) below buildings or in other enclosed spaces at, or close to, a sanitary landfill. With proper venting, methane should not pose a problem (except that it is a greenhouse gas). Carbon dioxide, on the other hand, is troublesome because of its density. As shown in Table 11-3, carbon dioxide is about 1.5 times as dense as air and 2.8 times as dense as methane; thus, it tends to move toward the bottom of the landfill. As a result, the concentration of carbon dioxide in the lower portions of a landfill may be high for years.

Upward migration of landfill gas. Methane and carbon dioxide can be released through the landfill cover into the atmosphere by convection and diffusion. The diffusive flow through the cover can be estimated using Eqs.(11-7) and (11-8) assuming the concentration gradient is linear and the soil is dry, thus $\alpha_{gas} = \alpha$. Assuming dry soil conditions introduces a safety factor in that any infiltration of water into the landfill cover will reduce the gas-filled porosity and thereby reduce the vapor flux from the landfill.

$$N_A = -\frac{D\alpha^{4/3}(C_{A_{atm}} - C_{A_{fill}})}{L} \tag{11-10}$$

where N_A = gas flux of compound A, g/cm$^2\cdot$s (lb $\cdot$ mol/ft$^2\cdot$d)
$C_{A_{atm}}$ = concentration of compound A at the surface of the landfill cover, g/cm^3 (lb $\cdot$ mol/ft^3)
$C_{A_{fill}}$ = concentration of compound A at bottom of the landfill cover, g/cm^3 (lb $\cdot$ mol/ft^3)
L = depth of the landfill cover, cm (ft)

Typical values for the coefficient of diffusion for methane and carbon dioxide are 0.20 cm^2/s (18.6 ft^2/d) and 0.13 cm^2/s (12.1 ft^2/d), respectively [26].

Downward migration of landfill gas. Ultimately, carbon dioxide, because of its density, can accumulate in the bottom of a landfill. If a soil liner is used, the carbon dioxide can move from there downward, primarily by diffusive transport through the liner, and through the underlying formation until it reaches the groundwater (note the movement of CO_2 can be limited with the use of a geomembrane liner). Carbon dioxide is readily soluble in water and can react with it to form carbonic acid, or

$$CO_2 + H_2O \rightarrow H_2CO_3 \tag{11-11}$$

This reaction lowers the pH, which in turn can increase the hardness and mineral content of the groundwater through solubilization. For example, if solid calcium carbonate is present in the soil structure, the carbonic acid will react with it to form soluble calcium bicarbonate, according to the following reaction:

$$CaCO_3 + H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^- \tag{11-12}$$

Similar reactions occur with magnesium carbonates. For a given carbon dioxide gas concentration, the reaction shown in Eq. (11-11) will proceed until equilibrium is reached, as described in Eq. (11-13).

$$\begin{array}{c} H_2O + CO_2 \\ \uparrow\downarrow \\ CaCO_3 + H_2CO_3 \leftrightarrow Ca^{2+} + 2HCO_3^- \end{array} \tag{11-13}$$

Thus, any process that increases the free carbon dioxide available to the solution will cause more calcium carbonate to dissolve. The resulting increase in hardness is the principal effect of the presence of carbon dioxide in groundwater. The solubility in water of the principal gases found in landfills can be computed using Henry's law as given in Appendix F. The effect of carbon dioxide on the the pH of leachate can be estimated using the first dissociation constant for carbonic acid (see Example 11-4 in Section 11-5).

Movement of Trace Gases. For the boundary conditions shown in Fig. 11-15, Eq. (11-10) can be modified for the trace gases found in landfills as follows [19]:

$$N_i = -\frac{D\alpha^{4/3}(C_{i_{atm}} - C_{i_s}W_i)}{L} \qquad (11\text{-}14)$$

where N_i = vapor flux of compound i, g/cm$^2 \cdot$ s
D = diffusion coefficient, cm^2/s
α = dry soil porosity, cm^3/cm^3 (ft^3/ft^3)
$C_{i_{atm}}$ = concentration of compound i at the surface of the landfill cover, g/cm^3
C_{i_s} = saturation vapor concentration of compound i, g/cm^3
W_i = scaling factor to account for the actual fraction of trace compound i in the waste
$C_{i_s}W_i$ = concentration of compound i at bottom of the landfill cover, g/cm^3
L = depth of the landfill cover, cm (ft)

Equation (11-14) can be simplified by assuming that $C_{i_{atm}}$ is zero; this assumption is reasonable because the concentration of the trace constituent reaching the surface

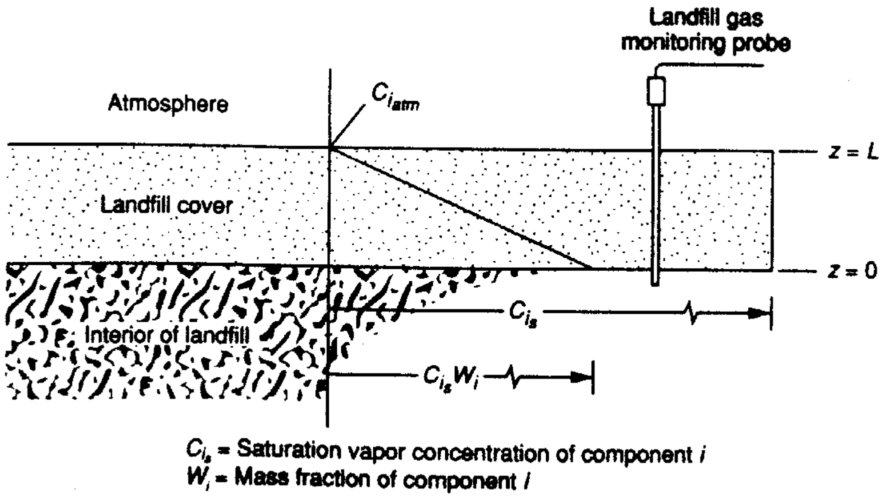


FIGURE 11-15
Definition sketch for the movement of trace landfill gases through a landfill cover [19].

TABLE 11-9
Selected physical properties for twelve trace compounds found in landfills[a]

	0°C			10°C			20°C			30°C			40°C			50°C		
Compound	D^b	vp[c]	C_s[d]	D	vp	C_s	D	vp	C_s	D	vp	C_s	D	vp	C_s	D	vp	C_s
Ethyl benzene	.052	2.0	12.48	.055	3.9	23.47	.059	7.3	42.44	.062	13	73.08	.066	22	119.7	.069	36	189.9
Toluene	.056	6.7	36.26	.060	12	62.65	.064	22	110.9	.068	37	180.4	.073	59	278.5	.077	92	420.9
Tetrachloro-ethene	.053	4.1	39.95	.057	7.9	74.27	.061	15.6	127.1	.065	24	210.7	.069	40	340.0	.073	63	581.9
Benzene	.066	27	123.9	.070	47	208.1	.075	76	325.0	.081	122	504.6	.086	185	740.7	.091	274	1063
1,2-Dichloro-ethane	.063	24	139.6	.068	41	230.0	.072	62	363.0	.077	107	560.7	.082	164	831.9	.088	243	1194
Trichloro-ethene	.059	20	154.5	.063	36	268.4	.067	60	424.8	.072	94	654.5	.077	146	984.1	.082	217	1417
1,1,1-Trichloro-ethane	.058	36	282.2	.062	61	461.3	.067	100	715.9	.071	153	1081	.076	231	1580	.081	338	2240
Carbon tetra-chloride	.058	32	289.3	.062	54	470.9	.066	90	741.2	.071	138	1124	.075	209	1648	.080	308	2353
Chloroform	.065	61	427.9	.070	100	676.7	.075	160	1026	.080	240	1517	.085	354	2166	.090	508	3012
1,2-Dichloro-ethene	.077	110	626.7	.082	175	961.8	.087	269	1428	.092	399	2048	.097	576	2862	.102	810	3901
Dichloro-methane	.074	155	773.6	.080	242	1165	.085	349	1702	.091	536	2410	.097	763	3322	.103	1060	4472
Vinyl chloride	.080	1280	4701	.085	1810	6413	.091	2548	8521	.098	3350	11090	.104	4410	14130	.110	5690	17660

[a] From Ref. 19.

[b] Diffusion coefficient, cm^2/s.

[c] Vapor pressure, mm Hg.

[d] Saturation vapor concentration, g/m^3.

of the landfill will be quickly diminished by both wind dispersal and diffusion into the air. By making this assumption, the estimate for the mass flux of the gas will be conservative; any increase in $C_{i_{atm}}$ will result in a decrease in the mass flux. The simplified form of Eq. (11-14) is

$$N_i = \frac{D\alpha^{4/3}(C_{i_s}W_i)}{L} \tag{11-15}$$

Estimated values of the diffusion coefficient D for twelve trace compounds are reported in Table 11-9 for temperatures varying from 0 to 50°C. Porosity values typically vary from 0.010 to 0.30 for different types of clay. The term $C_{i_s}W_i$ corresponds to the concentration of the compound in question at the top of the landfill just below the cover. If field measurements are not available, the value of the term $C_{i_s}W_i$ can be estimated using the data given in Table 11-10 for C_{i_s} and W_i for the reported trace compounds. The values for the term W_i shown in Table 11-10 were derived from measurements made at 44 municipal waste landfills in California. If a compound of interest is not listed in Table 11-10, one can use a value of 0.001 as an estimate for W_i. The saturation concentration, C_{i_s}, for other trace organic compounds may be found in Appendix H. If the value of the term $C_{i_s}W_i$ is to be estimated in the field, measurements should be taken by inserting a gas probe through the landfill cover, to a point just beyond the bottom of the cover, and recording both the concentration of the compound and the temperature at this point in the landfill. By obtaining actual field measurements, one can estimate the average emission rate very quickly. The movement of trace gases by diffusion is considered in Example 11-3.

TABLE 11-10
Measured and saturation gas phase concentrations of 10 trace compounds

	Concentration, mg/m³		
Compounds	Maximum measured[a]	Saturation value	Scaling factor, W_i
Benzene	135.9	319,000	0.0004
Chlorobenzene	6.8	54,000	0.0001
Ethylbenzene	414.5	40,000	0.01
1,1,1-Trichlorethane	86.3	715,900	0.0001
Chloroethene	89.2	8,521,000	0.00001
Tetrachloroethene	1331.7	126,000	0.01
Trichloroethene	85.1	415,000	0.0002
Dichloromethane	871.5	1,702,000	0.0005
Trichloromethane	63.9	1,027,000	0.00001
Toluene	1150.5	110,000	0.01

[a] Measurements taken from 44 California landfills (adapted from Ref. 5).

Example 11-3 Movement of trace gases. Estimate the emission of toluene, 1,1,1-trichloroethane, and vinyl chloride from the surface of a landfill due to diffusion. Assume the following conditions apply:

1. Temperature = 30°C
2. Landfill cover material = clay-loam mixture
3. Porosity of landfill cover material = 0.20
4. Landfill cover thickness = 2 ft (0.6 m)
5. Scaling factor to account for the actual fraction of trace compound present below landfill cover = 0.001
6. *Note:* $(\text{g/cm}^2 \cdot \text{s}) \times 0.864 \times 10^9 = \text{g/m}^2 \cdot \text{d}$

Solution

1. Estimate the concentration of the compounds just below the landfill cover.

   (*a*) From Table 11-9, the saturation concentrations for these compounds are:

Toluene:	180.4 g/m³	$= 180.4 \times 10^{-6}$ g/cm³
1,1,1-Trichloroethane:	1081 g/m³	$= 1081 \times 10^{-6}$ g/cm³
Vinyl chloride:	11,090 g/m³	$= 11{,}090 \times 10^{-6}$ g/cm³

   (*b*) Estimate the concentration of the compounds just below the landfill cover, $C_{i_s}W_i$, by multiplying the saturation concentration values by the scaling factor (0.001).

Toluene:	180.4×10^{-9} g/cm³
1,1,1-Trichloroethane:	1081×10^{-9} g/cm³
Vinyl chloride:	$11{,}090 \times 10^{-9}$ g/cm³

2. Estimate the mass emission rate using Eq. (11-15) and the diffusion coefficients given in Table 11-9.

   (*a*) For toluene

$$N_i = \frac{D\alpha^{4/3}(C_{i_s}W_i)}{L}$$

$$N_i = \frac{(0.068\ \text{cm}^2/\text{s})(0.20)^{4/3}(180.4 \times 10^{-9}\ \text{g/cm}^3)}{60\ \text{cm}}$$

$$= 2.39 \times 10^{-11}\ \text{g/cm}^2 \cdot \text{s}$$

   (*b*) For 1,1,1-trichloroethane

$$N_i = \frac{(0.071\ \text{cm}^2/\text{s})(0.20)^{4/3}(1081 \times 10^{-9}\ \text{g/cm}^3)}{60\ \text{cm}} = 1.5 \times 10^{-10}\ \text{g/cm}^2 \cdot \text{s}$$

   (*c*) For vinyl chloride

$$N_i = \frac{(0.098\ \text{cm}^2/\text{s})(0.20)^{4/3}(11{,}090 \times 10^{-9}\ \text{g/cm}^3)}{60\ \text{cm}} = 2.12 \times 10^{-9}\ \text{g/cm}^2 \cdot \text{s}$$

3. Convert the mass emission rates to units of $g/m^2 \cdot d$ using the conversion factor given above.

   (*a*) For toluene

$$N_i = (2.39 \times 10^{-11}\ g/cm^2 \cdot s) \times (0.864 \times 10^9) = 0.02\ g/m^2 \cdot d$$

   (*b*) For 1,1,1-trichloroethane

$$N_i = (1.5 \times 10^{-10}\ g/cm^2 \cdot s) \times (0.864 \times 10^9) = 0.13\ g/m^2 \cdot d$$

   (*c*) For vinyl chloride

$$N_i = (2.39 \times 10^{-9}\ g/cm^2 \cdot s) \times (0.864 \times 10^9) = 2.06\ g/m^2 \cdot d$$

Comment. In general, landfill covers composed of soil(s) offer little resistance to the movement of trace organic compounds found in landfills. It is interesting to compare the mass emissions that would occur for the trace compounds in this example based on convective flow. Typical convective velocity values for the principal gases range from 1 to 15 cm/d. The corresponding convective release of toluene would then range from (1 to 15 cm/d) $\times$ 180.4 $\times 10^{-9}$ g/cm^3 $\times$ (d/86,400 s) = 0.2 to 3.1 $\times 10^{-11}$ $g/cm^2 \cdot s$. The conclusion that can be drawn from this example is that the convective transport of the trace compounds is often of less importance than their diffusive transport. To limit the release of these trace compounds, many landfill operating agencies have chosen to cover completed landfills with a flexible membrane liner.

Passive Control of Landfill Gases

The movement of landfill gases is controlled to reduce atmospheric emissions, to minimize the release of odorous emissions, to minimize subsurface gas migration, and to allow for the recovery of energy from methane. Control systems can be classified as passive or active. In passive gas control systems, the pressure of the gas that is generated within the landfill serves as the driving force for the movement of the gas. In active gas control systems, energy in the form of an induced vacuum is used to control the flow of gas. For both the principal and trace gases, passive control can be achieved during times when the principal gases are being produced at a high rate by providing paths of higher permeability to guide the gas flow in the desired direction. A gravel-packed trench, for example, can serve to channel the gas to a flared vent system. When the production of the principal gases is limited, passive controls are not very effective because molecular diffusion will be the predominant transport mechanism. However, at this stage in the life of the landfill it may not be so important to control the residual emission of the methane in the landfill gas. Control of VOC emissions may necessitate the use of both passive and active gas control facilities.

Pressure Relief Vents/Flares in Landfill Cover. One of the most common passive methods for the control of landfill gases is based on the fact that the lateral migration of landfill gas can be reduced by relieving gas pressure within the landfill interior. For this purpose, vents are installed through the final landfill cover extending down into the solid waste mass (see Fig. 11-16). If the methane

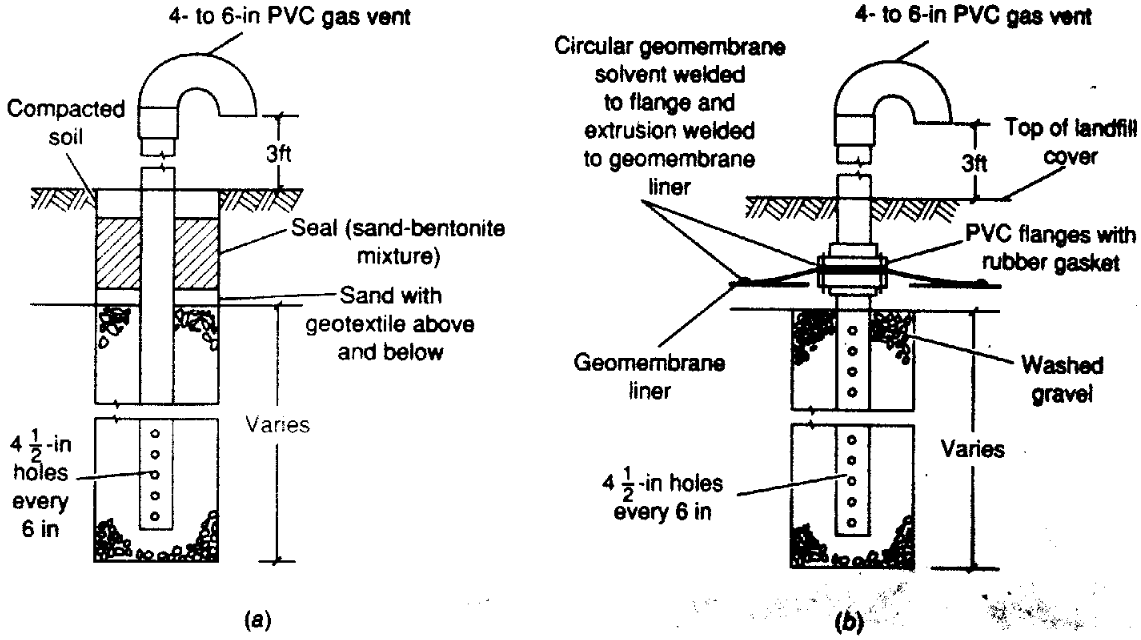


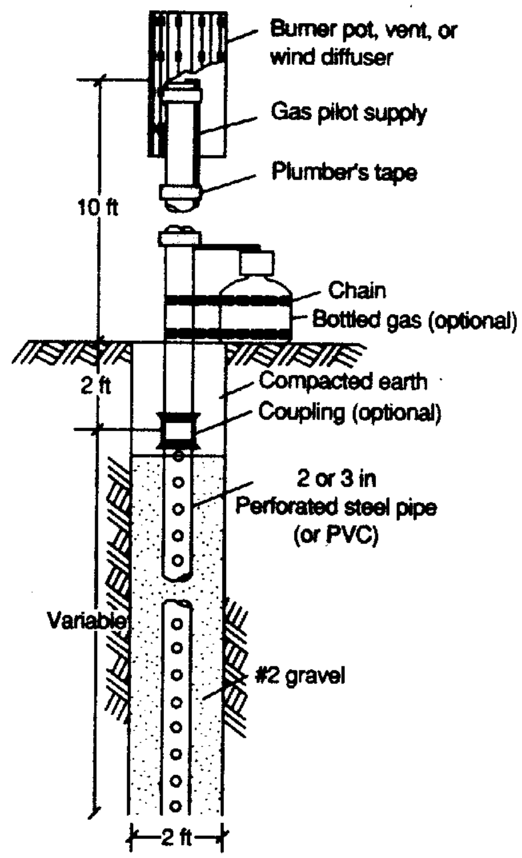
FIGURE 11-16
Typical gas vents used in the surface of a landfill for the passive control of landfill gas: (*a*) gas vent for landfill with a cover that does not contain a geomembrane liner and (*b*) gas vent for a landfill with a cover that contains a synthetic membrane liner.

in the venting gas is of sufficient concentration, several vents can be connected together and equipped with a gas burner (see Fig. 11-17*a*). Where waste gas burners are used the well should penetrate into the upper waste cells. The height of the waste burner can vary from 10 to 20 ft above the completed fill. The burner can be ignited either by hand or by a continuous pilot flame. To derive maximum benefit from the installation of a waste gas burner, a pilot flame should be used (see Fig. 11-17*b*). It should be noted, however, that passive vents with burners may not achieve the VOC and odor destruction efficiencies that are required by many urban air quality control agencies, and, thus, their use is not considered good practice. Gas burners are considered later in this section.

Perimeter Interceptor Trenches. A perimeter trench system, consisting of gravel-filled interceptor trenches containing horizontal perforated plastic pipe (typically polyvinyl chloride, PVC, or polyethylene, PE), can be used to intercept the lateral movement of landfill gases (see Fig. 11-18*a*). The perforated pipe is connected to vertical risers through which the landfill gas that collects in the trench backfill can be vented to the atmosphere. To facilitate gas collection in the trench, a membrane liner is often installed on the trench wall facing away from the landfill.

Perimeter Barrier Trench or Slurry Wall. Barrier trenches (see Fig. 11-18*b*) are usually filled with relatively impermeable materials such as bentonite or clay slurries. In this case, the trench becomes a physical barrier to lateral subsurface

(a)



(b)

FIGURE 11-17
Typical candlestick type waste gas burner used to flare landfill gas from a well vent or several interconnected well vents: (a) without pilot flame and (b) with pilot flame.

gas movement. Landfill gas is removed from the inside face of the barrier with gas extraction wells or gravel-filled trenches. However, slurry trenches may be subject to desiccation cracking when allowed to dry out, and hence are more commonly used in groundwater interception projects. The long-term effectiveness of barrier trenches for the control of the migration of landfill gases is uncertain.

Impermeable Barriers within Landfills. In modern landfills, the movement of landfill gases through adjacent soil formations is controlled by constructing barriers of materials that are more impermeable than the soil before filling operations start (see Fig. 11-18c). Some of the landfill sealants available for this use are identified in Table 11-11. In connection with the control of leachate, the use of compacted clays and geomembranes of various types singly and in multilayer configurations is most common. Because the principal gases as well as the trace gases will diffuse through clay liners, many agencies now require the use of geomembranes to limit the movement of landfill gases.

Use of Sorptive Barriers within Landfills for Trace Gases. Based on results from sampling programs such as that performed by the California Integrated Waste Management Board, it is apparent that trace gases are present in landfills in widely

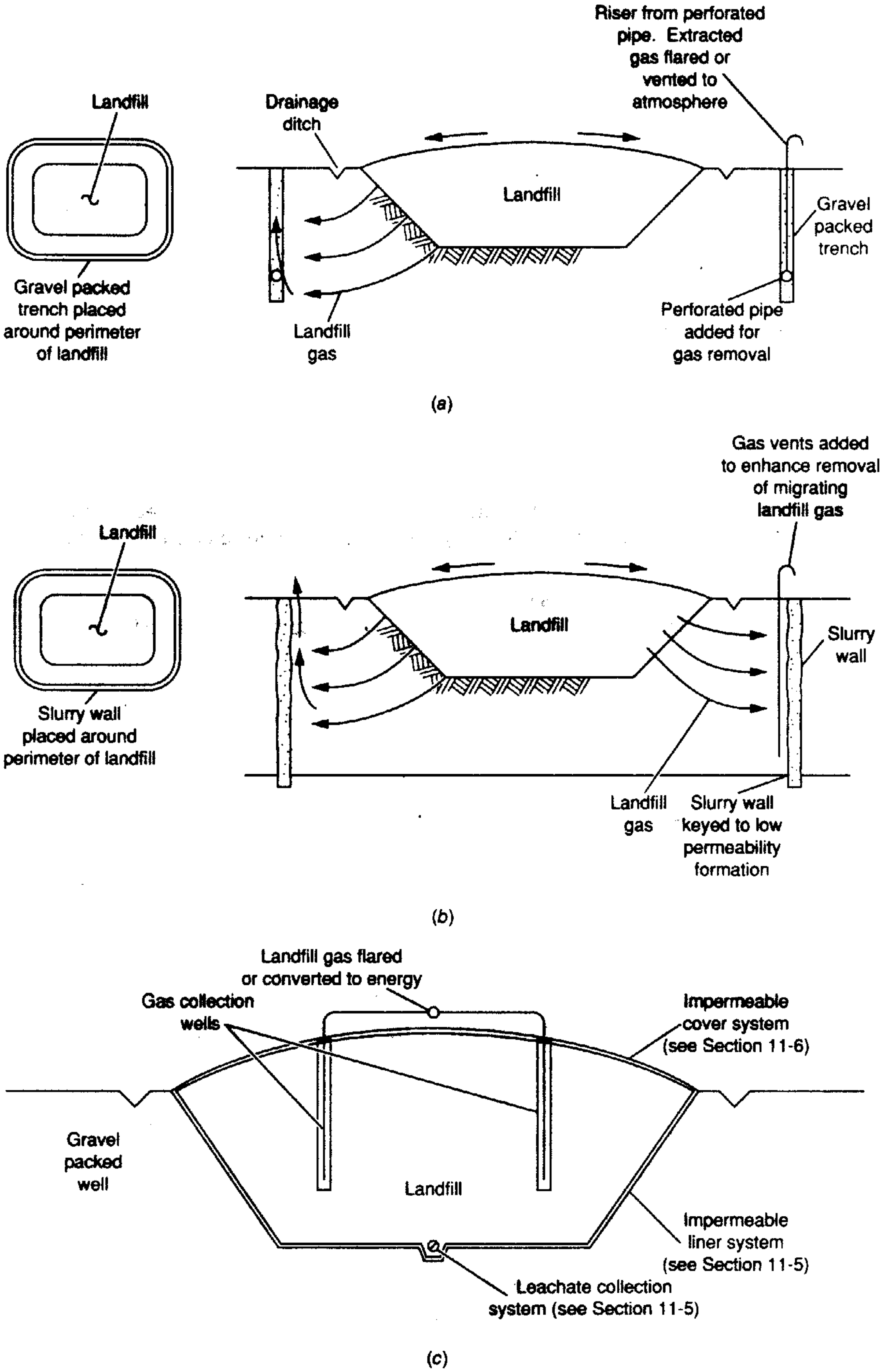


FIGURE 11-18
Passive facilities used for the control of landfill gas: (*a*) interceptor trench filled with gravel and perforated pipe, (*b*) perimeter barrier trench, and (*c*) use of impermeable liner in landfill. Note interceptor barrier perimeter trenches are used to control the off-site migration of landfill gas from existing unlined landfills.

TABLE 11-11
Landfill sealants for the control of gas and leachate movement

Sealant		
Classification	**Representative types**	**Remarks**
Compacted soil		Should contain some clay or fine silt
Compacted clay	Bentonites, illites, kaolinites	Most commonly used sealant for landfills; layer thickness varies from 6 to 48 in; layer must be continuous and not allowed to dry out and crack
Inorganic chemicals	Sodium carbonate, silicate, or pyrophosphate	Use depends on local soil characteristics
Synthetic chemicals	Polymers, rubber latex	Experimental; use in field not well established
Synthetic membrane liners	Polyvinyl chloride, butyl rubber, hypalon, polyethylene, nylon-reinforced liners	Commonly used for leachate control; increased usage for control of landfill gas
Asphalt	Modified asphalt, rubber-impregnated asphalt, asphalt-covered polyethylene fabric, asphalt concrete	Layer must be thick enough to maintain continuity under differential settling conditions
Others	Gunite concrete, soil cement, plastic soil cement	Not commonly used for control of leachate and gas movement because of shrinkage cracks after construction

varying concentrations. High concentration gradients result in a large diffusive component of the flow of trace gases, even during times when very little transport by convection from the flowing principal gas mixture is occurring. The use of sorptive material such as compost can be used to retard the release of trace gases. In turn, biotic and/or abiotic transformation mechanisms can have more time to degrade the sorbed trace compounds.

Active Control of Landfill Gas with Perimeter Facilities

The lateral movement of landfill gas can be controlled by using perimeter gas extraction wells and trenches and by creating a partial vacuum, which induces a pressure gradient toward the extraction well. The extracted gas is either flared to control the emission of methane and VOCs or used for the production of energy. The use of air injection wells is also considered in the following discussion.

Perimeter Gas Extraction and Odor Control Wells. Perimeter extraction wells (see Fig. 11-19*a*) are typically used in landfills with solid waste depths of at least 25 ft, where the distance between the landfill and off-site development is relatively

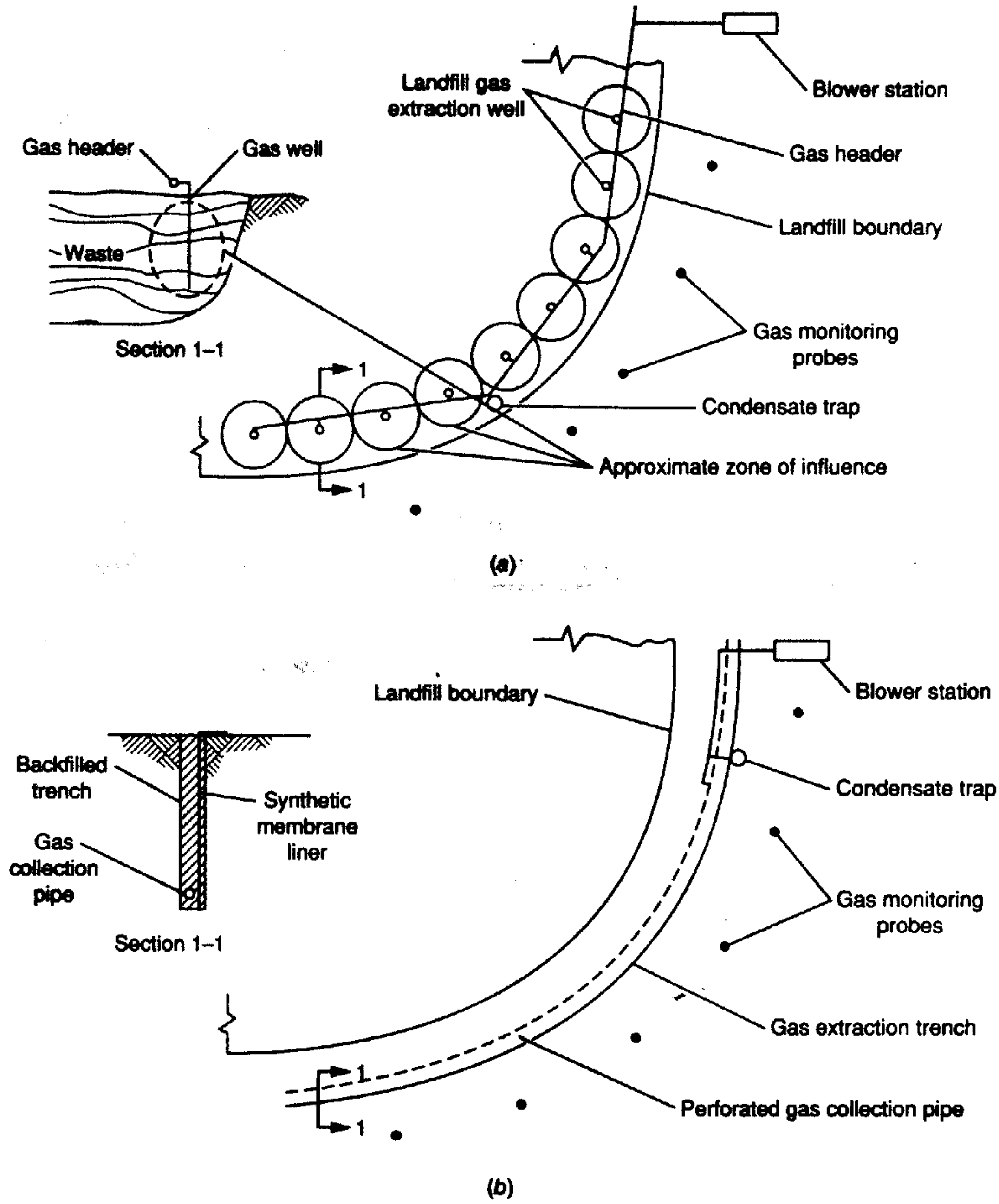


FIGURE 11-19
Active facilities used for the subsurface control of landfill gas migration: (*a*) perimeter landfill gas extraction wells and (*b*) perimeter landfill gas extraction trench.

small. They consist of a series of vertical wells installed either within the landfill along its edge or in the area between the edge of the landfill and the site boundary. The individual landfill gas extraction wells are connected by a common header pipe that in turn is connected to an electrically driven centrifugal blower, which induces a vacuum (negative pressure) in the collection header and the individual wells. When a vacuum is applied, a *zone* or *radius of influence* is created that extends into the solid waste mass surrounding each well and within which the gas that is generated is drawn to the well. Extracted landfill gas is usually vented or flared, under controlled conditions, at the blower station. The extracted gas can also be utilized as an energy source if the amount of gas that can be collected is of sufficient quantity and quality.

The typical extraction well design consists of a 4- to 6-in pipe casing (often PVC or PE) set in an 18- to 36-in borehole (see Fig. 11-20). The bottom one third to one half of the casing is perforated and set in a gravel backfill. The remaining length of the casing is not perforated and is set in soil (preferable) or solid waste backfill [44]. Wells are spaced such that their radii of influence overlap. Unlike water wells, the radius of influence for vertical wells is essentially a sphere extending in all directions from the extraction well (see Fig. 11-19*a*). For this reason, care must be taken to avoid *overpulling* on the system. Excessive extraction rates can cause air to infiltrate into the solid waste mass from the adjacent soil. To prevent the intrusion of air, the gas flow rate from each well

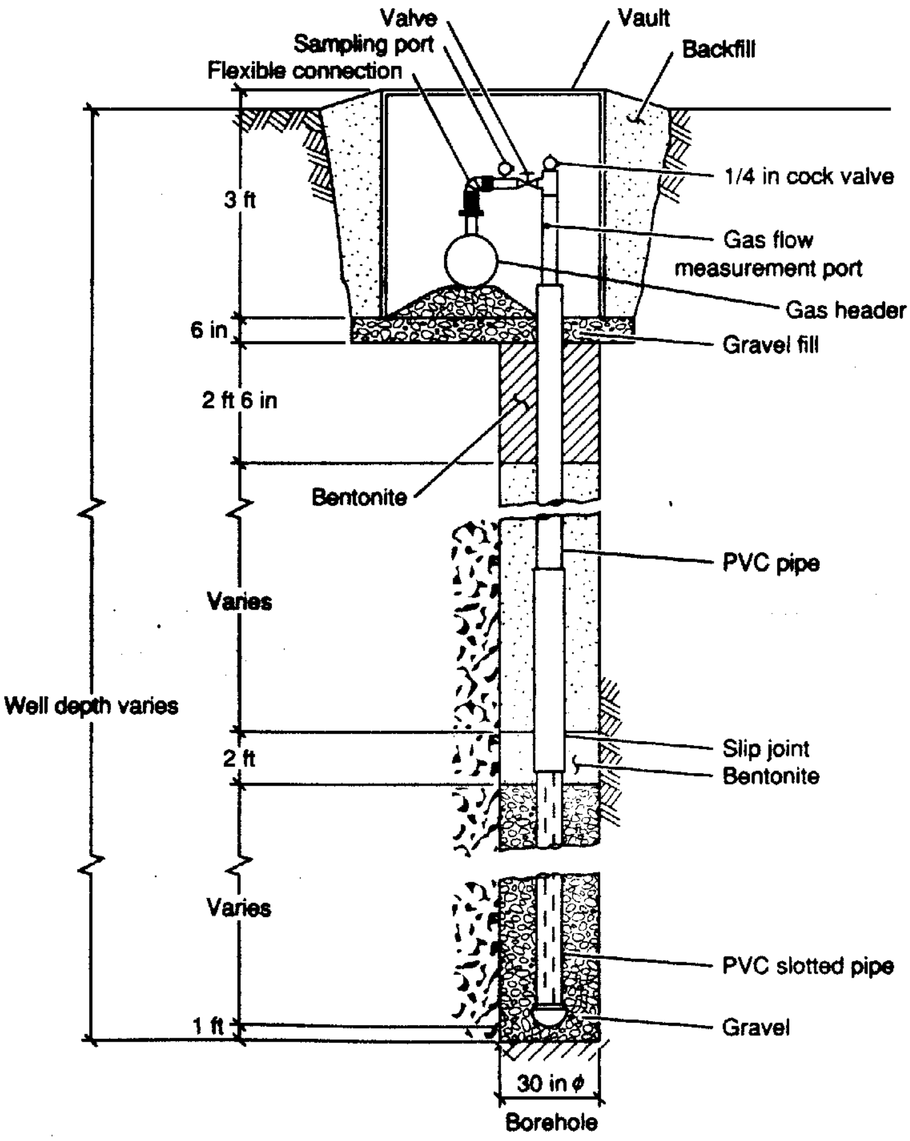


FIGURE 11-20
Representative detail of a landfill gas extraction well. (Courtesy of California Integrated Waste Management Board.)

must be controlled carefully. For this purpose, extraction wells are equipped with gas sampling ports and flow control valves. Depending on the depth of the landfill and other local conditions, well spacing for perimeter gas extraction wells will vary from 25 to 50 ft, although larger spacings have been used.

In large landfills, vertical perimeter wells are also used in conjunction with larger horizontal and vertical gas extraction wells located in the interior of the landfill. The vertical perimeter wells are used to control the off-site migration of landfill gases from the edges and faces of the landfill. Where the perimeter wells are used for the control of odorous emissions from the surfaces of the landfill, the surfaces of the landfill are maintained at a slight vacuum.

Perimeter Gas Extraction Trenches. Perimeter extraction trenches (see Fig. 11-19*b*) are usually installed in native soil adjacent to the landfill perimeter. They are typically used for shallow landfill disposal sites with depths of 25 feet or less. The trenches are gravel-filled and contain perforated plastic pipes that are connected through laterals to a collection header and centrifugal suction blower. Extraction trenches can extend vertically down from the landfill surface to the depth of the solid waste or to groundwater and can be further sealed on the surface with a membrane liner. The suction blower creates a zone of negative pressure in each trench, which extends toward the solid waste. Landfill gas migrating into this zone is drawn into the perforated pipe and collection header, and subsequently vented or flared at the blower station. Flow adjustments can be made via control valves at each trench.

Perimeter Air Injection Wells (Air Curtain System). Perimeter air injection wells consist of a series of vertical wells installed in natural soils between the limits of the solid waste landfill and the facilities to be protected against the intrusion of landfill gas. Air injection wells are typically installed near landfills with solid waste depths of 20 ft or more in areas of undisturbed soil between the landfill and the potentially affected properties.

Active Control of Landfill Gas with Vertical and Horizontal Gas Extraction Wells

Both vertical and horizontal gas wells have been used for the extraction of landfill gas from within landfills. In some installations both types of wells have been used. The management of the condensate that forms when landfill gas is extracted is also an important element in the design of gas recovery systems.

Vertical Gas Extraction Wells. A typical gas recovery system using vertical gas extraction wells is illustrated in Fig. 11-21. The wells are spaced so that their radii of influence overlap (see Fig. 11-22). For completed landfills without gas recovery facilities, the radius of influence for gas wells is sometimes determined by conducting gas drawdown tests in the field. Typically, an extraction well is installed along with gas probes at regular distances from the well, and the vacuum within the landfill is measured as a vacuum is applied to the extraction well. Both

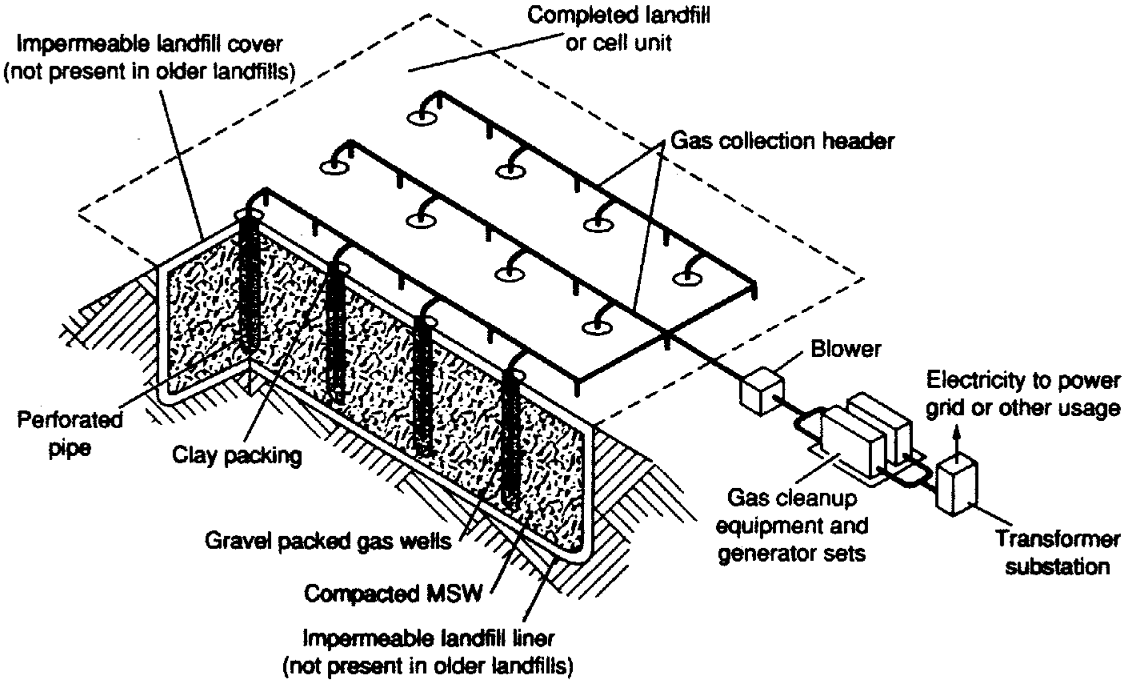


FIGURE 11-21
Landfill gas recovery system using vertical wells.

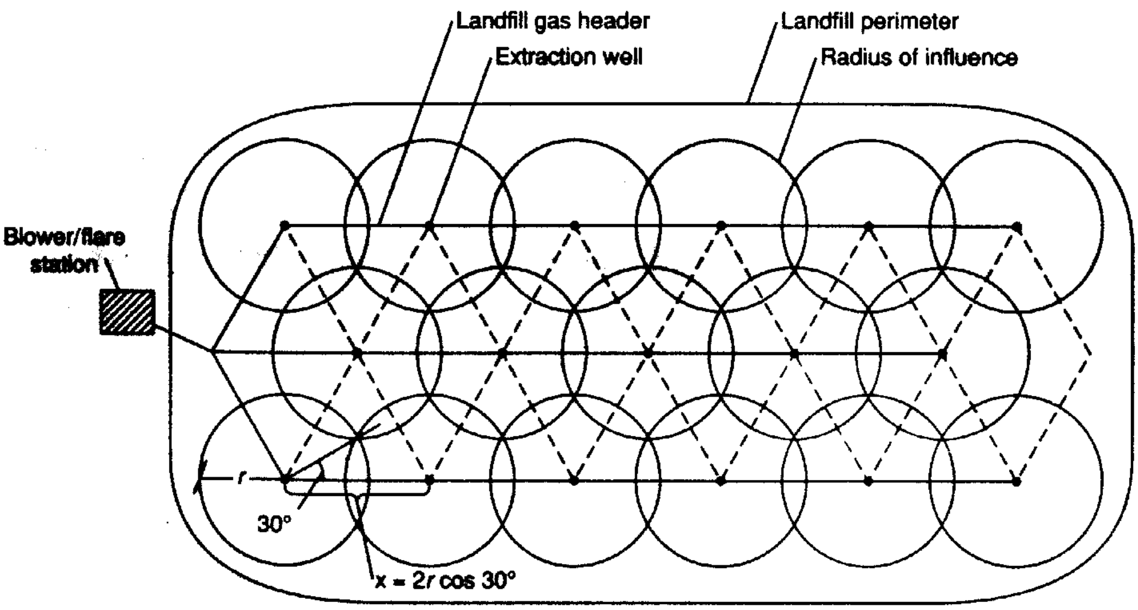


FIGURE 11-22
Equilateral triangular distribution for vertical gas extraction wells. (Courtesy of California Integrated Waste Management Board.)

short-term and long-term extraction tests can be conducted. Because the volume of gas produced will diminish with time, some designers prefer to use a uniform well spacing and to control the radius of influence of the well by adjusting the vacuum at the wellhead. Since the radius of influence of a vertical gas extraction well is essentially a sphere, the radius of influence will also depend on the depth of the landfill and on the design of the landfill cover. For deep landfills with a composite cover containing a geomembrane (see Section 11-6) a 150- to 200-ft spacing is common for landfill gas extraction wells. In landfills with clay and/or soil covers, a closer spacing (e.g., 100 ft) may be required to avoid pulling atmospheric gases into the gas recovery system.

Vertical gas extraction wells are usually installed after the landfill or portions of the landfill have been completed. In older landfills, vertical wells are installed both to recover energy and to control the movement of gases to adjacent properties. The typical extraction well design consists of 4- to 6-in pipe casing (usually PVC or PE) set in an 18- to 36-in borehole (see Fig. 11-20). The bottom third to one half of the casing is perforated and set in a gravel backfill. The remaining length of the casing is not perforated and is backfilled with soil and sealed with a clay [44]. Landfill gas recovery wells are typically designed to penetrate to 80 percent of the depth of the waste in the landfill, because their radii of influence will extend to the bottom of the landfill. However, to allay the public's fear concerning the escape of landfill gas, some designers now place gas recovery wells all the way to the bottom of the landfill. The available vacuum in the collection manifold at the well head is typically 10 in of water. The design of gas recovery facilities used in conjunction with the gas recovery wells is considered in Example 11-9 in Section 11-12.

Horizontal Gas Extraction Wells. An alternative to the use of vertical gas recovery wells is the use of horizontal wells. This usage was pioneered and developed by the County Sanitation Districts of Los Angeles County (see Figs. 11-23 and 11-24). The use of vertical perimeter wells in conjunction with horizontal gas extraction wells is also illustrated in Figs. 11-23 and 11-24. Horizontal wells are installed after two or more lifts have been completed (see Fig. 11-4). The horizontal gas extraction trench is excavated in the solid waste using a backhoe. The trench is then backfilled halfway with gravel and a perforated pipe with open joints is installed (see Fig. 11-25). The trench is then filled with gravel and capped with solid waste. By using a gravel-filled trench and a perforated pipe with open joints, the gas extraction trench remains functional even with the differential settling that will occur in the landfill with the passage of time. The horizontal trenches are installed at approximately 80 ft vertical intervals and at 200 ft horizontal intervals [45].

Management of Condensate in Gas Recovery Systems. Condensate forms when the warm landfill gas is cooled as it is transported in the header leading to the blower. Gas collection headers are usually installed with a minimum slope of 3 percent to allow for differential settlement. Because headers are constructed in

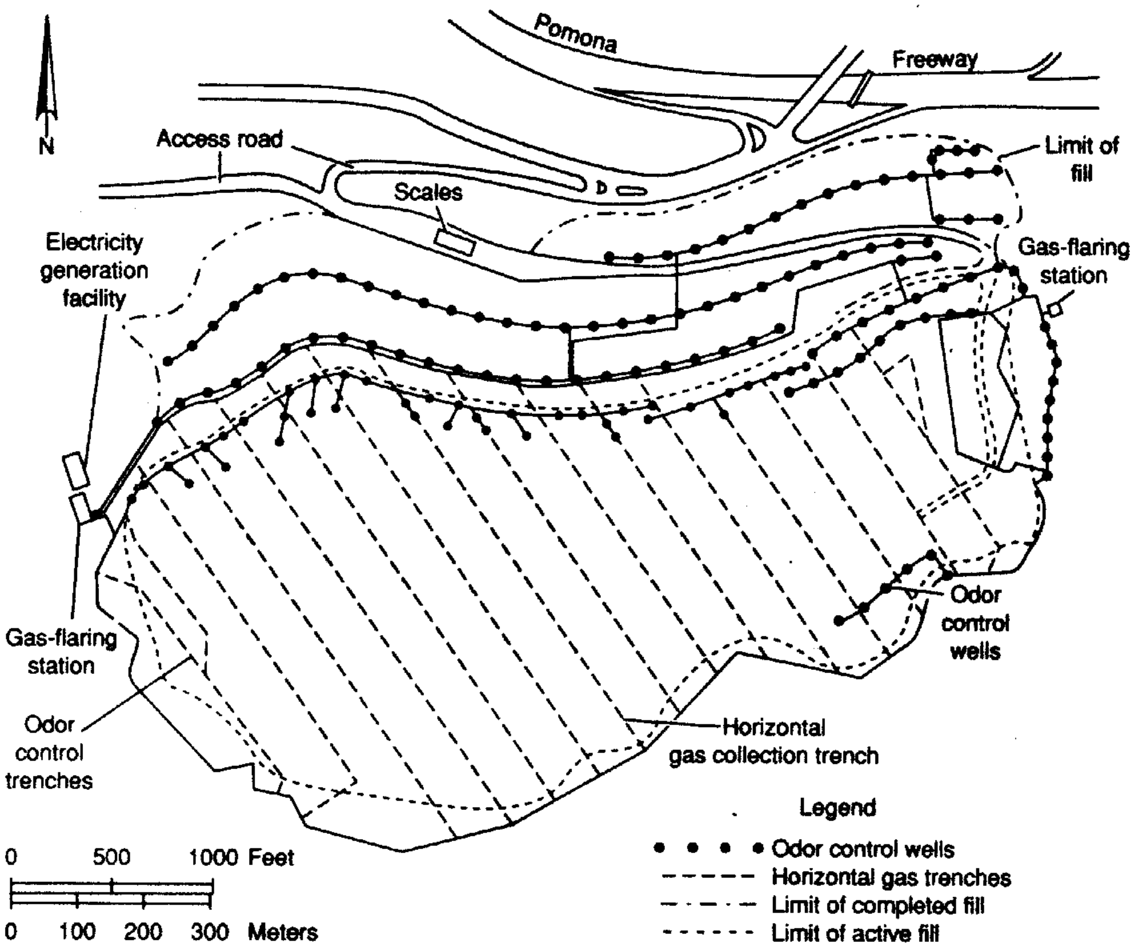


FIGURE 11-23
Plan view of gas collection facilities Puente Hills landfill. (Courtesy of County Sanitation Districts of Los Angeles County.)

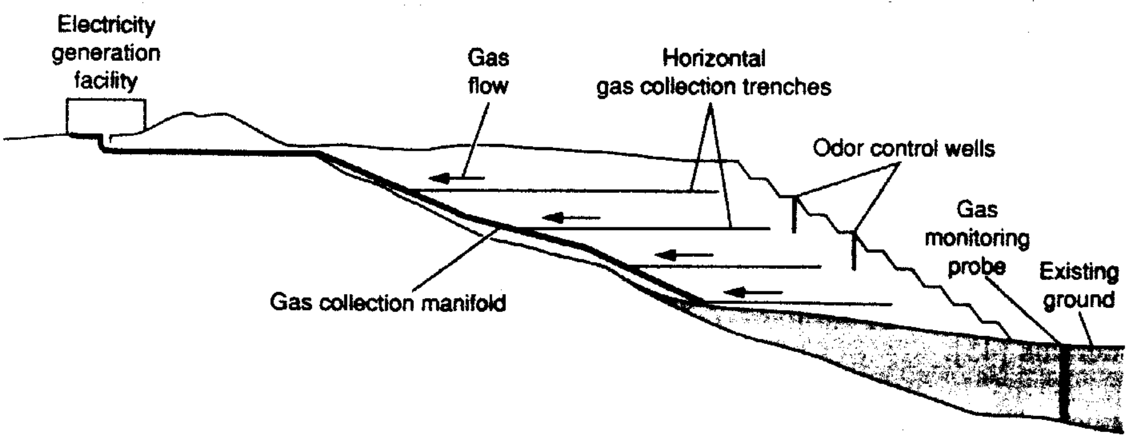


FIGURE 11-24
Sectional view through Puente Hills landfill showing horizontal gas collection trenches. (Courtesy of County Sanitation Districts of Los Angeles County.)

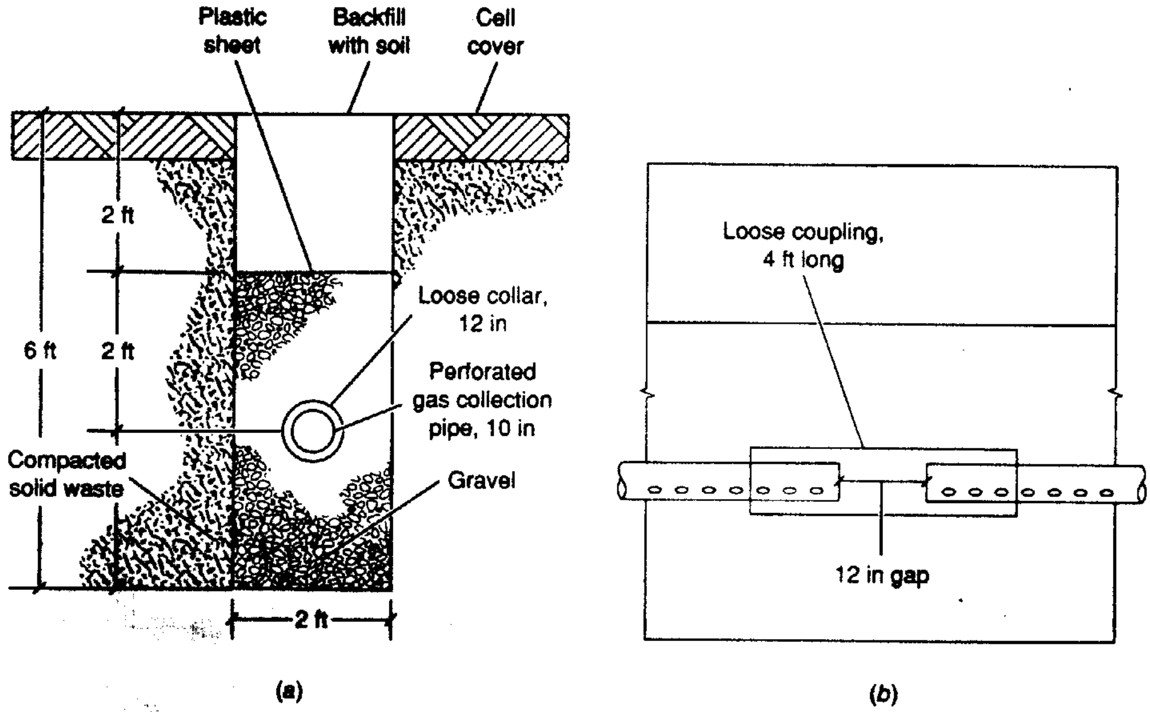


FIGURE 11-25
Details of horizontal gas extraction trench: (*a*) section through trench and (*b*) side view. (Courtesy of County Sanitation Districts of Los Angeles County.)

sections that slope up and down throughout the extent of the landfill, condensate traps are installed at low spots in the line (see Fig. 11-19*a*). A typical condensate trap in which the condensate is returned to the landfill is shown in Fig. 11-26*a*. In states where returning the condensate to the landfill is not allowed, the condensate traps are connected to holding tanks (see Fig. 11-26*b*). Condensate from the holding tanks is pumped out periodically and either transported to an authorized disposal facility or treated on-site before disposal or discharge to a local sewer. Computation of the volume of condensate formed is illustrated in Example 11-10 in Section 11-12.

Management of Landfill Gas

Typically, landfill gases that have been recovered from an active landfill are either flared or used for the recovery of energy in the form of electricity, or both. More recently, the separation of the carbon dioxide from the methane in landfill gas has been suggested as an alternative to the production of heat and electricity.

Flaring of Landfill Gases. A common method of treatment for landfill gases is thermal destruction; that is, methane and any other trace gases (including VOCs) are combusted in the presence of oxygen (contained in air) to carbon dioxide (CO_2), sulfur dioxide (SO_2), oxides of nitrogen, and other related gases. The thermal destruction of landfill gases is usually accomplished in a specially designed flaring facility (see Figs. 11-27 and 11-28). Because of concerns over air

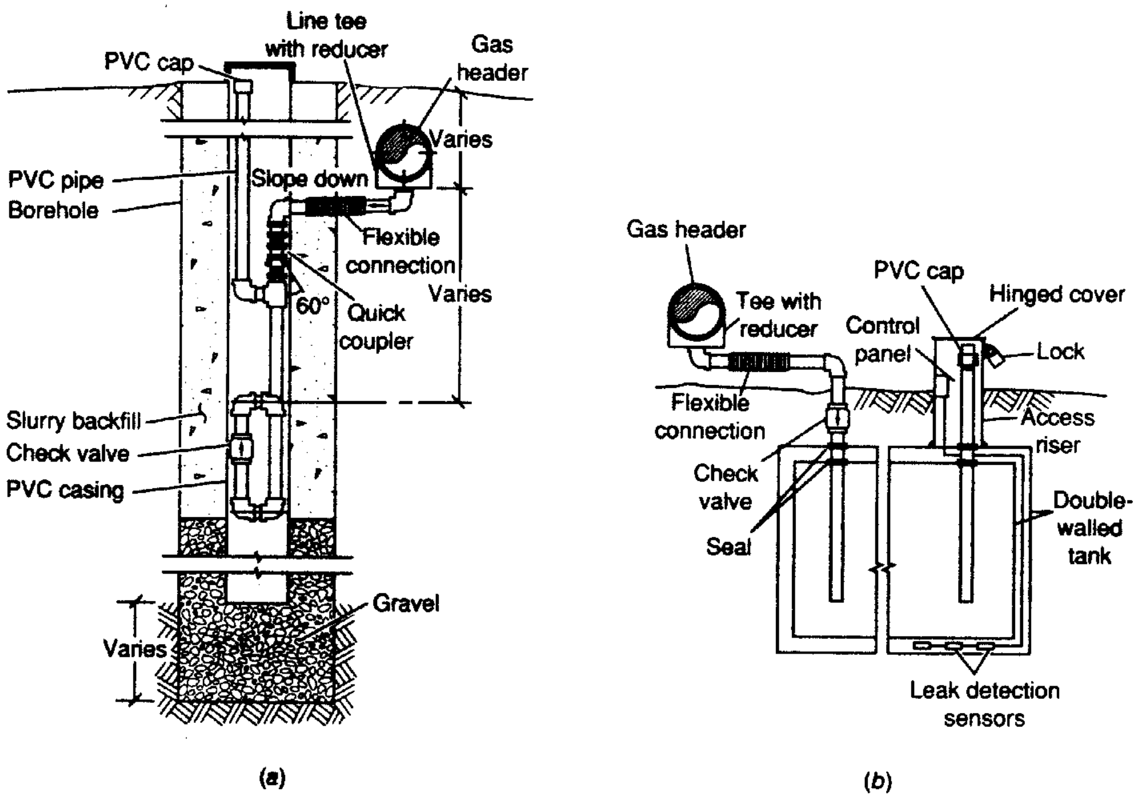


FIGURE 11-26
Typical condensate traps: (*a*) liquid is returned to landfill (courtesy of California Integrated Waste Management Board) and (*b*) liquid is stored in holding tank.

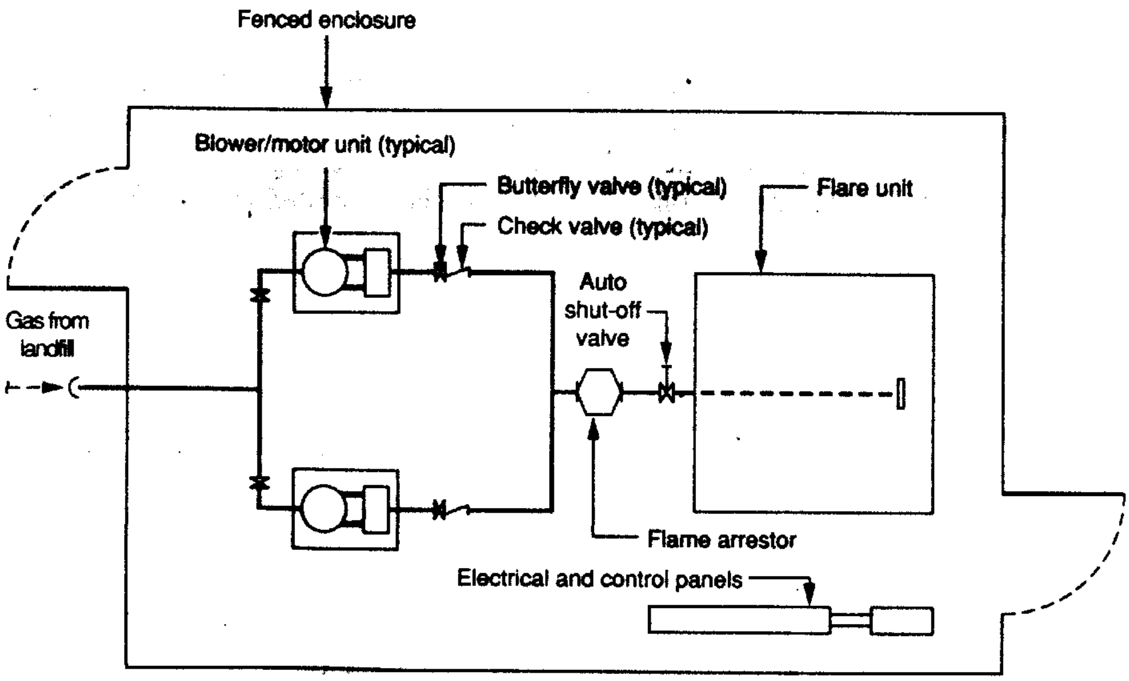


FIGURE 11-27
Schematic layout of blower/flare station for the flaring of landfill gas. (Courtesy of California Integrated Waste Management Board.)

FIGURE 11-28
View of large array of ground effects flares used to flare landfill gas.

pollution, modern flaring facilities are designed to meet rigorous operating specifications to ensure effective destruction of VOCs and other similar compounds that may be present in the landfill gas. For example, a typical requirement might be a minimum combustion temperature of 1500°F and a residence time of 0.3 to 0.5 s, along with a variety of controls and instrumentation in the flaring station. Typical requirements for a modern flaring facility are summarized in Table 11-12.

TABLE 11-12
Important design elements for enclosed ground-level landfill gas flares[a]

Item	Comments
Temperature indicator and recorder	Used to measure and record gas temperature in the flare stack. Whenever the flare is in operation, a temperature of 1500°F or greater must be maintained in the stack as measured by the temperature indicator 0.3 s after passing through the burner.
Automatic pilot restart system	To ensure continuous operation
Failure alarm with an automatic isolation system	The alarm and isolation system are used to isolate the flare from the landfill gas supply line, shut off the blower, and notify a responsible party of the shutdown.
Automatically controlled combustion air louvers	Used to control the amount of combustion air and the temperature of the flame
Source test ports with adequate and safe access provided	Test ports used for monitoring the combustion process and for sampling air emissions.
View ports	A sufficient number of view ports must be available to allow visual inspection of the temperature sensor location within the flare.
Heat shield	A heat shield should be provided around the top of the flare shroud for use during source testing.

[a] Adapted from Ref. 44.

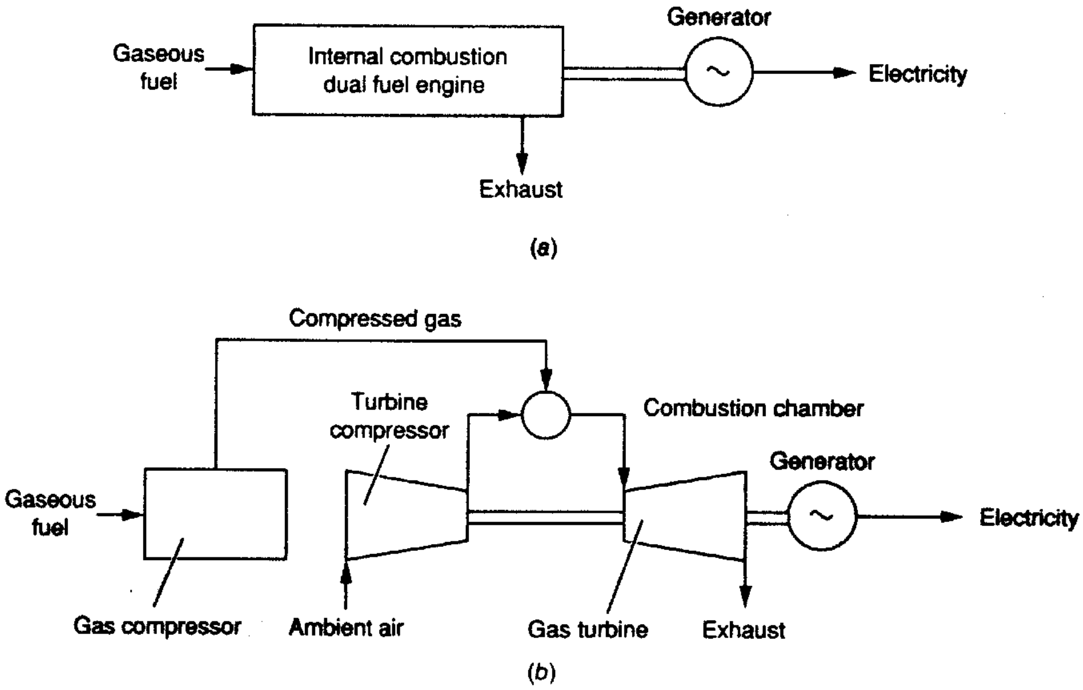


FIGURE 11-29
Schematic flow diagrams for the recovery of energy from gaseous fuels: (*a*) using internal combustion engine and (*b*) using a gas turbine.

Landfill Gas Energy Recovery Systems. Landfill gas is usually converted to electricity (see Figs. 11-29 and 11-30). In smaller installations (up to 5 MW), it is common to use dual fuel internal combustion piston engines (see Figs. 11-29*a* and 11-30*a*) or gas turbines (see Fig 11-29*b*). In larger installations, the use of steam turbines is common (see Fig. 11-30*b*). Where piston-type engines are used, the landfill gas must be processed to remove as much moisture as possible so as

(*a*) (*b*)

FIGURE 11-30
Views of gas conversion facilities: (*a*) using dual fuel internal combustion piston engines and (*b*) using boilers and a steam turbine (see also Fig. 13-25*a*).

to limit damage to the cylinder heads. If the gas contains H_2S, the combustion temperature must be controlled carefully to avoid corrosion problems. Alternatively, the landfill gas can be passed through a scrubber containing iron shavings, or through other proprietary scrubbing devices, to remove the H_2S before the gas is combusted.

Combustion temperatures will also be critical where the landfill gas contains VOCs released from wastes placed in the landfill before the disposal of hazardous waste in municipal landfills was banned. The typical service cycle for dual fuel engines running on landfill gas varies from 3000 to 10,000 hours before the engine must be overhauled. In Fig. 11-30*a*, low-Btu landfill gas is compressed under high pressure so that it can be used more effectively in the gas turbine. The typical service cycle for gas turbines running on landfill gas is approximately 10,000 hours.

Gas Purification and Recovery. Where there is a potential use for the CO_2 contained in the landfill gas, the CH_4 and CO_2 in landfill gas can be separated. The separation of the CO_2 from the CH_4 can be accomplished by physical adsorption, chemical adsorption, and by membrane separation. In physical and chemical adsorption, one component is adsorbed preferentially using a suitable solvent. Membrane separation involves the use of a semipermeable membrane to remove the CO_2 from the CH_4. Semipermeable membranes have been developed that allow CO_2, H_2S, and H_2O to pass while CH_4 is retained. Membranes are available as flat sheets or as hollow fibers. To increase efficiency of separation, the flat sheets are spiral wound on a support medium while the hollow fibers are grouped together in bundles.

11-5 COMPOSITION, FORMATION, MOVEMENT, AND CONTROL OF LEACHATE IN LANDFILLS

Leachate may be defined as liquid that has percolated through solid waste and has extracted dissolved or suspended materials. In most landfills leachate is composed of the liquid that has entered the landfill from external sources, such as surface drainage, rainfall, groundwater, and water from underground springs and the liquid produced from the decomposition of the wastes, if any. The composition, formation, movement, and control of leachate are considered in this section.

Composition of Leachate

When water percolates through solid wastes that are undergoing decomposition, both biological materials and chemical constituents are leached into solution. Representative data on the characteristics of leachate are reported in Table 11-13 for both new and mature landfills. Because the range of the observed concentration values for the various constituents reported in Table 11-13 is rather large, especially for new landfills, great care should be exercised in using the typical values that are given. Typical physical, chemical, and biological monitoring parameters that are used to characterize leachate are summarized in Table 11-14.

TABLE 11-13
Typical data on the composition of leachate from new and mature landfills[a]

Constituent	Value, mg/L[b] New landfill (less than 2 years) Range[c]	Typical[d]	Mature landfill (greater than 10 years)
BOD_5 (5-day biochemical oxygen demand)	2,000–30,000	10,000	100–200
TOC (total organic carbon)	1,500–20,000	6,000	80–160
COD (chemical oxygen demand)	3,000–60,000	18,000	100–500
Total suspended solids	200–2,000	500	100–400
Organic nitrogen	10–800	200	80–120
Ammonia nitrogen	10–800	200	20–40
Nitrate	5–40	25	5–10
Total phosphorus	5–100	30	5–10
Ortho phosphorus	4–80	20	4–8
Alkalinity as $CaCO_3$	1,000–10,000	3,000	200–1,000
pH	4.5–7.5	6	6.6–7.5
Total hardness as $CaCO_3$	300–10,000	3,500	200–500
Calcium	200–3,000	1,000	100–400
Magnesium	50–1,500	250	50–200
Potassium	200–1,000	300	50–400
Sodium	200–2,500	500	100–200
Chloride	200–3,000	500	100–400
Sulfate	50–1,000	300	20–50
Total iron	50–1,200	60	20–200

[a] Developed from Refs. 2, 8, 9, 11, 39, 46.

[b] Except pH, which has no units.

[c] Representative range of values. Higher maximum values have been reported in the literature for some of the constituents.

[d] Typical values for new landfills will vary with the metabolic state of the landfill.

Variations in Leachate Composition. Note that the chemical composition of leachate will vary greatly depending on the age of landfill and the events preceding the time of sampling. For example, if a leachate sample is collected during the acid phase of decomposition (see Fig. 11-11), the pH value will be low and the concentrations of BOD_5, TOC, COD, nutrients, and heavy metals will be high. If, on the other hand, a leachate sample is collected during the methane fermentation phase (see Fig. 11-11), the pH will be in the range from 6.5 to 7.5, and the BOD_5, TOC, COD, and nutrient concentration values will be significantly lower. Similarly the concentrations of heavy metals will be lower because most metals are less soluble at neutral pH values. The pH of the leachate will depend not only on the concentration of the acids that are present but also on the partial pressure of the CO_2 in the landfill gas that is in contact with the leachate. The effect of the CO_2 in the landfill gas is illustrated in Example 11-4 below.

The biodegradability of the leachate will vary with time. Changes in the biodegradability of the leachate can be monitored by checking the BOD_5/COD

TABLE 11-14
Leachate sampling parameters[a]

Physical	Organic constituents	Inorganic constituents	Biological
Appearance	Organic chemicals	Suspended solids (SS), total dissolved solids (TDS)	Biochemical oxygen demand (BOD)
pH	Phenols	Volatile suspended solids (VSS), volatile dissolved solids (VDS)	Coliform bacteria (total; fecal; fecal streptococci)
Oxidation-reduction potential	Chemical oxygen demand (COD)	Chloride	Standard plate count
Conductivity	Total organic carbon (TOC)	Sulfate	
Color	Volatile acids	Phosphate	
Turbidity	Tannins, lignins	Alkalinity and acidity	
Temperature	Organic-N	Nitrate-N	
Odor	Ether soluble (oil and grease)	Nitrite-N	
	Methylene blue active substances (MBAS)	Ammonia-N	
	Organic functional groups as required	Sodium	
	Chlorinated hydrocarbons	Potassium	
		Calcium	
		Magnesium	
		Hardness	
		Heavy metals (Pb, Cu, Ni, Cr, Zn, Cd, Fe, Mn, Hg, Ba, Ag)	
		Arsenic	
		Cyanide	
		Fluoride	
		Selenium	

[a] Adapted from Ref. 44.

ratio. Initially, the ratios will be in the range of 0.5 or greater. Ratios in the range of 0.4 to 0.6 are taken as an indication that the organic matter in the leachate is readily biodegradable. In mature landfills, the BOD_5/COD ratio is often in the range of 0.05 to 0.2. The ratio drops because leachate from mature landfills typically contains humic and fulvic acids, which are not readily biodegradable.

As a result of the variability in leachate characteristics, the design of leachate treatment systems is complicated. For example, a treatment plant designed to treat a leachate with the characteristics reported for a new landfill would be quite different from one designed to treat the leachate from a mature landfill. The problem of interpreting the analytical results is complicated further by the fact that the leachate that is being generated at any point in time is a mixture of leachate derived from solid waste of different ages.

Trace Compounds. The presence of trace compounds (some of which may pose health risks) in leachate will depend on the concentration of these compounds in the gas phase within the landfill. The expected concentrations can be estimated using Henry's law as given in Appendix F and the Henry's law constants given in Table 5-8. As more communities and operators of landfills institute programs to limit the disposal of hazardous wastes with MSW, the quality of the leachate from new landfills is improving with respect to the presence of trace constituents.

Example 11-4 Estimate the pH of the leachate in contact with landfill gas. Assume the composition of the landfill gas in contact with the leachate is 50 percent carbon dioxide and 50 percent methane, the landfill gas is saturated with water vapor at a temperature of 50°C (122°F), and the pressure within the landfill is atmospheric. The alkalinity of the leachate is 500 mg/L.

Solution

1. From Appendix F, the saturation concentration of carbon dioxide for the stated conditions is given as 379 mg/L.
2. Determine the pH of the leachate using the first dissociation constant for carbonic acid as given in Appendix G.

$$\frac{[H^+][HCO_3^-]}{[H_2CO_3^*]} = K_1$$

where $[H^+]$ = molar concentration of the hydrogen ion, mol/L
$[HCO_3^-]$ = molar concentration of the bicarbonate ion, mol/L
$[H_2CO_3^*]$ = molar concentration of carbonic acid, mol/L
$[H_2CO_3^*] = [CO_{2,aq}] + [H_2CO_3]$

For all practical purposes it can be assumed that the computed concentration value of $CO_{2,aq}$ is equal to the term $[H_2CO_3^*]$ and that at the pH values encountered in landfills all of the alkalinity is due to the bicarbonate ion, thus,

(*a*) The molar concentrations of HCO_3^- and $H_2CO_3^*$ are

$$[HCO_3^-] = \frac{500 \text{ mg/L}}{50{,}000 \text{ mg/mol}} = 0.01 \text{ mol/L}$$

$$[H_2CO_3^*] \approx [CO_2] = \frac{379 \text{ mg/L}}{44{,}000 \text{ mg/mol}} = 0.00861 \text{ mol/L}$$

(*b*) Compute the pH of the leachate. The value of first dissociation constant, K_1, at 50°C as given in Appendix G is 5.07×10^{-7}

$$\frac{[H^+][0.01]}{[0.00861]} = 5.07 \times 10^{-7}$$

$$[H^+] = 4.37 \times 10^{-7}$$

$$\text{pH} = 6.36$$

Water Balance and Leachate Generation in Landfills

The potential for the formation of leachate can be assessed by preparing a water balance on the landfill [14]. The water balance involves summing the amounts of water entering the landfill and subtracting the amounts of water consumed in chemical reactions and the quantity leaving as water vapor. The potential leachate quantity is the quantity of water in excess of the moisture-holding capacity of the landfill material.

Description of Water Balance Components for a Landfill Cell. The components that make up the water balance for a landfill cell are identified in Fig. 11-31. The principal sources include the water entering the landfill cell from above, the moisture in the solid waste, the moisture in the cover material, and the moisture in the sludge, if the disposal of sludge is allowed. The principal sinks are the water leaving the landfill as part of the landfill gas (i.e., water used in the formation of the gas), as saturated water vapor in the landfill gas, and as leachate. Each of these components is considered below.

Water entering from above. For the upper layer of the landfill, the water from above corresponds to the precipitation that has percolated through the cover material. For the layers below the upper layer, water from above corresponds to the water that has percolated through the solid waste above the layer in question. One of the most critical aspects in the preparation of a water balance for a landfill

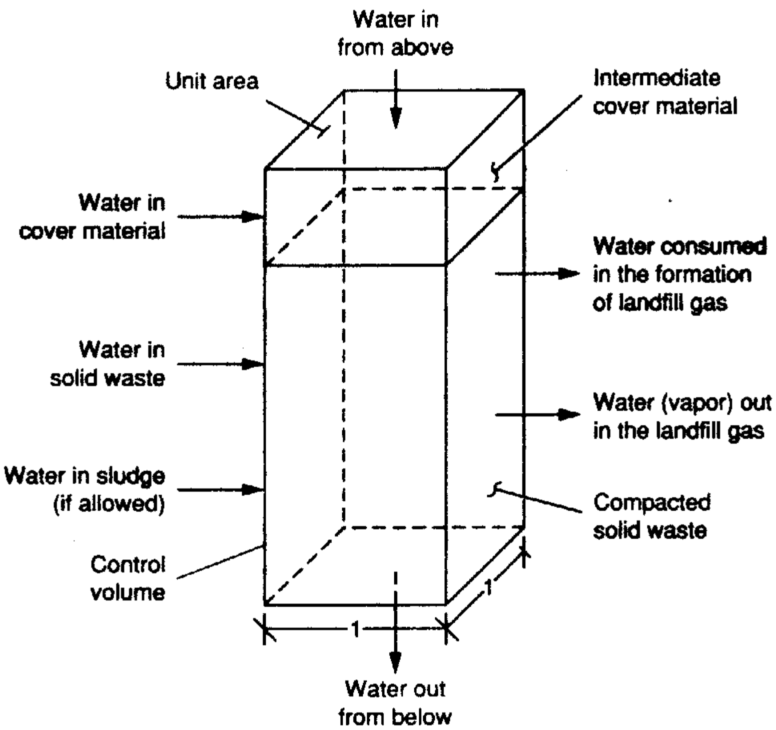


FIGURE 11-31
Definition sketch for water balance used to assess leachate formation in a landfill.

is to determine the amount of the rainfall that actually percolates through the landfill cover layer. Where a geomembrane is not used, the amount of rainfall that percolates through the landfill cover can be determined using the Hydrologic Evaluation of Landfill Performance (HELP) model [41, 42]. A simplified method for estimating the amount of percolation that can be expected is presented in Section 11-6.

Water entering in solid waste. Water entering the landfill with the waste materials is that moisture inherent in the waste material as well as moisture that has been absorbed from the atmosphere or from rainfall (where the storage containers are not sealed properly). In dry climates, some of the inherent moisture contained in the waste can be lost, depending on the conditions of the storage. The moisture content of residential and commercial MSW is about 20 percent, as reported in Table 4-1. However, because of the variability of the moisture content during the wet and dry seasons, it may be necessary to conduct a series of tests during the wet and dry periods.

Water entering in cover material. The amount of water entering with the cover material will depend on the type and source of the cover material and the season of the year. The maximum amount of moisture that can be contained in the cover material is defined by the field capacity (FC) of the material, that is, the liquid which remains in the pore space subject to the pull of gravity. Typical values for soils range from 6–12 percent for sand to 23–31 percent for clay loams. The FC of soils is considered further in Section 11-6 in connection with the storage of water in landfill covers.

Water leaving from below. Water leaving from the bottom of the *first* cell of the landfill is termed *leachate*. As noted previously, water leaving the bottom of the second and subsequent cells corresponds to the water entering from above for the cell below the cell in question. In landfills where intermediate leachate collection systems are used, water leaving from the bottom of the cell placed directly over the intermediate leachate collection system is also termed leachate.

Water consumed in the formation of landfill gas. Water is consumed during the anaerobic decomposition of the organic constituents in MSW. The amount of water consumed by the decomposition reactions can be estimated using the formula for the rapidly decomposable material developed in Example 11-2. The mass of water taken up per pound of dry organic waste consumed can be estimated as follows:

$$\underset{1741.0}{C_{68}H_{111}O_{50}N} + \underset{288.0}{16H_2O} \rightarrow \underset{560.0}{35CH_4} + \underset{1452.0}{33CO_2} + \underset{17}{NH_3}$$

The mass of water consumed per pound of dry rapidly biodegradable volatile solids (RBVS) destroyed is

$$\text{Water consumed} = \frac{288.0}{1741.0} = 0.165 \text{ lb } H_2O/\text{lb RBVS destroyed}$$

Using a gas production value of 13.9 ft^3/lb RBVS destroyed (from Example 11-2), the corresponding value for the amount of water consumed per cubic foot of gas produced is

$$\text{Water consumed} = \frac{(0.165 \text{ lb } H_2O/\text{lb RBVS destroyed})}{(13.9 \text{ ft}^3/\text{lb RBVS destroyed})} = 0.0119 \text{ lb } H_2O/\text{ft}^3$$

Water lost as water vapor. Landfill gas usually is saturated in water vapor. The quantity of water vapor escaping the landfill is determined by assuming the landfill gas is saturated with water vapor and applying the perfect gas law as follows:

$$p_v V = nRT \tag{11-16}$$

where p_v = vapor pressure of H_2O at temperature T, lb/in^2 (see Appendix B)
V = volume, ft^3
n = number of pound moles
R = universal gas constant = 1543 ft · lb/(lb · mole) · °R
T = temperature, degrees Rankine = (460 + T, °F) = °R

The numerical value for the mass of water vapor contained per cubic foot of landfill gas at 90°F is obtained as follows:

p_v = 0.70 lb/in^2 = 100.8 lb/ft^2 (see Appendix B)

V = 1.0 ft^3

n = number of pound moles

R = universal gas constant = 1543 ft · lb/(lb · mole) · °R

T = (460 + 90) = 550°R

$$n = \frac{(p_v)(V)}{RT} = \frac{(100.8)(1.0)}{(1543)(550)} = 0.00012 \text{ lb} \cdot \text{moles}$$

$$= (0.00012 \text{ lb} \cdot \text{mole})(18 \text{ lb/lb} \cdot \text{mole}) = 0.0022 \text{ lb } H_2O/\text{ft}^3 \text{ landfill gas}$$

Other water losses and gains. There will be some loss of moisture to evaporation as the waste is being landfilled. The amounts are not large and are often ignored. The decision to include these variables in the water balance analysis will depend on local conditions.

Landfill Field Capacity. Water entering the landfill that is not consumed and does not exit as water vapor may be held within the landfill or may appear as leachate. Both the waste material and the cover material are capable of holding water against the pull of gravity. The quantity of water that can be held against the pull of gravity is referred to as field capacity. The potential quantity of leachate is the amount of moisture within the landfill in excess of the landfill FC. The FC, which varies with the overburden weight, can be estimated using the following equation [21, 22]:

$$FC = 0.6 - 0.55\left(\frac{W}{10{,}000 + W}\right) \qquad (11\text{-}17)$$

where FC = field capacity (i.e., the fraction of water in the waste based on the dry weight of the waste)
W = overburden weight calculated at the midheight of the waste in the lift in question

The application of Eq. (11-17) is illustrated in Example 11-11 in Section 11-12.

Preparation of Landfill Water Balance. The terms that compose the water balance can be put into equation form as follows:

$$\Delta S_{SW} = W_{SW} + W_{TS} + W_{CM} + W_{A(R)} - W_{LG} - W_{WV} - W_E + W_{B(L)} \qquad (11\text{-}18)$$

where ΔS_{SW} = change in the amount of water stored in solid waste in landfill, lb/yd^3
W_{SW} = water (moisture) in incoming solid waste, lb/yd^3
W_{TS} = water (moisture) in incoming treatment plant sludge, lb/yd^3
W_{CM} = water (moisture) in cover material, lb/yd^3
$W_{A(R)}$ = water from above (for upper landfill layer, water from above corresponds to rainfall or water from snowfall), lb/yd^2
W_{LG} = water lost in the formation of landfill gas, lb/yd^3
W_{WV} = water lost as saturated water vapor with landfill gas, lb/yd^3
W_E = water lost due to surface evaporation, lb/yd^2
$W_{B(L)}$ = water leaving from bottom of element (for the cell placed directly above a leachate collection system, water from bottom corresponds to leachate), lb/yd^2

The landfill water balance is prepared by adding the mass of water entering a unit area of a particular layer of the landfill during a given time increment to the moisture content of that layer at the end of the previous time increment, and subtracting the mass of water lost from the layer during the current time increment. The result is referred to as the available water in the current time increment for the particular layer of the landfill. To determine whether any leachate will form, the field capacity of landfill is compared with the amount of water that is present. If the field capacity is less than the amount of water present, then leachate will be formed.

In general, the quantity of leachate is a direct function of the amount of external water entering the landfill. In fact, if a landfill is constructed properly, the production of measurable quantities of leachate can be eliminated. When wastewater treatment plant sludge is added to solid wastes to increase the amount of methane produced, leachate control facilities must be provided. In some cases leachate treatment facilities may also be required.

Movement of Leachate in Unlined Landfills

Under normal conditions, leachate is found in the bottom of landfills. From there its movement in unlined landfills is downward through the underlying strata, although some lateral movement may also occur, depending on the characteristics of the surrounding material. Because of the importance of vertical seepage in the contamination of groundwater, this subject is considered further in the following discussion.

Darcy's Law. The rate of seepage of leachate from the bottom of a landfill can be estimated using Darcy's law, which can be expressed as follows [10]:

$$Q = -KA\frac{dh}{dl} \tag{11-19}$$

where Q = leachate discharge per unit time, gal/yr
K = coefficient of permeability, gal/ft^2 · yr
A = cross-sectional area through which the leachate flows, ft^2
dh/dl = hydraulic gradient, ft/ft
h = head loss, ft
l = length of flow path, ft

The minus sign in Darcy's law arises from the fact that the head loss, dh, is always negative. The coefficient of permeability is also known as the hydraulic conductivity, the effective permeability, or the seepage coefficient. In U.S. customary units, the coefficient of permeability is expressed in gallons per day per square foot, or feet per day. The conversion between these factors is accomplished by noting that 7.48 gal/ft^2 · yr = 1 ft/yr. Typical values for the permeability coefficient for various soils are given in Table 11-15.

Estimation of Vertical Seepage of Leachate. Before Darcy's law is applied to the estimation of seepage rates from a landfill, it is helpful to review the physical

TABLE 11-15
Typical permeability coefficients for various soils[a]

	Coefficient of permeability, K	
Material	**ft/d**	**gal/ft^2 · d**
Uniform coarse sand	1333	9970
Uniform medium sand	333	2490
Clean, well-graded sand and gravel	333	2490
Uniform fine sand	13.3	100
Well-graded silty sand and gravel	1.3	9.7
Silty sand	0.3	2.2
Uniform silt	0.16	1.2
Sandy clay	0.016	0.12
Silty clay	0.003	0.022
Clay (30 to 50 percent clay sizes)	0.0003	0.0022
Colloidal clay	0.000003	0.000022

[a] Adapted from Refs. 10 and 40 and based on laminar flow.

Note: ft/d × 0.3048 = m/d
gal/ft^2 · d × 0.0408 = m^3/m^2 · d

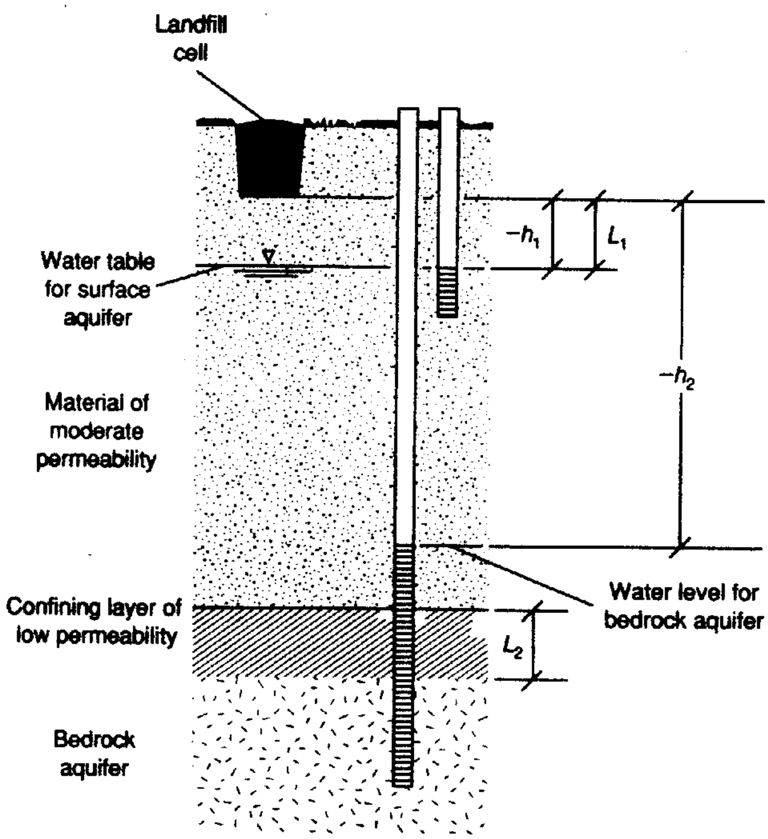


FIGURE 11-32
Definition sketch for determination of seepage from landfills and from surface to subsurface aquifers.

conditions of the problem by referring to Fig. 11-32. There, a landfill cell has been placed in a surface aquifer, composed of material of moderate permeability, that overlies a bedrock aquifer. In this situation, it is possible to have two different piezometric water surfaces if wells are placed in the surface and bedrock aquifers. With respect to the movement of leachate, two problems are of interest. The first is the rate at which leachate seeps from the bottom of the landfill into the groundwater in the surface aquifer. The second is the rate at which groundwater from the surface aquifer moves into the bedrock aquifer. These two problems are considered in the following analysis, but the question of how the mixing of the leachate and groundwater occurs in the surface aquifer is beyond the scope of this text.

In the first problem, the leachate flow rate from the landfill to the upper groundwater is computed by assuming that the material below the landfill to the top of the water table is saturated and that a small layer of leachate exists at the bottom of the fill. Under these conditions the application of Darcy's equation is as follows:

$$Q(\text{gal/yr}) = -K(\text{gal/ft}^2 \cdot \text{yr}) \times A(\text{ft}^2)\frac{-h_1(\text{ft})}{L_1(\text{ft})} \qquad (11\text{-}20)$$

but because $h_1 = L_1$,

$$Q(\text{gal/yr}) = K(\text{gal/ft}^2 \cdot \text{yr}) \times A(\text{ft}^2)$$

If one assumes that flow occurs through 1.0 ft^2, then

$$Q(\text{gal/yr}) = K(\text{gal/ft}^2 \cdot \text{yr})(\text{ft}^2) \tag{11-21}$$

Thus, the leachate discharge rate per unit area is equal to the value of K multiplied by square feet. For example, if the upper stratum of material in Fig. 11-32 were sandy clay, the corresponding seepage rate would be 0.12 gal/ft^2 · d (see Table 11-15). The computed value represents the maximum amount of seepage that would be expected, and this value should be used for design purposes. Under normal conditions, the actual rate would be less than this value because the soil column below the landfill would not be saturated. Also, most of the leachate reaching the bottom of the landfill would have been removed in the leachate collection system.

In the second problem, the rate of movement of water from the upper aquifer to the lower aquifer would be given by Eq. (11-20). In this case, the thickness of the confining layer is used to determine the hydraulic gradient.

Hydraulic Equivalency. In some states the concept of hydraulic equivalency is used to assess alternative liner designs. Three equivalent liner configurations are illustrated in Fig. 11-33. If Dàrcy's law is applied to the first configuration, the flow rate per unit area is equal to 2.67 K. Applying Darcy's law to the remaining two liner configurations yields the same result. From this analysis one can see that the water level maintained within the landfill is an important design consideration.

Breakthrough Time. The breakthrough time in years for leachate to penetrate a clay liner of a given thickness can be estimated using the following equation:

$$t = \frac{d^2\alpha}{K(d + h)} \tag{11-22}$$

where t = breakthrough time, yr
d = thickness of clay liner, ft

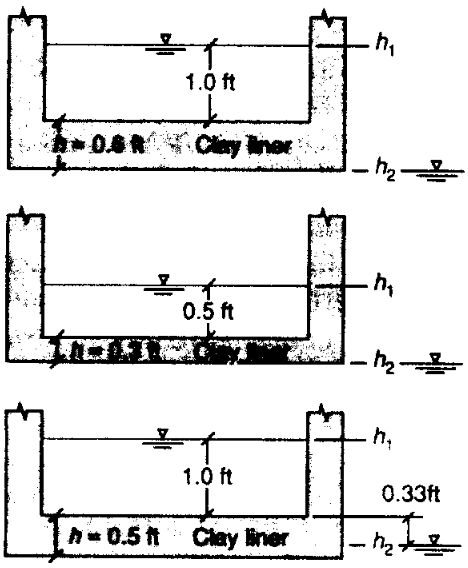


FIGURE 11-33
Definition sketch for assessing the equivalency of landfill liners. (Note that the discharge through each liner configuration is the same.)

α = effective porosity
K = coefficient of permeability, ft/yr
h = hydraulic head, ft

Typical effective porosity values for clays with a coefficient of permeability in the range from 10^{-6} to 10^{-8} cm/s will vary from 0.1 to 0.3, depending on the specific type of clay.

Fate of Constituents in Leachate in Subsurface Migration

The major concern with the movement of leachate into the subsurface aquifer below unlined and lined landfills is the fate of the constituents found in leachate. Mechanisms that are operative in the attenuation of the constituents found in leachate as the leachate migrates through the subsurface soil include mechanical filtration, precipitation and coprecipitation, sorption (including ion exchange), gaseous exchange, dilution and dispersion, and microbial activity [2, 29, 36]. The fate of heavy metals and trace organics, the two constituents of greatest interest, is considered in the following discussion.

Heavy Metals. In general, heavy metals are removed by ion exchange reactions as leachate travels through the soil while trace organics are removed primarily by adsorption. The ability of a soil to retain the heavy metals found in leachate is a function of the cation exchange capacity (CEC) of the soil. The uptake and release of positively charged ions by a soil is referred to as cation, or base, exchange. The total CEC of a soil is defined as the number of milliequivalents (meq) of cations that 100 grams of soil will adsorb. The CEC of a soil depends on the amount of mineral and organic colloidal matter present in the soil matrix. Typical CEC values, at a pH value of 7, are 100 to 200 meq/100 g for organic colloids, 40 to 80 meq/100 g for 2:1 clays (montmorillonite minerals), and 5 to 20 meq/100 g for 1:1 clays (kaolinite minerals). The reported CEC values are affected by the pH of the solution; they drop to about 10 percent of the given values at a pH value of 4. As noted previously, the presence of carbon dioxide in the bottom of a landfill will tend to lower the pH of the leachate [36].

The capacity of a clay landfill liner to take up heavy metals can be estimated as follows. Assume the CEC of the liner material is 100 meq/100 g. If the density of the clay material used in the liner is 137 lb/ft^3 (specific gravity equals 2.2), then about 3000 meq of cations can be adsorbed per cubic foot of liner material. Using a typical value of 20 mg/meq for the heavy metals, the amount of metal that could be adsorbed per cubic foot is equal to 60 g. If the concentration of heavy metals in the leachate was 100 mg/L, the heavy metals could be removed from about 600 L of leachate. If the permeability of the clay is equal to 1×10^{-7} cm/s, then 2.83 L would pass through 1 ft^2 each year. At this rate of percolation, it would take 212 years to saturate the original ft^3 of clay. If the amount of leachate allowed to percolate through the liner were limited to one tenth of that value by designing the leachate collection system properly, then the time required to

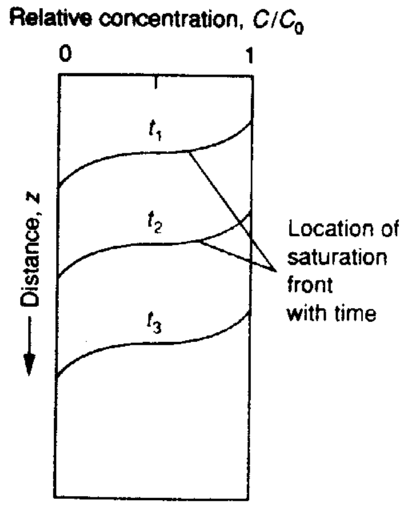


FIGURE 11-34
Typical movement of heavy metals saturation front in clay liner.

saturate the ft^3 of clay would be approximately 2000 years. Even with all of the simplifying assumptions that went into the above analysis, it can be concluded that with a properly designed landfill cover and clay liner, heavy metals should not pose a problem. The saturation front for a typical heavy metal with time can be depicted as shown in Fig. 11-34.

Trace Organics. Adsorption is the most common way in which the organic constituents in leachate are removed as it moves through a porous medium. If hydrodynamic dispersion is neglected, the materials balance for a contaminant subject to adsorption in a groundwater aquifer is given by the following modified form of Eq. (11-4):

$$\frac{\partial S}{\partial t}\frac{\rho_b}{\alpha} + \frac{\partial C}{\partial t} = -v_z\frac{\partial C}{\partial z} \tag{11-23}$$

where S = mass of solute sorbed per unit mass of dry soil, g/g
ρ_b = bulk density of soil, g/m^3
α = porosity
C = concentration of contaminant in the liquid phase, g/m^3
v_z = average fluid velocity in z direction, m/s

The mass of material sorbed per unit mass of dry soil is related to the concentration of the contaminant in the liquid phase and the soil distribution coefficient, as described in the following equation:

$$S = K_{SD} \times C \tag{11-24}$$

where K_{SD} = soil distribution coefficient, m^3/g

Note that Eq. (11-24) describes linear sorption. For some of the organic compounds found in landfills, the sorption may be nonlinear. Differentiating Eq. (11-24) with respect to time and substituting $(K_{SD})\partial C/\partial t$ for $\partial s/\partial t$ in Eq. (11-23) yields

$$-v_z\frac{\partial C}{\partial z} = \left(1 + \frac{\rho_b}{\alpha}K_{SD}\right)\frac{\partial C}{\partial t} \tag{11-25}$$

Where the partitioning of the contaminant between the soil and the groundwater can be described adequately by the soil distribution coefficient K_{SD}, the retardation of the contaminant front relative to the liquid can be described with the following relationship:

$$R = \frac{v_z}{v_{zc}} = \left(1 + \frac{\rho_b}{\alpha} K_{SD}\right) \tag{11-26}$$

where R = retardation factor, unitless
v_z = average velocity of groundwater, m/s
v_{zc} = average velocity of the $C/C_o = 0.5$ point of the retarded contaminant concentration profile, m/s

If it is assumed that α for most soils varies from 0.2 to 0.4 and that the corresponding values for ρ_b are approximately 1.6 to 2.1×10^6 g/m^3, then Eq. (11-26) can be written as follows:

$$R = \frac{v_z}{v_{zc}} = (1 + 4 \times 10^6 K_{SD}) \text{ to } (1 + 10 \times 10^6 K_{SD}) \tag{11-27}$$

If K_{SD} equals zero, the contaminant is nonreactive and no retardation occurs (see Fig. 11-35). If K_{SD} is greater than about 10^{-4} the contaminant is essentially immobile. The value of K_{SD} can be estimated by using the following expression:

$$K_{SD} = 6.3 \times 10^{-7} f_{OC}(K_{OW}) \tag{11-28}$$

where f_{OC} = fraction of organic carbon in the soil, g/g
K_{OW} = octanol:water distribution coefficient

Values for K_{OW} for various organic compounds are given in Appendix H.

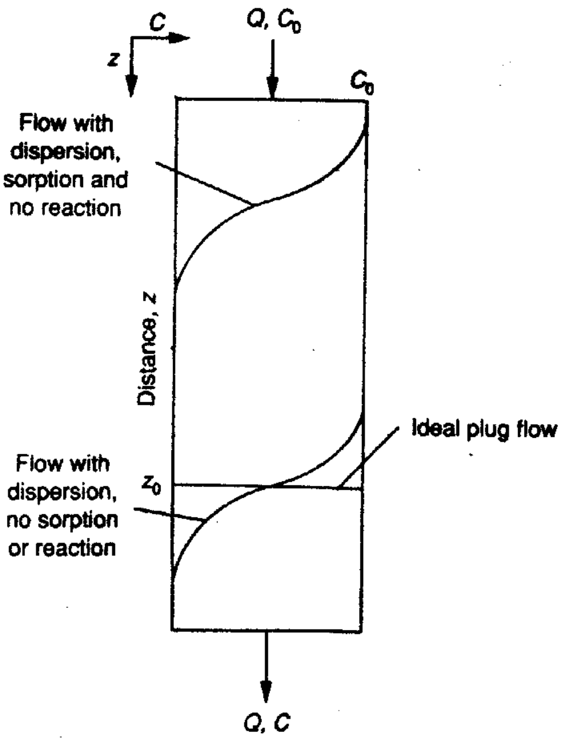


FIGURE 11-35
Typical retardation of trace organic compounds in subsurface movement.

Retardation of the organic constituents found in leachate is important because the retained material can be subjected to biological and chemical conversion reactions, in some cases rendering the retained material harmless.

Control of Leachate in Landfills

As leachate percolates through the underlying strata, many of the chemical and biological constituents originally contained in it will be removed by the filtering and adsorptive action of the material composing the strata. In general, the extent of this action depends on the characteristics of the soil, especially the clay content. Because of the potential risk involved in allowing leachate to percolate to the groundwater, best practice calls for its elimination or containment.

Landfill liners are now commonly used to limit or eliminate the movement of leachate and landfill gases from the landfill site. To date (1992), the use of clay as a liner material has been the favored method of reducing or eliminating the seepage (percolation) of leachate from landfills (see Table 11-11). Clay is favored for its ability to adsorb and retain many of the chemical constituents found in leachate and for its resistance to the flow of leachate. However, the use of combination composite geomembrane and clay liners is gaining in popularity, especially because of the resistance afforded by geomembranes to the movement of both leachate and landfill gases. The characteristics, advantages, and disadvantages of the geomembranes liners (also known as flexible membrane liners, FMLs) that have been used for MSW landfills are summarized in Table 11-16. Typical specifications for geomembrane liners are given in Table 11-17.

Liner Systems for MSW. The objective in the design of landfill liners is to minimize the infiltration of leachate into the subsurface soils below the landfill thus eliminating the potential for groundwater contamination. A number of liner designs have been developed to minimize the movement of leachate into the subsurface below the landfill. Some of the many types of liner designs that have been used are illustrated in Fig. 11-36. In the multilayer landfill liner designs illustrated in Fig. 11-36, each of the various layers has a specific function. For example, in Fig. 11-36*a* the clay layer and the geomembrane serve as a composite barrier to the movement of leachate and landfill gas. The sand or gravel layer serves as a collection and drainage layer for any leachate that may be generated within the landfill. The geotextile layer is used to minimize the intermixing of the soil and sand or gravel layers. The final soil layer is used to protect the drainage and barrier layers. A modification of the liner design shown in Fig. 11-36*a* involves the installation of leachate collection pipes in the leachate collection layer. Composite liner designs employing a geomembrane and clay layer provide more protection and are hydraulically more effective than either type of liner alone.

In Fig. 11-36*b*, a specifically designed open weave plastic mesh (geonet) and geotextile filter cloth (see Fig. 11-37*a*) are placed over the geomembrane which, in turn, is placed over compacted clay layer. A protective soil layer is placed above the geotextile. The geonet and the geotextile function together as the drainage

TABLE 11-16
Guidelines for leachate control facilities

Item	Comments
Synthetic flexible membrane liners (FMLs)	Liners must be designed and constructed to contain fluids, which include wastes and leachates. For MSW waste management units, synthetic liners are not required. However, if this alternative is selected, synthetic liners must have a minimum thickness of 40 mils. These liners must be installed to cover all natural geologic materials that are likely to be in contact with waste or leachate at a waste management unit.
Bottom seals	No specific regulations exist governing the application of bottom seals at MSW waste management units. Design, construction, and installation of bottom seals are subject to the approval of the local enforcement agencies.
Artificial earthen liners	Clay liners are optional for MSW landfills. If required by site conditions, clay liners for MSW waste management units must be a minimum of 1 ft thick and must be installed at a relative compaction of at least 90 percent. A clay liner must exhibit a maximum permeability of 1×10^{-6} cm/s. Clay liners, if installed, must cover all natural geologic materials that are likely to be in contact with waste or leachate at a waste management unit.
Subsurface barriers	A subsurface barrier is intended to be used in conjunction with natural geologic materials to assure that lateral permeability standards are satisified. Barriers may be required by regional agencies at MSW waste management units where there is potential for lateral movement of fluid, including waste and leachate, and the permeability of natural geologic materials is used for waste containment in lieu of a liner. Barriers must be a minimum of 2 ft thick for clay material or a minimum of 40 mils for synthetic materials. These structures are required to be keyed a minimum of 5 ft into natural geologic materials that satisfy permeability requirements of 1×10^{-6} to 1×10^{-7} cm/s. If cutoff walls are used, excavations for waste management units must also be keyed into natural geologic materials exhibiting permeabilities of no greater than 1×10^{-6} cm/s. Barriers are required to have fluid collection systems upgradient of the structure. The systems must be designed, constructed, operated, and maintained to prevent the buildup of hydraulic head against the structure. The collection system must be inspected regularly and accumulated fluid removed.

layer to convey leachate to the leachate collection system. The permeability of the liner system that is composed of a drainage layer and a filter layer is equivalent to that of coarse sand (see Table 11-15). Because of the potential for the geotextile filter cloth to clog, many designers favor the use of a sand or gravel layer as the drainage layer.

In the liner system shown in Fig. 11-36*c*, two composite liners, commonly identified as the primary and secondary composite liners, are used. The

TABLE 11-17
Performance tests used to measure properties of synthetic geomembrane liners and typical values for these properties[a]

Test	Test method	Typical values
Strength category		
Tensile properties	ASTM D638, Type IV; dumbbell 2 in/min	
Tensile strength at yield		2400 lb/in^2
Tensile strength at break		4000 lb/in^2
Elongation at yield		15%
Elongation at break		700%
Toughness		
Tear resistance initiation	ASTM D1004 die C	45 lb
Puncture resistance	FTMS 101B, method 2031	230 lb
Low temperature brittleness	ASTM D746, procedure B	−94°F
Durability		
Carbon black percent	ASTM D1603	2%
Carbon black dispersion	ASTM D3015	A-1
Accelerated heat aging	ASTM D 573, D1349	Negligible strength change after 1 month at 110°C
Chemical resistance		
Resistance to chemical waste mixtures	EPA method 9090	10% tensile strength change over 120 days
Resistance to pure chemical reagents	ASTM D543	10% tensile strength change over 7 days
Stress cracking resistance		
Environmental stress crack resistance	ASTM D1693, condition C	1500 h

[a] Adapted from Refs. 2, 52.

primary composite liner is used for the collection of leachate, whereas the secondary composite liner serves as a leak-detection system and a backup for the primary composite liner. A modification of the liner system shown in Fig. 11-36*c*, involves replacing the sand drainage layer with a geonet drainage system as shown in Fig. 11-35*b*. The two-layer composite liner shown in Fig. 11-35*d* is the same as the liner shown in Fig. 11-36*c*, with the exception that the clay layer below the first geomembrane liner is replaced with a geosynthetic clay liner (GCL). A manufactured product, the GCL is made from a high-quality bentonite clay (from Wyoming) and an appropriate binding material (see Fig. 11-37*b*). The bentonite clay is essentially a sodium montmorillonite mineral that has the capacity to absorb as much as 10 times its weight in water. As the clay absorbs water, it becomes putty-like and very resistant to the movement of water. Permeabilities as low as 10^{-10} cm/s have been observed. Available in large sheets (12 to 14 by

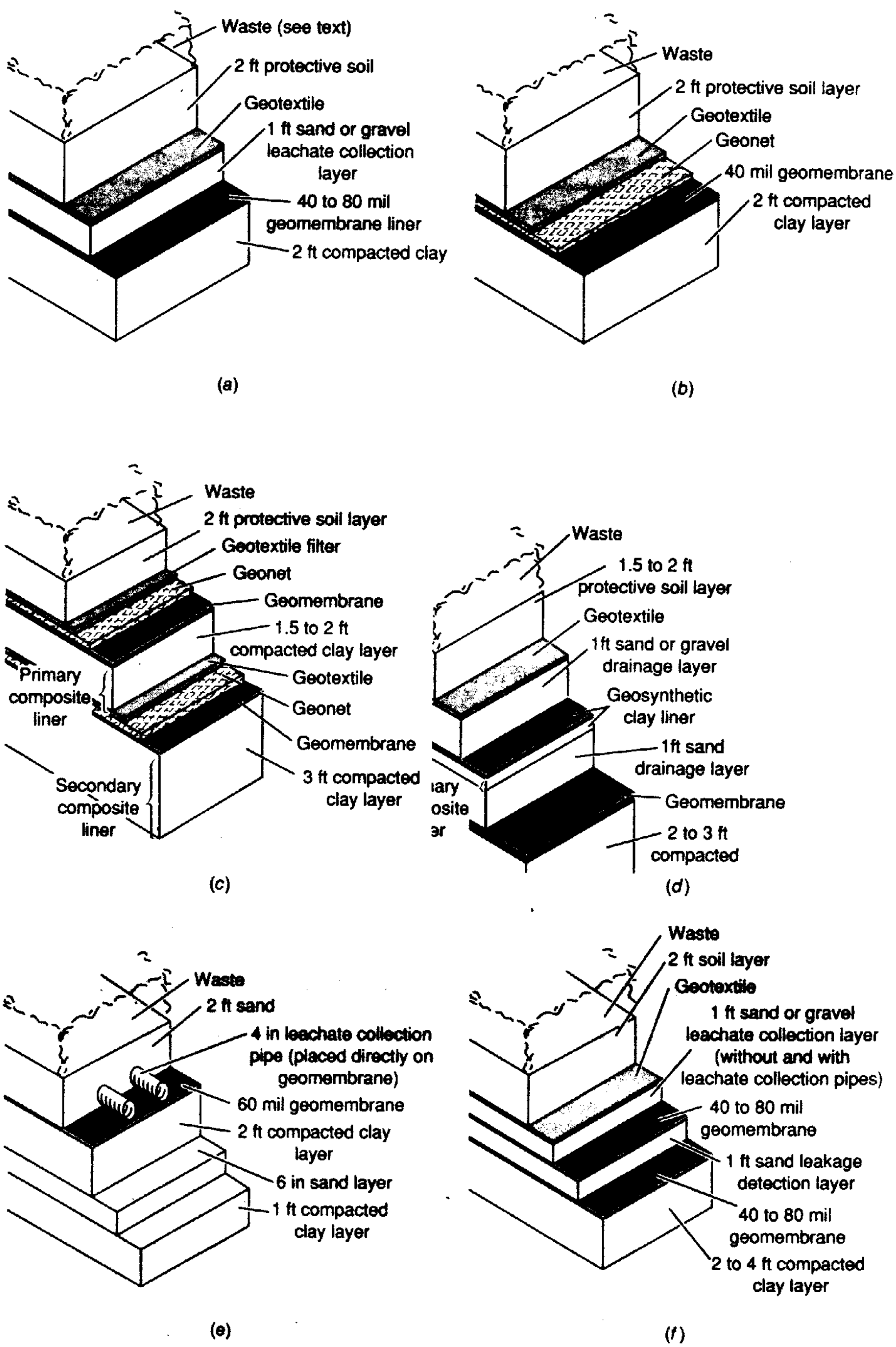
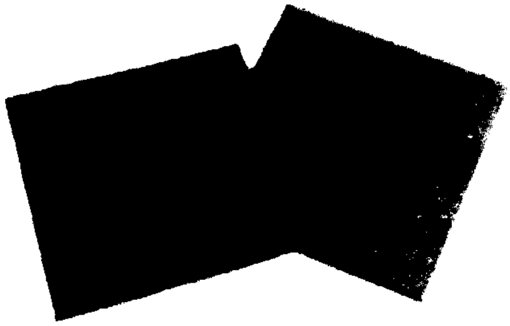
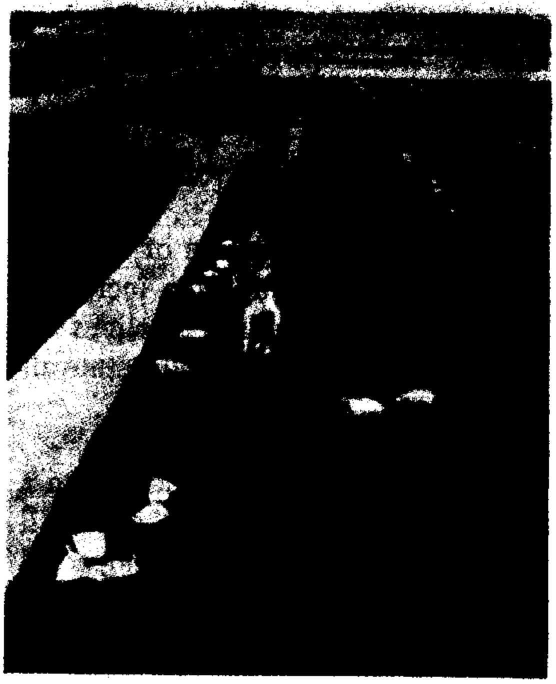


FIGURE 11-36
Typical landfill liners: (*a*, *b*) single-composite barrier types and (*c*–*f*) double-composite barrier types. Note in the double-liner systems the first composite liner is often identified as the primary liner or as the leachate collection system, while the second composite liner is identified as the leachate detection layer. Leachate detection probes are normally placed between the first and second liners.

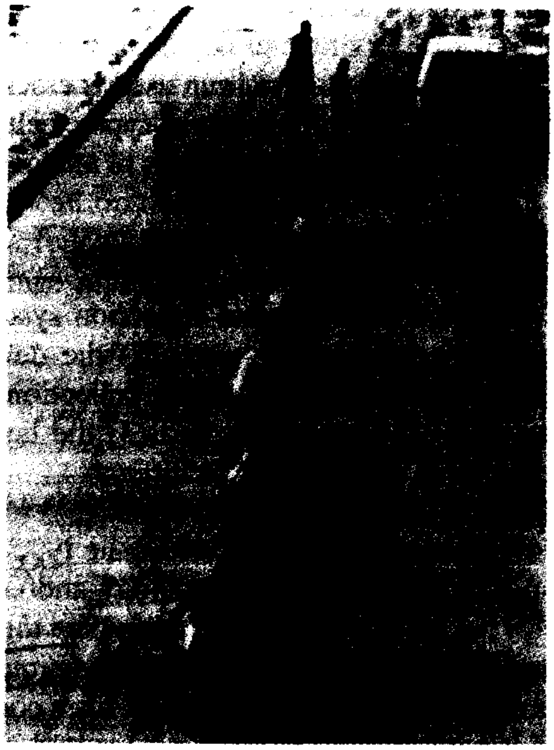
(a)



(b)



(c)



(d)

FIGURE 11-37

Manufactured materials used in the construction of landfill liners: (a) geonet used as a drainage layer is placed over a geomembrane; geotextile (shown folded back) is used to separate materials; (b) geosynthetic clay liner; bentonite clay at about 1 lb/ft^2 (gray side) is bonded to geomembrane; (c) geomembrane being installed on compacted clay layer; and (d) geosynthetic clay liner being installed with clay side up. ((b) and (d) courtesy of Gundle Lining Systems, Inc.)

100 ft), GCLs are overlapped in the construction of a liner system. Two additional two-layer liner systems are shown in Figs. 11-36*e* and 11-36*f*. In the two-layer composite layer landfill systems shown in Figs. 11-36*c* through *f*, leak-detection sensors are usually placed between the two liners (see Fig. 11-57, p. 461).

Liner Systems for Monofills. Liner systems for monofills usually comprise two geomembranes, each provided with a drainage layer and a leachate collection system (see Figs. 11-36*c* and 11-36*d*). A leachate detection system is placed between the first and second liners as well as below the lower liner. In many installations, a thick (3 to 5 ft) clay layer is used below the two geomembranes for added protection [7].

Construction of Clay Liners. In all of the liner designs illustrated in Fig. 11-36, great care must be exercised in the construction of the clay layer. Perhaps the most serious problem with the use of clay is its tendency to form cracks due to desiccation. It is critical that the clay not be allowed to dry out as it is being placed. To insure that the clay liner performs as designed, the clay liner should be laid in 4- to 6-in layers with adequate compaction between the placement of succeeding layers (see Fig. 11-38). Laying the clay in thin layers avoids the possibility of leaks due to the alignment of clods that could occur if the clay layer is applied in a single pass. Another problem that has been encountered when clays of different types have been used is cracking due to differential swelling. To avoid differential swelling only one type of clay must be used in the construction of the liner.

Leachate Collection Systems

The design of a leachate collection system involves (1) the selection of the type of liner system to be used, (2) the development of the grading plan including the placement of the leachate collection and drainage channels and pipelines for the removal of leachate, and (3) the layout and design of the leachate removal, collection, and holding facilities.

Selection of Liner System. The type of liner system selected will depend to a large extent on the local geology and environmental requirements of the landfill site. For example, in locations where there is no groundwater, a single compacted clay liner may be sufficient. In locations where both leachate and gas migration must be controlled, a combined liner comprising a clay liner and a geomembrane liner with an appropriate drainage and soil protection layer will be necessary.

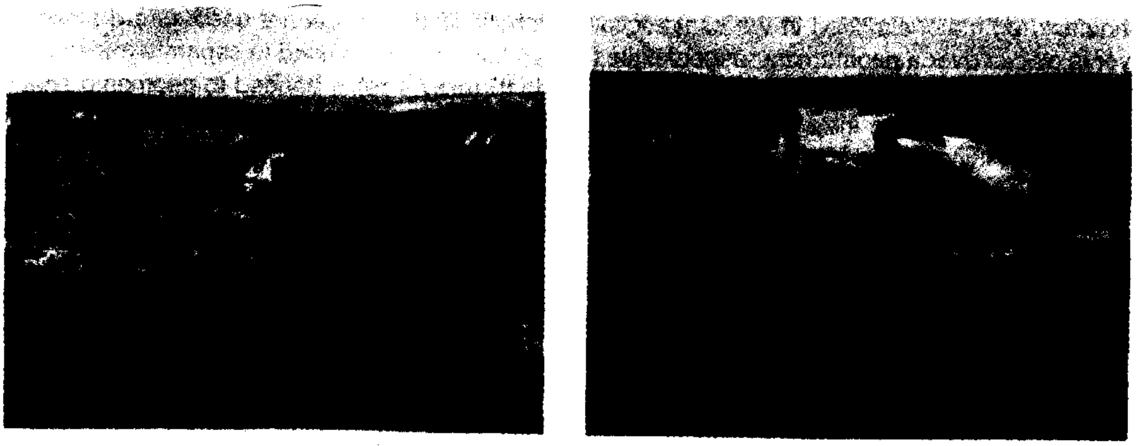


FIGURE 11-38
Preparation of compacted clay layer before geomembrane liner is placed.

Design of Leachate Collection Facilities. A variety of liner designs have been used for the removal of leachate from landfills. The sloped terrace and piped bottom designs are discussed below.

Sloped terraces. To avoid the accumulation of leachate in the bottom of a landfill, the bottom area is graded into a series of sloped terraces. As shown in Fig. 11-39*a*, the terraces are shaped so that the leachate that accumulates on the surface of the terraces will drain to leachate collection channels. Perforated pipe placed in each leachate collection channel (see Fig. 11-39*b*) is used to convey the collected leachate to a central location, from which it is removed for treatment or reapplication to the surface of the landfill.

The cross-slope of the terraces is usually 1 to 5 percent, and the slope of the drainage channels is 0.5 to 1.0 percent. The slope and maximum length of the drainage channel is selected based on the capacity of the drainage facilities. The flow rate capacity of the drainage facilities is estimated using Manning's equation. The design objective is not to allow the leachate to pond in the bottom of the landfill so as to create a significant hydraulic head on the landfill liner (less than 1 ft at the highest point as specified in the new federal Subtitle D landfill regulations). The depth of flow in the perforated drainage pipe increases continually from the

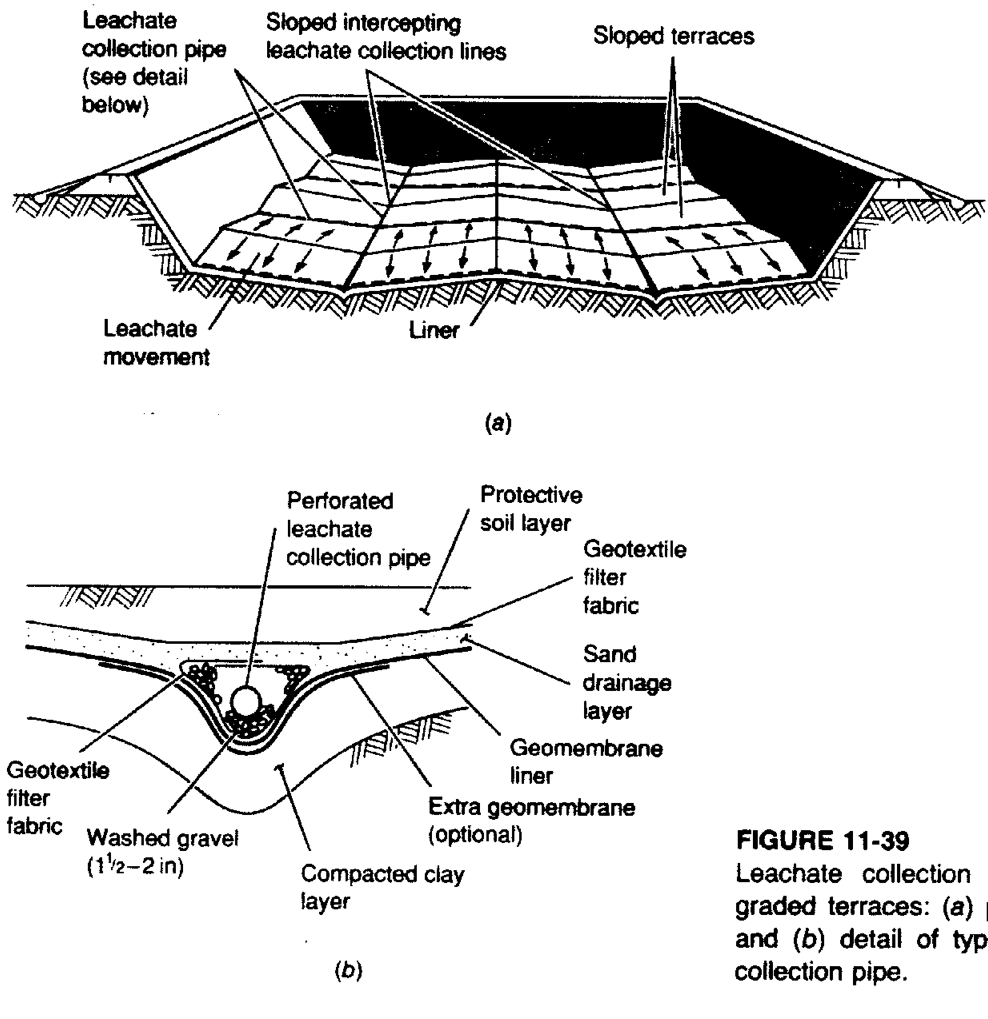


FIGURE 11-39
Leachate collection system with graded terraces: (*a*) pictorial view and (*b*) detail of typical leachate collection pipe.

upper reaches of the drainage channel to the lower reaches. In very large landfills, the drainage channels will be connected to a larger cross-collection system.

Piped bottom. An alternative plan for the collection of leachate is shown in Fig. 11-40. As shown, the bottom area is then divided into a series of rectangular strips by clay barriers placed at appropriate distances (see Fig. 11-40*a*). The barrier's spacing corresponds to the width of a landfill cell. Leachate collection pipes are then placed lengthwise directly on the geomembrane. The 4-in leachate collection pipes have laser-cut perforations, similar to a well screen, over one-half of the circumference. The laser-cuts are spaced 0.25 in apart and the size of the laser cut is 0.0001 in, corresponding to the smallest sand size. To promote effective drainage, the bottom is sloped from 1.2 to 1.8 percent. The leachate collection pipes, spaced every 20 ft, are covered with a two-foot layer of sand (see Fig. 11-40*b*) before landfilling commences. The use of a multiple-pipe leachate collection system will ensure the rapid removal of leachate from the bottom of the landfill. Further, the use of a 2-ft sand layer serves to filter the leachate before it is collected for treatment. The first 3-ft layer of solid waste, placed directly on the sand layer, is not compacted [33].

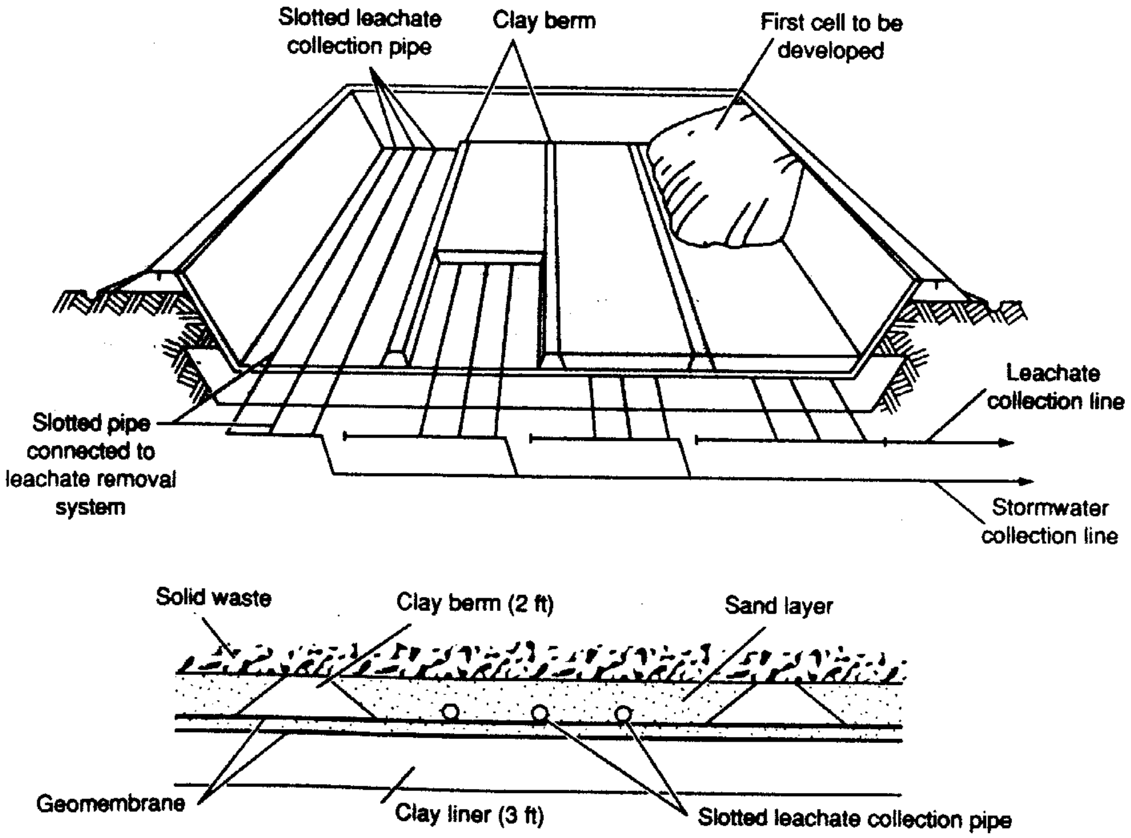


FIGURE 11-40
Typical leachate collection system using multiple leachate collection pipes: (*a*) pictorial view and (*b*) detail of typical leachate collection pipes (adapted from Ref. 33).

A unique feature of the design shown in Fig. 11-40 is the method used to remove the stormwater from the unused portion of the landfill. The method is detailed in Fig. 11-41. In the unused portion of the landfill, stormwater is collected in the lines that will ultimately be used for the collection of leachate. When the next landfill cell is to be placed in service, the leachate piping is reconnected to the leachate collection system, and the leachate collection pipe which extends into the next diked strip is capped [33].

Leachate Removal, Collection, and Holding Facilities. Two methods have been used for the removal of leachate that accumulates within a landfill. In Fig. 11-42*a*, the leachate collection pipe is passed through the side of the landfill. Where this method is used, great care must be taken to ensure that the seal where the pipe penetrates the landfill liner is sound. An alternative method used for the removal of leachate from landfills involves the use of an inclined collection pipe located within the landfill (see Fig. 11-42*b*). Leachate collection facilities are used where the leachate is to be recycled from or treated at a central location. A typical leachate collection access vault is shown in Fig. 11-43*a*. In some locations, the leachate removed from the landfill is collected in a holding tank such as shown in Fig. 11-43*b*. The capacity of the holding tank will depend on the type of treatment facilities that are available and the maximum allowable discharge rate to the treatment facility. Typically, leachate holding tanks are designed to hold from 1 to 3 days of leachate production during the peak leachate production period. Both double- and single-walled tanks have been used, but the double-

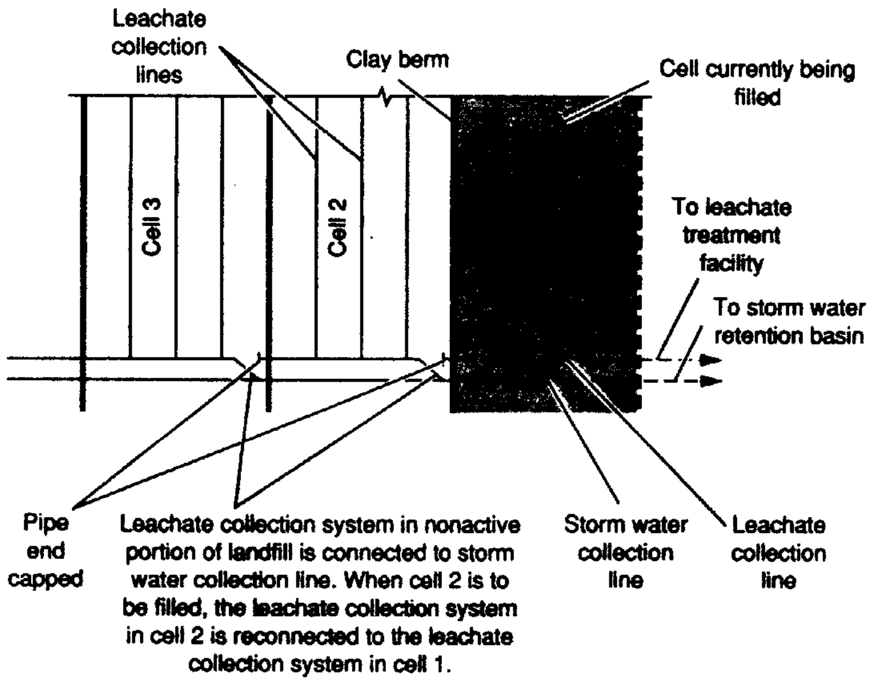


FIGURE 11-41
Storm water management in area-type landfill. (Courtesy of C. C. Miller, see also Ref. 33.)

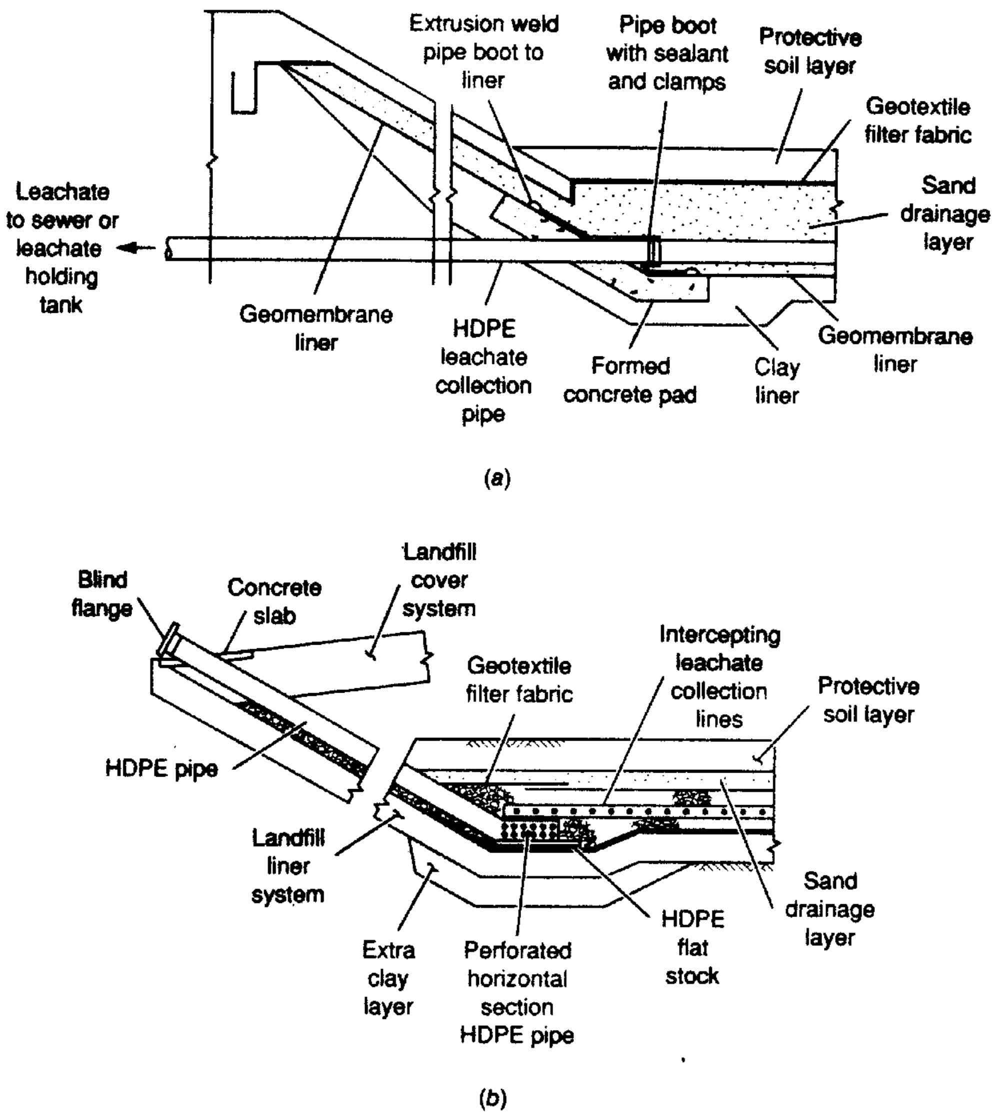


FIGURE 11-42
Typical systems used to remove leachate from landfills: (*a*) leachate collection pipe passed through side of landfill and (*b*) inclined leachate collection pipe located within landfill. Leachate is removed with a pump.

walled tanks are preferred over single-walled tanks because of the added safety afforded. Although both plastic and metallic tanks have been used, plastic tanks are more corrosion resistant.

Leachate Management Options

The management of leachate, when and if it forms, is key to the elimination of the potential for a landfill to pollute underground aquifers. A number of alternatives have been used to manage the leachate collected from landfills including: (1) leachate recycling, (2) leachate evaporation, (3) treatment followed by disposal, and (4) discharge to municipal wastewater collection systems. These options are discussed briefly below.

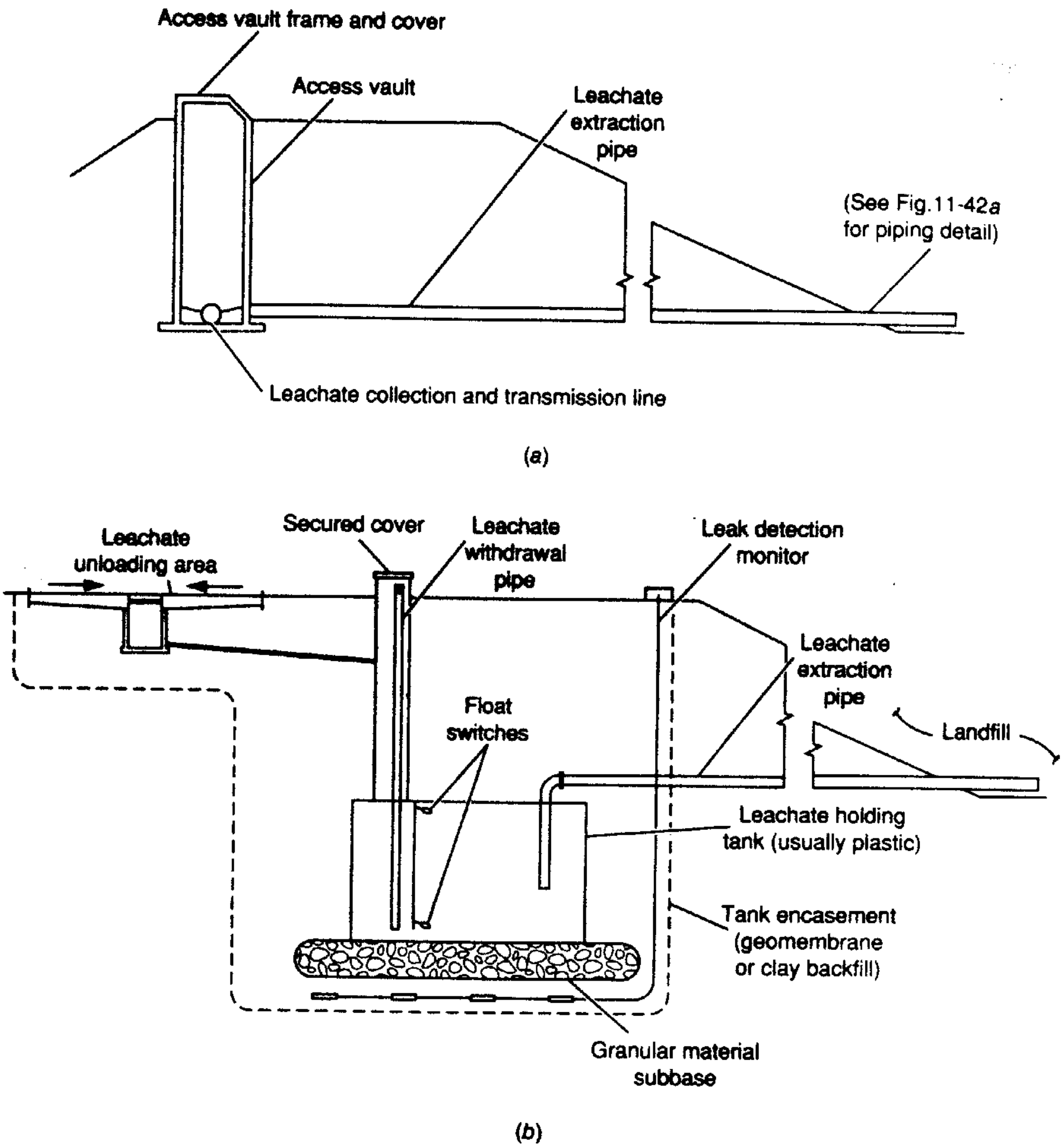


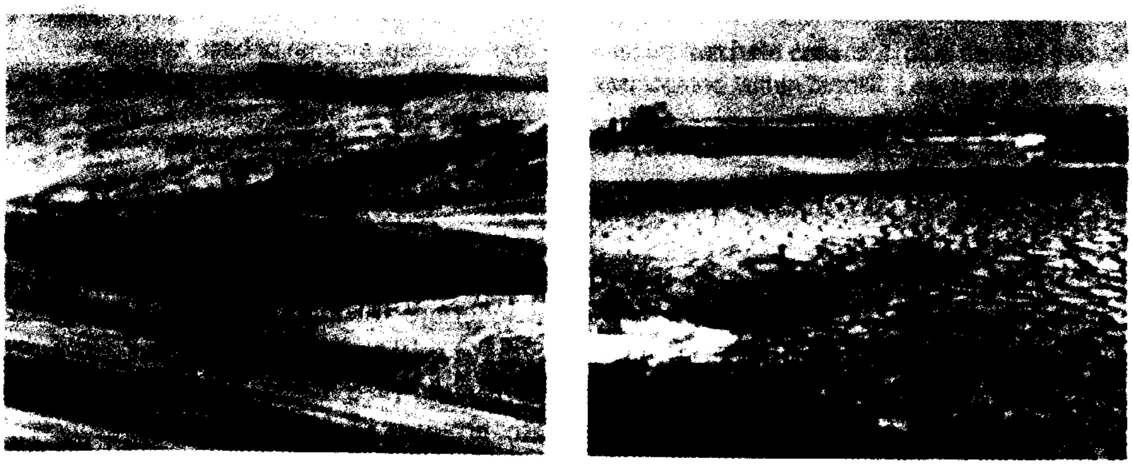
FIGURE 11-43
Examples of leachate collection facilities: (*a*) leachate collection and transmission vault and (*b*) leachate holding tank.

Leachate Recycling. An effective method for the treatment of leachate is to collect (see Fig. 11-42) and recirculate the leachate through the landfill. During the early stages of landfill operation the leachate will contain significant amounts of TDS, BOD_5, COD, nutrients, and heavy metals (see Table 11-13). When the leachate is recirculated, the constituents are attenuated by the biological activity and by other chemical and physical reactions occurring within the landfill. For example, the simple organic acids present in the leachate will be converted to CH_4 and CO_2. Because of the rise in pH within the landfill when CH_4 is produced, metals will be precipitated and retained within the landfill. An additional benefit of leachate recycling is the recovery of landfill gas that contains CH_4.

Typically, the rate of gas production is greater in leachate recirculation systems. To avoid the uncontrolled release of landfill gases when leachate is recycled for treatment, the landfill should be equipped with a gas recovery system. Ultimately, it will be necessary to collect, treat, and dispose of the residual leachate. In large landfills it may be necessary to provide leachate storage facilities.

Leachate Evaporation. One of the simplest leachate management systems involves the use of lined leachate evaporation ponds (see Fig. 11-44). Leachate that is not evaporated is sprayed on the completed portions of the landfill. In locations with high rainfall, the lined leachate storage facility is covered with a geomembrane during the winter season to exclude rainfall. The accumulated leachate is disposed of by evaporation during the warm summer months, by uncovering the storage facility, and by spraying the leachate on the surface of the operating and completed landfill. Odorous gases that may accumulate under the surface cover are vented to a compost or soil filter (see Fig. 11-45) [3, 51]. Soil beds are typically 2 to 3 ft deep, with organic loading rates of about 0.1 to 0.25 lb/ft^3 of soil. During the summer when the pond is uncovered, surface aeration may be required to control odors. If the storage pond is not large it can be left covered year round. Another example involves treatment of the leachate (usually biologically) with winter storage and spray disposal of the treated effluent on nearby lands during the summer. If enough land is available, spraying of effluent can be carried out on a continuous basis, even when it is raining.

Leachate Treatment. Where leachate recycling and evaporation is not used, and the direct disposal of leachate to a treatment facility is not possible, some from of pretreatment or complete treatment will be required. Because the characteristics of the collected leachate can vary so widely, a number of options have been used for



(a) (b)

FIGURE 11-44
Views of lined evaporation ponds: (a) for leachate—see also Fig. 11-64 (liquid in pond is rainwater) and (b) for leachate and treatment plant sludges.

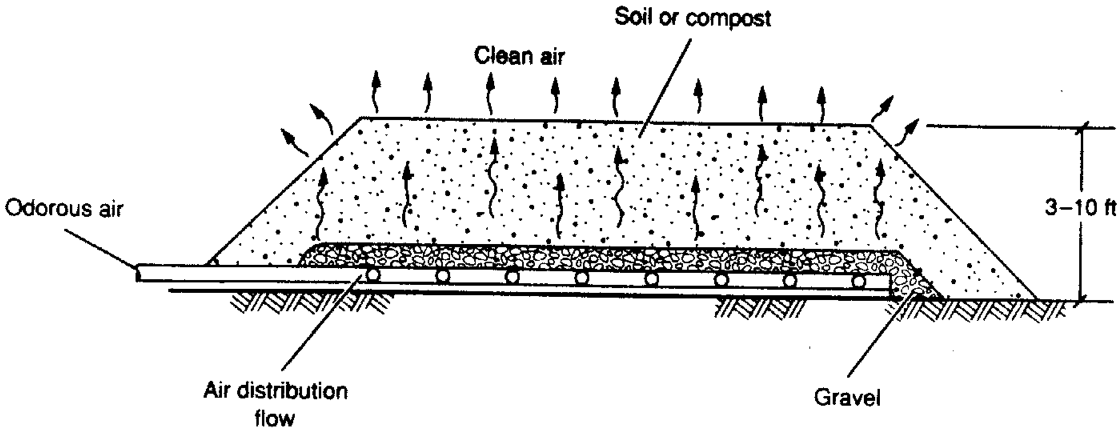


FIGURE 11-45
Typical compost or soil filter used to remove odors from gases [51].

the treatment of leachate. The principal biological and physical/chemical treatment operations and processes used for the treatment of leachate are summarized in Table 11-18. The treatment process or processes selected will depend to a large extent on the contaminant(s) to be removed. Typical examples of the types of aerobic and anaerobic biological processes that have been used for the treatment of leachate are shown in Fig. 11-46. Design details on the treatment options reported in Table 11-18 may be found in Ref. 49.

Selection of treatment facilities. The type of treatment facilities used will depend primarily on the characteristics of the leachate and secondarily on the geographic and physical location of the landfill. Leachate characteristics of concern include TDS, COD, SO_4^{2-}, heavy metals, and nonspecific toxic constituents. Leachate containing extremely high TDS concentrations (e.g., $> 50{,}000$ mg/L) may be difficult to treat biologically. High COD values favor anaerobic treatment processes because aerobic treatment is expensive. High sulfate concentrations may limit the use of anaerobic treatment processes because of the production of odors from the biological reduction of sulfate sulfide (see Eqs. 4-12 through 4-14). Heavy metal toxicity is also a problem with many biological treatment processes. Another important question is how large should the treatment facilities be? The capacity of the treatment facilities will depend on the size of the landfill and the expected useful life. The presence of nonspecific toxic constituents is often a problem with older landfills that received a variety of wastes, before environment regulations governing the operation of landfills were enacted.

Integrated leachate management system. An example of an integrated leachate management system is shown in Fig. 11-47. Liquid (leachate) that moves down through the solid waste is first filtered as it passes the sand layer in the landfill (see Fig. 11-40). The collected leachate is transported to a treatment lagoon where septage is also added. The liquid in the lagoon is aerated to reduce the organic content and to control odors. Liquid from the lagoon is then applied to

TABLE 11-18
Representative biological, chemical, and physical processes and operations used for the treatment of leachate[a]

Treatment process	Application	Comments
Biological processes		
Activated sludge	Removal of organics	Defoaming additives may be necessary; separate clarifier needed
Sequencing batch reactors	Removal of organics	Similar to activated sludge, but no separate clarifier needed; only applicable to relatively low flow rates
Aerated stabilization basins	Removal of organics	Requires large land area
Fixed film processes (trickling filters, rotating biological contactors)	Removal of organics	Commonly used on industrial effluents similar to leachates, but untested on actual landfill leachates
Anaerobic lagoons and contactors	Removal of organics	Lower power requirements and sludge production than aerobic systems; requires heating; greater potential for process instability; slower than aerobic systems
Nitrification/denitrification	Removal of nitrogen	Nitrification/denitrification can be accomplished simultaneously with the removal of organics
Chemical processes		
Neutralization	pH control	Of limited applicability to most leachates
Precipitation	Removal of metals and some anions	Produces a sludge, possibly requiring disposal as a hazardous waste
Oxidation	Removal of organics; detoxification of some inorganic species	Works best on dilute waste streams; use of chlorine can result in formation of chlorinated hydrocarbons
Wet air oxidation	Removal of organics	Costly; works well on refractory organics
Physical operations		
Sedimentation/flotation	Removal of suspended matter	Of limited applicability alone; may be used in conjunction with other treatment processes
Filtration	Removal of suspended matter	Useful only as a polishing step
Air stripping	Removal of ammonia or volatile organics	May require air pollution control equipment
Steam stripping	Removal of volatile organics	High energy costs; condensate steam requires further treatment
Adsorption	Removal of organics	Proven technology; variable costs depending on leachate
Ion exchange	Removal of dissolved inorganics	Useful only as a polishing step
Ultrafiltration	Removal of bacteria and high molecular weight organics	Subject to fouling; of limited applicability to leachate
Reverse osmosis	Dilute solutions of inorganics	Costly; extensive pretreatment necessary
Evaporation	Where leachate discharge is not permissible	Resulting sludge may be hazardous; can be costly except in arid regions

[a] Adapted from Ref. 43.

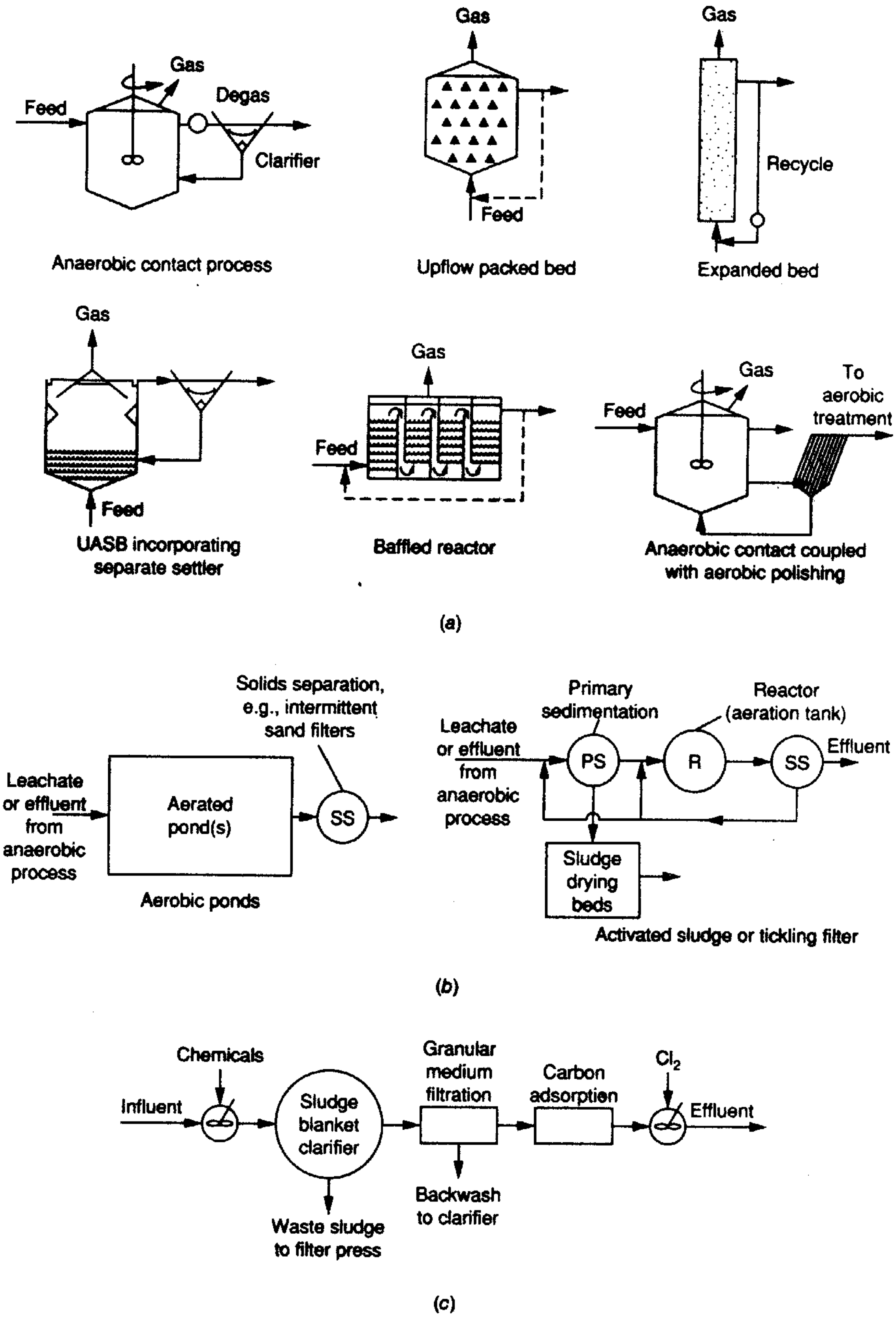


FIGURE 11-46

Typical processes used for the treatment of leachate: (*a*) anaerobic processes, (*b*) aerobic processes, and (*c*) chemical treatment process for the removal of heavy metals and selected organics.

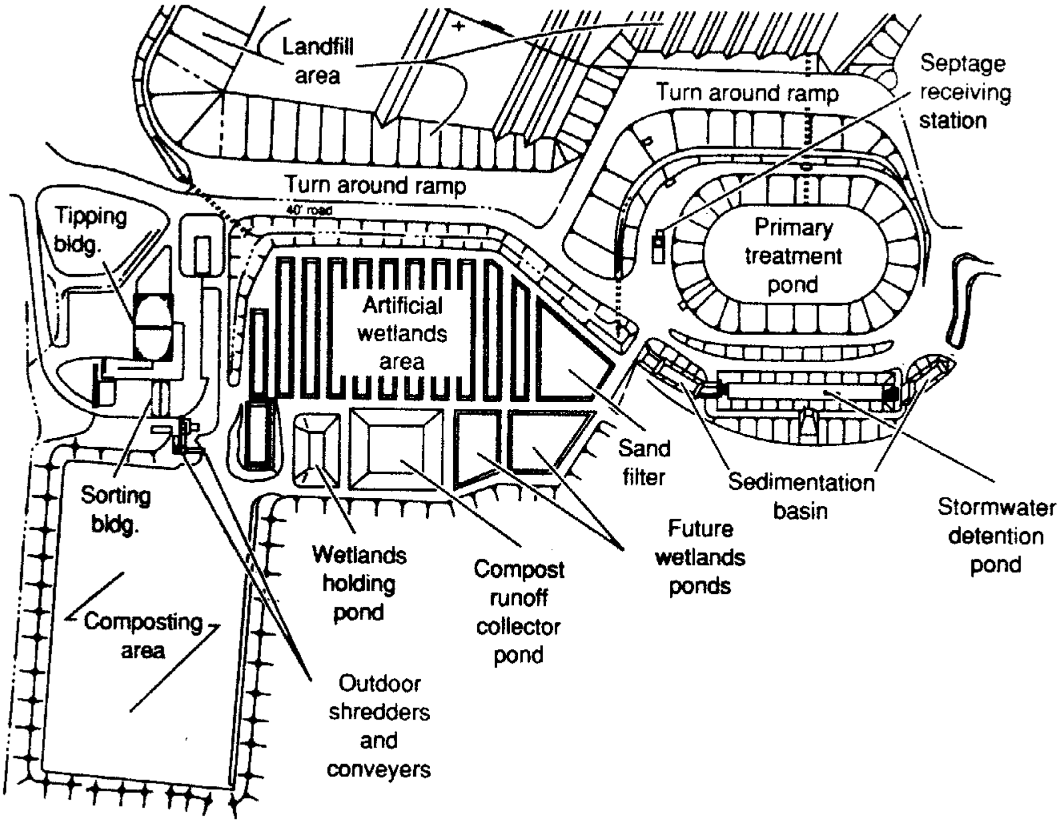


FIGURE 11-47
Integrated leachate treatment system employing constructed wetlands (from Ref. 33).

shredded MSW that is to be composted and used for intermediate cover material in the landfill (see Fig. 11-51 in Section 11-6). Recyclable materials and metals are removed before the MSW is shredded. Application of the leachate to the shredded MSW provides the moisture needed for optimum composting and reduces the volume of leachate through evaporation. The excess leachate is filtered as it passes through the shredded waste and the sand filter underdrain system. The collected leachate is piped to a series of constructed wetlands. The wetlands are used to remove organic material, nutrients, heavy metals, and other trace organics. The effluent from the constructed wetlands is passed through a slow sand filter and then used for spray irrigation on the grass-covered landscape at the landfill.

Discharge to Wastewater Treatment Plant. In those locations where a landfill is located near a wastewater collection system or where a pressure sewer can be used to connect the landfill leachate collection system to a wastewater collection system, leachate is often discharged to the wastewater collection system. In many cases pretreatment, using one or more of the methods reported in Table 11-18, may be required to reduce the organic content before the leachate can be discharged to the sewer. In locations where sewers are not available, and evaporation and spray disposal are not feasible, complete treatment followed by surface discharge may be required.

11-6 SURFACE WATER MANAGEMENT

Equally important in controlling the movement of leachate is the management of all surface waters including rainfall, stormwater runoff, intermittent streams, and artesian springs. The management of surface water is introduced in this section. With the use of a properly designed cover layer, an appropriate surface slope (3 to 5 percent), and adequate stormwater drainage, surface infiltration can be controlled effectively. With proper surface water controls, it may not be necessary to provide an impermeable surface barrier. Topics considered in this section include (1) surface water control systems, (2) design of intermediate cover layers, (3) design of final cover layers, and (4) determination of the percolation through the cover.

Surface Water Control Systems

Elimination or reduction of the amount of surface water that enters the landfill is of fundamental importance in the design of a sanitary landfill because surface water is the major contributor to the total volume of leachate. Stormwater runoff from the surrounding area must not be allowed to enter the landfill and surface water runoff (from rainfall) must not be allowed to accumulate on the surface of the landfill.

Surface Water Drainage Facilities. In those locations where stormwater runoff from the surrounding areas can enter the landfill (e.g., landfills located in canyons), the site must be graded appropriately and properly designed drainage facilities must be installed (see Fig. 11-48). The drainage facilities may be designed to remove the runoff from the surrounding area only, or from the surrounding area as well as the surface of the landfill. In locations where the entire landfill liner system is installed at one time, the design of the liner must allow for the diversion of stormwater not falling on the wastes being landfilled. The diversion of stormwater from the unused portion of a landfill is illustrated in Fig. 11-41.

In locations where only the surface water from the top of the landfill must be removed, the drainage facilities should be designed to limit the travel distance of the surface water. In many designs, a series of interceptor ditches are used. Flow from the interceptor ditches is routed to a larger main ditch for removal from the site. Examples of the types of drainage facilities used to protect landfills are illustrated in Fig. 11-49.

Stormwater Storage Basins. In many cases, it may be necessary to construct stormwater storage basins to contain the diverted stormwater flows so as to minimize downstream flooding. Typically stormwater must be collected from the completed portions of the landfill as well as from areas yet to be filled. An example of a stormwater retention/storage basin is illustrated in Fig. 11-50. Standard hydrological procedures are followed in sizing the stormwater basins [20, 27, 28].

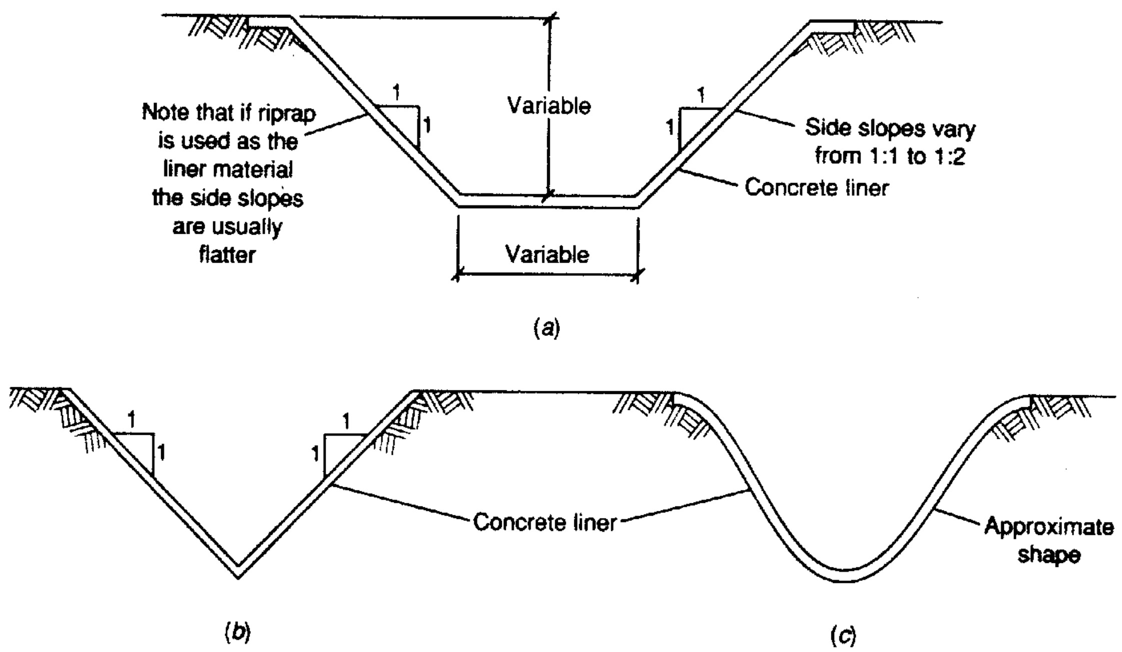


FIGURE 11-48
Examples of drainage facilities used at landfills: (*a*) trapezoidal lined ditch, (*b*) vee lined ditch, and (*c*) shaped vee lined ditch. Note that the trapezoidal ditch cross section is expandable to accomodate a wide range of flows.

Intermediate Cover Layers

Intermediate cover layers are used to cover the wastes placed each day to eliminate the harboring of disease vectors, to enhance the aesthetic appearance of the landfill site, and to limit the amount of surface infiltration. The greatest amount of water that enters a landfill and ultimately becomes leachate enters during the period when the landfill is being filled. Some of the water, in the form of rain and snow, enters while the wastes are being placed in the landfill. Water also enters the landfill by first infiltrating and subsequently percolating through the intermediate landfill cover. Thus, the materials and method of placement of the intermediate cover can limit the amount of surface water that enters the landfill.

Materials Used for Intermediate Cover Layers. Generalized ratings for the suitability of various types of materials that have been used as intermediate landfill cover are reported in Table 11-19. Of the materials listed, only compost produced from yard waste and MSW, the geosynthetic clay liner, and clay are effective in limiting the entry of surface water into the landfill. To be effective, the intermediate cover, using the materials cited above, must be sloped properly to enhance surface water runoff.

In some landfill operations, a very thick layer of soil (3 to 6 ft) is placed temporarily over the completed cell. Any rainfall that infiltrates the intermediate cover layer is retained by virtue of its field capacity. When a second lift is to be placed over the first lift, the soil is removed and stockpiled before filling

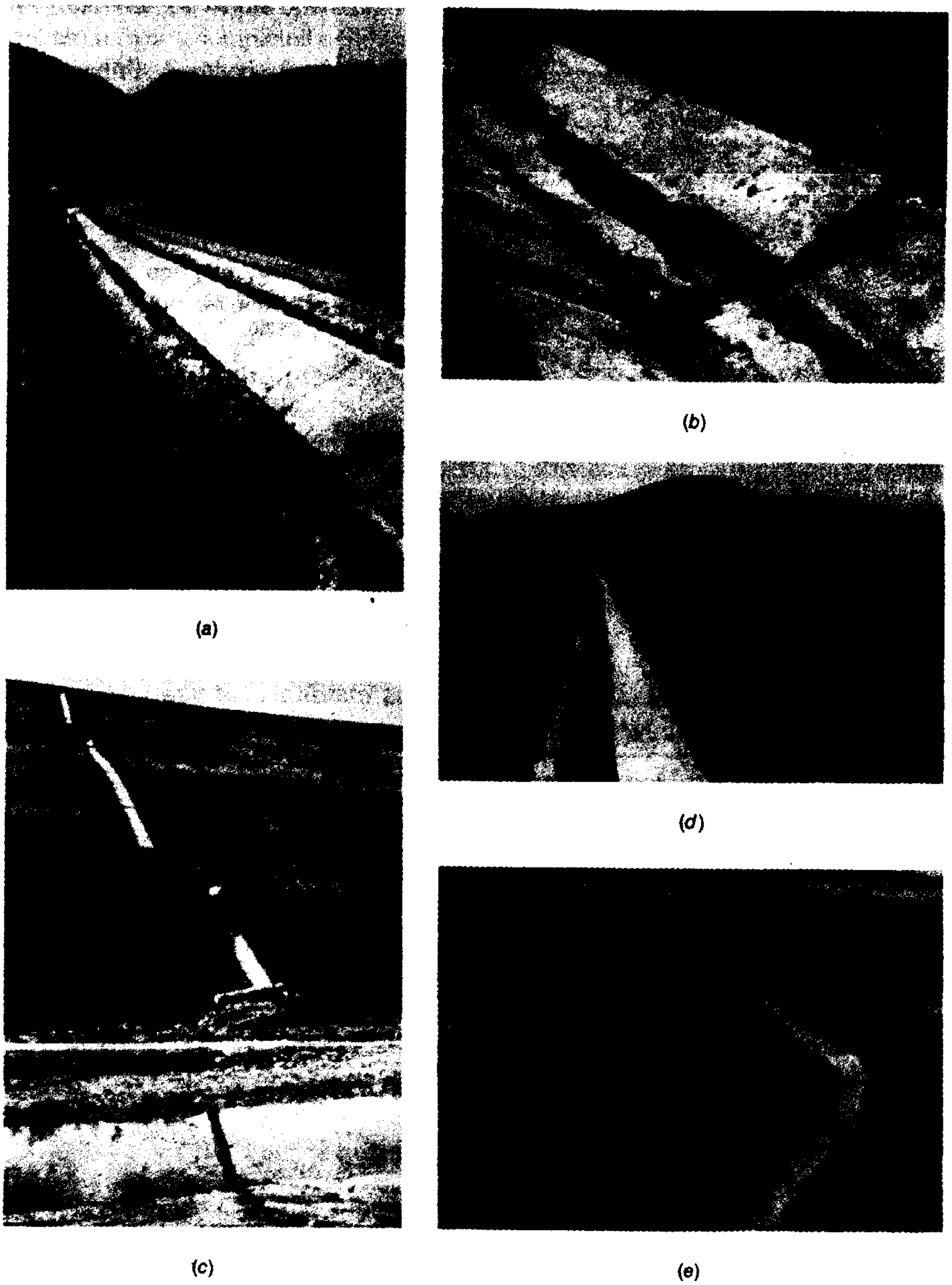


FIGURE 11-49
Views of drainage facilities used at landfills: (*a*) trapezoidal lined ditch; (*b*) trapezoidal lined ditch built in sections; (*c*) half-section corrugated pipe used to transport surface runoff from upper benches of landfill (note trapezoidal drainage channel in foreground); (*d*) typical vee type ditch used in upper portion of drainage area; and (*e*) shaped vee type ditch used to transfer runoff from upper portions of drainage area to stormwater retention basin.

FIGURE 11-50
View of large riprap lined stormwater retention/storage basin at a large landfill. The size of the basin can be estimated from the size of the vehicles parked in the bottom of the basin.

TABLE 11-19
Generalized ratings of the suitability of various materials for use as intermediate landfill cover[a]

	Generalized ratings[b]						
Function	**Yard waste mulch**	**Yard waste compost**	**MSW compost**	**Geosynthetic clay liner**	**Typical native soil**	**Clayey-silty sand**	**Clay**
Provides pleasing appearance and controls blowing paper	G–E	G–E	G	E	E	E	E[c]
Prevents rodents from burrowing or tunneling	P	P	P	G–E	P	F–G	P
Keeps flies from emerging	F	F–G	F	E	G	P	E[c]
Minimizes the entry of surface water into landfill	P	G–E	F–G	E	F–G[d]	P	E[c]
Retains rainfall and snowmelt	P	G–E	F–G	G	F–G[d]	P	G[c]
Minimizes landfill gas venting through cover	P	P	P	F–G	P	P	P–F[c]

[a] Adapted in part from Ref. 4.

[b] E = excellent; G = good; F = fair; P = poor.

[c] Except when allowed to dry out and cracks develop in the cover layer.

[d] When a thick layer of soil is used, the rating is G–E.

begins. The use of the operating technique of temporarily storing additional cover material over a completed cell can significantly limit the amount of water entering the landfill. Synthetic foam has also been used as an intermediate landfill cover material. In general, foam works well, except when it rains.

Intermediate Cover Layers Using Waste Materials. As noted in Section 11-4, where the amount of native soil available for use as intermediate cover material is limited, alternative waste materials have been used for the purpose. Suitable materials that can be used as a substitute for native soil include compost and mulch produced from yard wastes and compost produced from MSW (see Fig. 11-51). An important advantage of using compost and mulch produced from MSW is that the landfill volume that would have been occupied by the soil used for intermediate cover is now available for the disposal of waste materials. In locations where the

(a)

(b)

FIGURE 11-51
Composting of processed MSW for use as intermediate landfill cover: (*a*) shredding facility for commingled MSW from which selected recyclable materials and ferrous metals have been removed and (*b*) composting of the shredded MSW using the windrow method.

amount of cover material is limited, the use of composted MSW can increase the capacity of the landfill significantly.

In the composting operation shown in Fig. 11-51, approximately 40 percent of the waste from household and selected commercial solid waste is shredded after selected recyclable materials have been removed manually and ferrous metal has been removed using two stages of magnetic separation. The shredded material is placed in windrows for composting. Leachate from the landfill is sprayed on the shredded waste to increase the moisture content for optimum composting. The compost product is used as intermediate cover for the remaining 60 percent of the waste that was placed in the landfill directly. Where composted MSW is used as intermediate cover, the compost need not be cured fully before being used as intermediate cover material. Excess compost produced at the landfill site is stored there until needed. Cured compost placed on the MSW deposited in the landfill also serves as an odor filter (see Fig. 11-45). The use of composted MSW for intermediate cover is expected to increase significantly in the coming years, as the conservation of landfill capacity becomes a more important issue [33].

Other waste materials that have been used as intermediate cover material include old carpets, construction and demolition wastes, and agricultural residues. Old carpets can be stockpiled as they are received at the landfill and used as required. Carpets have also been used as part of the final cover design for landfills. The question of whether an intermediate cover layer is even needed or should be required is currently the subject of renewed debate [53].

Final Cover Layers

The primary purposes of the final landfill cover are (1) to minimize the infiltration of water from rainfall and snowfall after the landfill has been completed, (2) to limit the uncontrolled release of landfill gases, (3) to suppress the proliferation of vectors, (4) to limit the potential for fires, (5) to provide a suitable surface for the revegetation of the site, and (6) to serve as the central element in the reclamation of the site. To meet these purposes the landfill cover (1) must be able to withstand climatic extremes (e.g., hot/cold, wet/dry, and freeze/thaw cycles); (2) must be able to resist water and wind erosion; (3) must have stability against slumping, cracking and slope failure, and downslope slippage or creep; (4) must resist the effects of differential landfill settlement caused by the release of landfill gas and the compression of the waste and the foundation soil; (5) must resist failure due to landfilling operations such as surcharge loads due to stockpiling and the travel of collection vehicles across completed portions of the landfill; (6) must resist deformations caused by earthquakes; (7) must withstand alterations to cover materials caused by constituents in the landfill gas; and (8) must resist the disruptions caused by plants, burrowing animals, worms, and insects [18, 23]. It is important to note that under current legislation all of these purposes and attributes must continue to be satisfied far into the future. The general features of a landfill cover, some typical types of landfill cover designs, and the long-term performance requirements for landfill covers are considered below.

General Features of Landfill Covers. A modern landfill cover, as shown in Fig. 11-52, is made up of a series of layers, each of which has a special function. The subbase soil layer is used to contour the surface of the landfill and to serve as a subbase for the barrier layer. In some cover designs, a gas collection layer is placed below the soil layer to transport landfill gas to gas management facilities. The barrier layer is used to restrict the movement of liquids into the landfill and the release of landfill gas through the cover. The drainage layer is used to transport rainwater and snowmelt that percolates through the cover material away from the barrier layer and to reduce the water pressure on the barrier layer. The protective layer is used to protect the drainage and barrier layers. The surface layer is used to contour the surface of the landfill and to support the plants that will be used in the long-term closure design of the landfill.

It should be noted that not all of the layers will be required in each location. For example, a gas collection layer may not be required where an active gas recovery system is in place. Sometimes the subbase layer can also be used as the gas collection layer. Of the layers identified in Fig. 11-52, the barrier layer is the most critical for the reasons cited above [18, 23]. Although clay has been used in many existing landfills as the barrier layer, a number of problems are inherent with its use. For example, clay is difficult to compact on a soft foundation, compacted clay can develop cracks due to desiccation, clay can be damaged by freezing, clay will crack due to differential settling, the clay layer in a landfill cover is difficult to repair once damaged, and finally, the clay layer does not restrict the movement of landfill gas to any significant extent. As a consequence, the use of one or more geomembranes is recommended over the use of clay as a barrier layer in landfill covers. Geosynthetic clay liners (see Fig. 11-37*b*) have also been used for the barrier layer.

Typical Cover Designs. Some of the many types of cover designs that have been proposed and used are illustrated in Fig. 11-53. In Fig. 11-53*a*, the geotextile filter cloth is used to limit the intermixing of the soil with the sand layer. If the available topsoil at the landfill site is not suitable for plant growth, a suitable topsoil must be brought to the site or the available topsoil should be amended to improve its characteristics for plant growth. The modification of a soil through the addition of suitable amendments is discussed in Chapter 16. The use of a composite barrier

Component	*Typical materials*
Surface layer Protective layer	Cover soil, available locally or imported
Drainage layer	Sand, gravel, or geonet and geotextile separator
Barrier layer	Geomembrane (see Table 11-17)
Subbase	Compacted and graded native soil

FIGURE 11-52
Typical components that constitute a landfill cover.

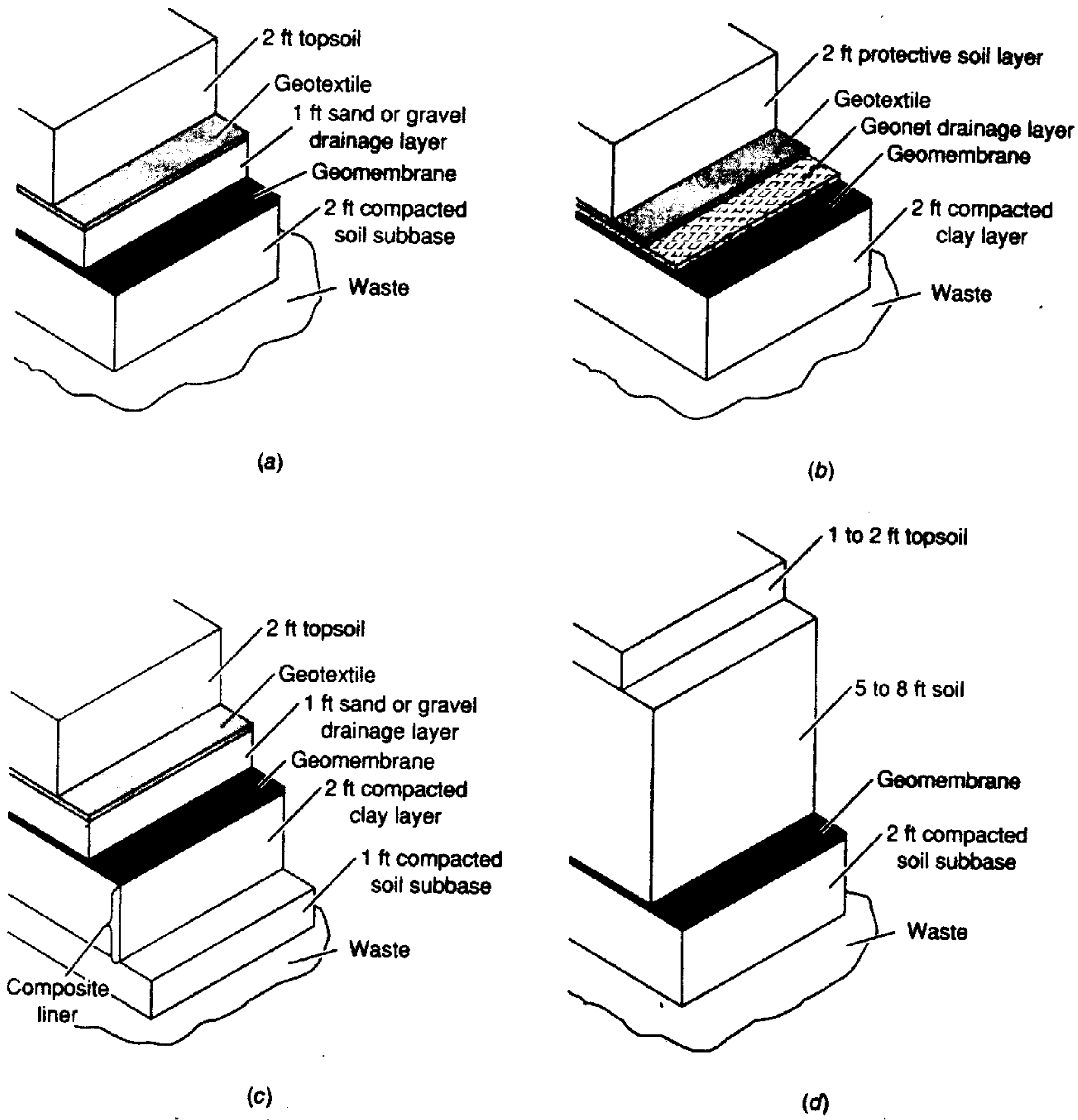


FIGURE 11-53
Typical landfill final cover configurations.

design composed of a geomembrane and clay layer is illustrated in Fig. 11-53*b*. In the design illustrated in Fig. 11-53*c*, a sand or gravel layer is substituted for the geonet drainage layer in Fig 11-53*b*. In the cover design illustrated in Fig. 11-53*d*, a 6- to 10-ft thick layer of soil is used as the cover layer. Functionally, the soil layer is sloped adequately to maximize surface runoff. The depth of soil is used to retain rainfall that does not run off and infiltrates into the soil cover. The flexible membrane liner is used to limit the release of landfill gases. Astro Turf™ has also been placed over a flexible membrane liner. Use of the Astro Turf™ is advantageous because the amount of maintenance required is minimized.

Long-Term Performance and Maintenance of Landfill Covers. Regardless of the design of the final landfill cover, the following question must be considered.

How will the integrity and performance of the landfill cover be maintained as the landfill settles, owing to the loss of weight resulting from the production of landfill gas and to long-term consolidation? For example, how will a composite liner be repaired to maintain adequate drainage? Typically, if settlement occurs, the landfill cover material is stripped back, soil or composted waste is added to adjust the grade, and the various layers are replaced. Where a thick soil cover is used, proper surface drainage may be restored by regrading the cover layer. Where vegetation is planted on the soil cover layer, a sprinkler system will be required to sustain the vegetation during the summer. In landfills where Astro Turf™ is used, when the turf starts to fall apart, the landfill cover is opened, the used turf is placed in the landfill, the flexible membrane is repaired, and a new Astro Turf™ layer is added to the top. Landscaping and the long-term maintenance of closed landfills are considered in Chapter 16.

Determination of Percolation Rate through Intermediate and Final Cover Layers

If one assumes (1) that the cover material is saturated, (2) that a thin layer of water is maintained on the surface, and (3) that there is no resistance to flow below the cover layer, then the theoretical amount of water, expressed in gallons, that could enter the landfill per unit area in a 24-h period for various cover materials is given in Table 11-15 in column 3. Clearly, these data are only theoretical values, but they can be used in assessing the worst possible situation. In actual practice, the amount of water entering the landfill will depend on local hydrological conditions, the design of the landfill cover, the final slope of the cover, and whether vegetation has been planted. In general landfill cover designs employing a flexible membrane liner are constructed to eliminate the percolation of rainwater or snowmelt into the waste below the landfill cover.

Estimation of the percolation of rainwater or snowmelt through the soil layer above the drainage layer (see Fig. 11-54*a*) or through a cover layer composed of soil only (see Fig. 11-54*b*) is usually accomplished using one of the many available hydrologic simulation programs. Perhaps the best known is the Hydrologic Evaluation of Landfill Performance (HELP) model [41, 42]. Percolation through the landfill cover layer can also be estimated using a standard hydrological water balance. Referring to Fig. 11-54, one can calculate the water balance for a soil landfill cover by the following expression:

$$\Delta S_{LC} = P - R - \text{ET} - \text{PER}_{SW} \tag{11-29}$$

where ΔS_{LC} = change in the amount of water held in storage in a unit volume of landfill cover, in

P = amount of precipitation per unit area, in

R = amount of runoff per unit area, in

ET = amount of water lost through evapotranspiration per unit area, in

PER_{SW} = amount of water percolating through unit area of landfill cover into compacted solid waste, in

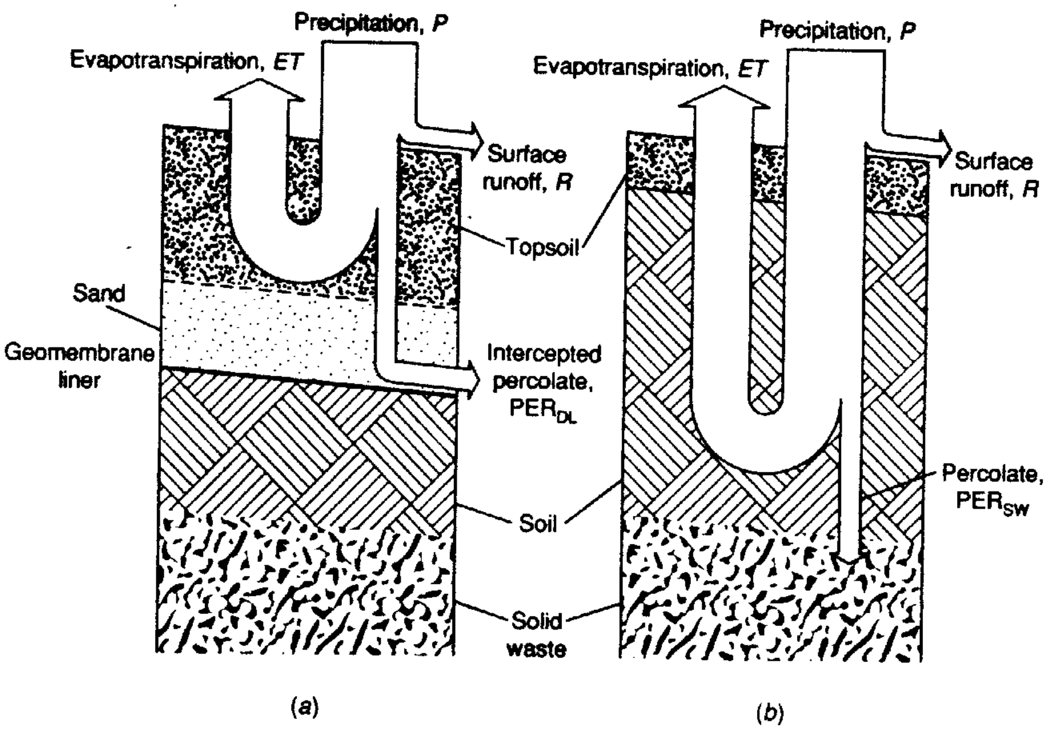


FIGURE 11-54
Definition sketch for moisture balance for landfill: (*a*) for landfill cover containing a drainage layer and geomembrane liner and (*b*) for landfill with no drainage layer (or geomembrane liner).

TABLE 11-20
Typical field capacity (FC) and permanent wilting point (PWP) values for various soil classifications[a]

Soil classification	Value, %			
	Field capacity		Permanent wilting point	
	Range	Typical	Range	Typical
Sand	6–12	6	2–4	4
Fine sand	8–16	8	3–6	5
Sandy loam	10–18	14	4–8	6
Fine sandy loam	14–22	18	6–10	8
Loam	18–26	22	8–12	10
Silty loam	19–28	24	9–14	10
Light clay loam	20–30	26	10–15	11
Clay loam	23–31	27	11–15	12
Silty clay	27–35	31	12–17	15
Heavy clay loam	29–36	32	14–18	16
Clay	31–39	35	15–19	17

[a] Adapted from Refs. 17, 27, 50.

TABLE 11-21
Typical runoff coefficients for storms of 5- to 10-year frequency*

		Runoff coefficient			
		With grass		Without grass	
Type of cover	Slope, %	Range	Typical	Range	Typical
Sandy loam	2	0.05–0.10	0.06	0.06–0.14	0.10
	3–6	0.10–0.15	0.12	0.14–0.24	0.18
	7	0.15–0.20	0.17	0.20–0.30	0.24
Silt loam	2	0.12–0.17	0.14	0.25–0.35	0.30
	3–6	0.17–0.25	0.22	0.35–0.45	0.40
	7	0.25–0.36	0.30	0.45–0.55	0.50
Tight clay	2	0.22–0.33	0.25	0.45–0.55	0.50
	3–6	0.30–0.40	0.35	0.55–0.65	0.60
	7	0.40–0.50	0.45	0.65–0.75	0.70

*Developed in part from Refs. 15, 27, 51.

The total amount of water that can be stored in a unit volume of soil will depend on the field capacity (FC) and the permanent wilting percentage (PWP). Soil moisture tension at FC is typically between 1/10 and 1/3 atm [17]. The PWP is defined as the amount of water left in a soil when plants are no longer able to extract any more. Soil moisture tension at PWP is approximately 15 atm [17]. The difference between the FC and PWP represents the amount of water that can be stored in a soil. Typical FC and PWP values for representative soils are given in Table 11-20. If a layered landfill cover is used, the field capacity of each layer must be considered in the analysis. Typical runoff coefficients for completed landfill covers are given in Table 11-21. Monthly precipitation and evapotranspiration data are site-specific, but local weather bureau data are usually acceptable. The application of Eq. (11-29) is illustrated in Example 11-12 in Section 11-12.

11-7 STRUCTURAL AND SETTLEMENT CHARACTERISTICS OF LANDFILLS

The structural characteristics and settlement of the landfill must be considered in the design of gas collection facilities, during filling operations, and before a decision is reached on the final use to be made of a completed landfill.

Structural Characteristics

When solid waste is initially placed in a landfill it behaves in a manner that is quite similar to other fill material. The nominal angle of repose for waste material placed in a landfill is approximately 1.5 to 1. Because solid waste has a tendency to slip when the slope angle is too steep, the slopes used for the completed portions of a landfill will vary from 2.5:1 to 4:1, with 3:1 being the most common. Because of the problems encountered with slippage due to settlement, many landfills where the height of the landfill will exceed 50 ft are benched (see Fig. 11-2). Benches help maintain slope stability and are also used for the placement of surface water drainage channels and for the location of landfill gas recovery piping.

In general, the construction of permanent facilities on completed landfills is not recommended because of the uneven settlement characteristics, variable bearing capacity of the upper layers of the landfill, and the potential problems that can result from gas migration, even with the use of gas collection facilities. When the final use of the landfill is known before waste placement begins, it is possible to control the deposition of certain materials during the operation of the landfill. For example, relatively inert materials such as construction and demolition wastes can be placed in those locations where buildings and/or other physical facilities are to be placed in the future.

Settlement of Landfills

As the organic material in landfill decomposes and weight is lost as landfill gas and leachate components, the landfill settles. Settlement also occurs as a result of increasing overburden mass as landfill lifts are added and as water percolates into and out of the landfill. Landfill settlement results in ruptures of the landfill surface and cover and breaks and misalignments of gas recovery facilities. It also interferes with subsequent use of the landfill after closure.

Effect of Waste Decomposition. Once placed in a landfill, the organic components of the waste will decompose, resulting in loss of as much as 30 to 40 percent of the total original mass. The loss of mass results in a loss of volume, which becomes available for refilling with new waste. The volume that is lost is usually filled in when the second lift is placed over the first lift. Weight and volume will also be lost after a landfill is closed. Evaluation of the effect of waste decomposition on settlement is considered in Example 11-13 in Section 11-12.

Effect of Overburden Pressure (Height). The specific weight of the material placed in the landfill will increase with the weight of the material placed above it, so that the average specific weight of waste in a lift depends on the depth of the lift. The maximum specific weight of solid waste residue in a landfill under overburden pressure will vary from 1750 to 2150 lb/yd^3 [21, 22]. The following relationship can be used to estimate the increase in the specific weight of the waste as a function of the overburden pressure:

$$SW_p = SW_i + \frac{p}{a + bp} \tag{11-30}$$

where SW_p = specific weight of the waste material at pressure p, lb/yd^3
SW_i = initial compacted specific weight of waste, lb/yd^3

p = overburden pressure, lb/in^2
a = empirical constant, (yd^3/in^2)(lb/in^2)
b = empirical constant, yd^3/lb

Typical specific weight versus applied pressure curves for compacted solid waste for several initial specific weights are shown in Fig. 11-55. For an initial specific weight of 1000 lb/yd^3 and a maximum specific weight of 2000 lb/yd^3, Eq. (11-30) can be written as follows:

$$D_{W_p} = 1000 \text{ lb/yd}^3 + \frac{p, \text{ lb/in}^2}{0.0133 \text{ (yd}^3\text{/lb)(lb/in}^2) + (0.001 \text{ yd}^3\text{/lb)}(p, \text{ lb/in}^2)}$$

The increase in the specific weight of the waste material in the landfill is important (1) in determining the actual amount of waste that can be placed in a landfill up to a given grade limitation and (2) in determining the degree of settlement that can be expected in a completed landfill after closure. Both of these issues are addressed in Example 11-13 in Section 11-12.

Extent of Settlement. The extent of settlement depends on the initial compaction, the characteristics of the wastes, the degree of decomposition, the effects of consolidation when water and air are forced out of the compacted solid waste, and the height of the completed fill. Representative data on the degree of settlement to be expected in a landfill as a function of the initial compaction are shown in Fig. 11-56. It has been found in various studies that about 90 percent of the ultimate settlement occurs within the first five years. In dry climates the settling rate is usually less. The settlement of landfills is modeled in Example 11-13 in Section 11-12.

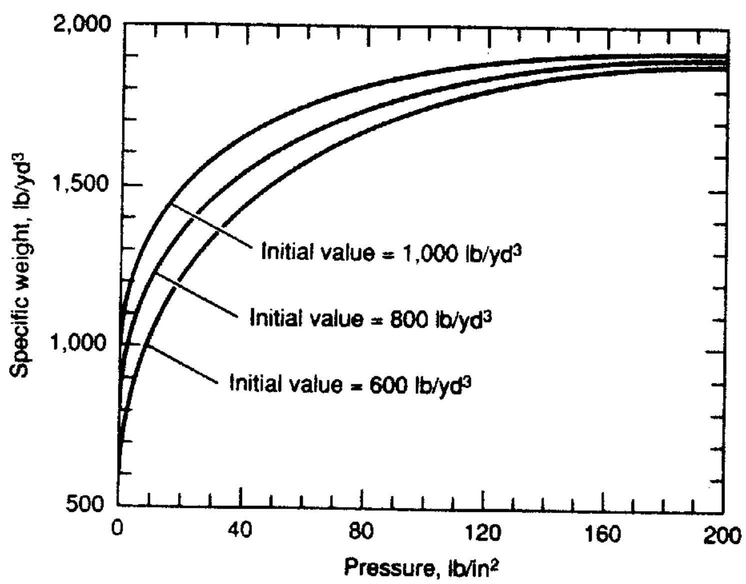


FIGURE 11-55
Specific weight of solid waste placed in landfill as function of the initial compacted specific weight of the waste and the overburden pressure.

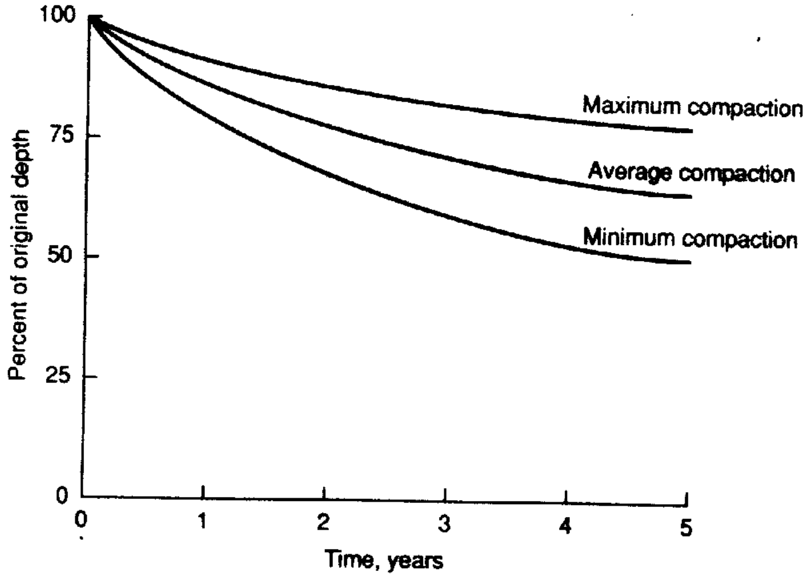


FIGURE 11-56
Surface settlement of compacted landfills.

11-8 ENVIRONMENTAL QUALITY MONITORING AT LANDFILLS

Environmental monitoring is conducted at sanitary landfills to ensure that no contaminants that may affect public health and the surrounding environment are released from the landfill. The monitoring required may be divided into three general categories: (1) vadose zone monitoring for gases and liquids, (2) groundwater monitoring, and (3) air quality monitoring. Environmental monitoring involves the use of both sampling and nonsampling methods. Sampling methods involve the collection of a sample for analysis, usually at an offsite laboratory. The typical instrumentation of a landfill for environmental monitoring is illustrated in Fig. 11-57. Nonsampling methods are used to detect chemical and physical changes in the environment as a function of an indirect measurement such as a change in electrical current. Representative devices that have been used to monitor landfill sites are listed in Table 11-22.

Vadose Zone Monitoring

The vadose zone is defined as that zone from the ground surface to where the permanent groundwater is found (see Fig. 11-58). An important characteristic of the vadose zone is that the pore spaces are not filled with water, and that the small amounts of water that are present coexist with air. Vadose zone monitoring at landfills involves both liquids and gases.

Liquid Monitoring in the Vadose Zone. Monitoring for liquids in the vadose zone is necessary to detect any leakage of leachate from the bottom of a landfill. In the vadose zone, moisture held in the interstices of the soil particles or within

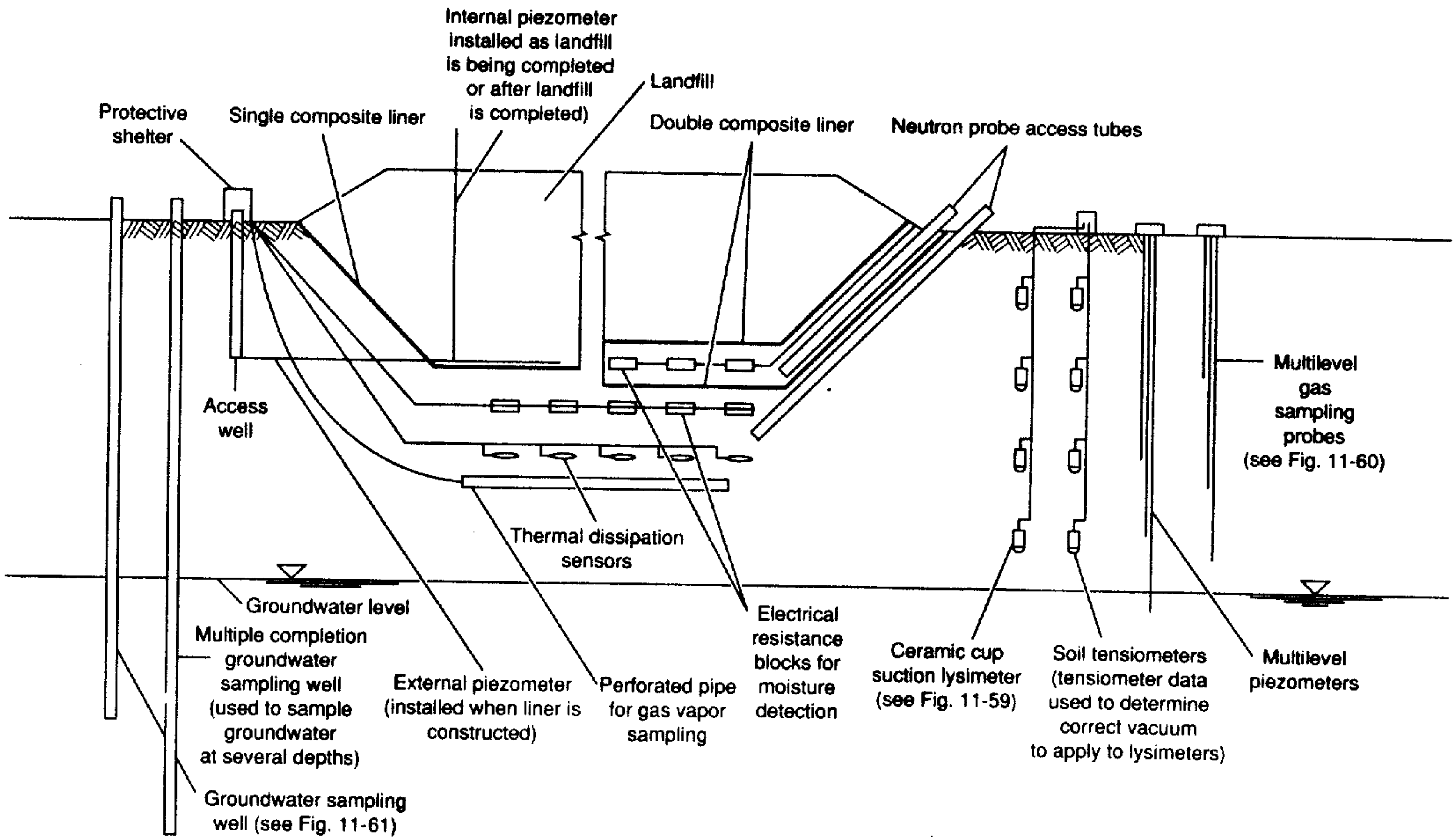


FIGURE 11-57
Instrumentation of a landfill for the collection of environmental monitoring data. Note not all of the instrumentation shown would be used at an individual landfill.

TABLE 11-22
Representative devices used to monitor landfill gases and leachate at landfills

Type	Application/description
	Sampling methods[a]
Air quality	
Active air sampler	Continuous collection and analysis of gas samples
Air collection bag	Collection of air grab samples for analysis
Evacuated flask	Collection of air grab samples for analysis
Gas syringe	Collection of air grab samples for analysis
Groundwater	
Monitoring wells; single and multiple depth	Used to collect groundwater samples. Multiple extraction wells are used to collect samples from different depths
Piezometers	Used to collect groundwater samples
In landfills	
Piezometers	Used to collect leachate samples. Piezometers can be installed before filling of the landfill is initiated or after the landfill has been completed.
Vadose zone	
Collection lysimeter	Used to collect liquid samples below landfill liners
Soil gas probes; single and multiple depth	Used to monitor landfill gases and volatile organic compounds (VOC) in the soil. The gas may be analyzed *in situ* using a portable gas chromatograph or tested in a laboratory after it has been absorbed in charcoal.
Suction cup lysimeter	Used to obtain liquid samples from the vadose zone
	Nonsampling methods[b]
Groundwater	
Conductivity cells	Used to monitor changes in groundwater conductivity. Conductivity cells are ofter located in or near monitoring wells
In landfills	
Piezometers	Used to measure the depth of leachate in landfills
Temperature blocks	Used to measure temperature
Temperature probes	Used to measure temperature
Vadose zone	
Electrical probes	Used to determine the salinity of the vadose zone. A four-probe array is installed so that conductivity of the soil can be measured.

(continued)

porous rock is always held at pressures below atmospheric pressure. To remove the moisture it is necessary to develop a negative pressure or vacuum to pull the moisture away from the soil particles. Because suction must be applied to draw moisture out of the soil in the vadose zone, conventional wells or other open cavities cannot be used to collect samples in this zone. The sampling devices used for sample extraction in the unsaturated zone are called suction lysimeters.

TABLE 11-22 (*continued*)

Type	Application/description
	Nonsampling methods (*continued*)
Vadose zone (*cont.*)	
Electrical resistance blocks	Used to measure changes in water content of the vadose zone. Electrode blocks embedded in porous material are installed in the soil. Electrical properties of the blocks change with the changing water content of the vadose zone.
Gamma ray attenuation probes	Used for detecting changes in moisture content of the vadose zone. Based on the attenuation of gamma rays transmission and scattering. In the transmission method, two wells are installed at a known distance apart. A single well is used in the scattering method. Usually limited to shallow depth because of difficulties in installing parallel wells.
Heat dissipation sensors	Used to monitor water content of the vadose zone by measuring the rate of heat dissipation from the block to the surrounding soil.
Neutron moisture meter	Used to obtain a profile of the moisture content of the soil below the landfill. Meter can be installed below a landfill or moved through a borehole next to the landfill.
Salinity sensors	Used to monitor soil salinity. Electrodes attached to a porous ceramic cup are installed in the soil.
Tensiometers	Used to measure the matric potential of soil. Tensiometers measure the negative pressure (capillary pressure) that exists in unsaturated soil.
Thermocouple psychrometers	Used to detect changes in moisture content. Operation is based on cooling of a thermocouple junction by the peltier effect. Wet bulb and dew point. The dew point method is used more commonly in landfill monitoring.
Time domain reflectrometry (TDR)	Based on the difference in dielectric properties of water and soil. Wide-frequency bandwidth and short pulse length that are sensitive to the high-frequency electrical properties of the material are measured.
Wave sensing devices	Use of both seismic and acoustic wave propagation properties for leak detection. In the seismic wave technique, the difference in travel time of Rayleigh waves between the source and geophones is used to detect leaks. In the acoustic emmission monitoring (AEM) technique, sound waves generated by flowing water from a leak are utilized in leak detection.

[a] Methods involving the collection of samples for subsequent laboratory analysis.

[b] Methods involving physical and electrical measurements.

Three commonly used classes of lysimeters are (1) the ceramic cup, (2) the hollow fiber, and (3) the membrane filter [2, 43].

The most commonly used device for obtaining samples of moisture in the vadose zone is the ceramic cup sampler (see Fig. 11-59), which consists of a porous cup or ring made of ceramic material that is attached to a short section of nonporous tubing (e.g., PVC). When placed in the soil, because of its pores

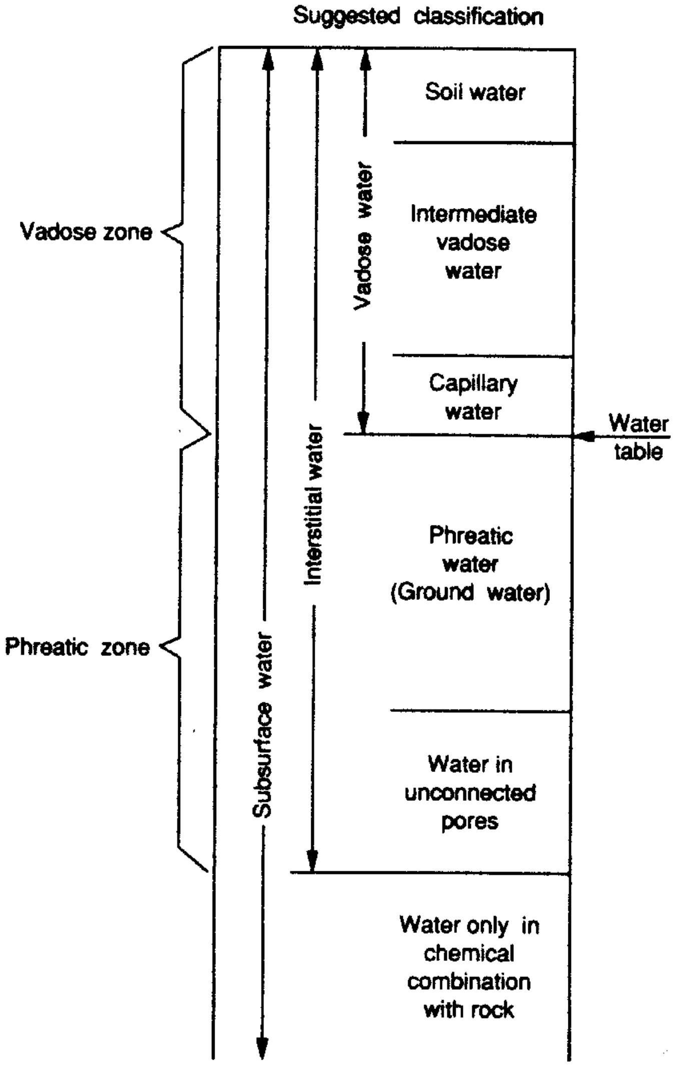


FIGURE 11-58
Classification of subsurface water. (Courtesy of California Integrated Waste Management Board.)

it becomes an extension of the pore space of the soil. Soil moisture is drawn in through the porous ceramic element by the application of a vacuum. When a sufficient amount of water has collected in the sampler, the collected sample is pulled to the surface through a narrow tube by the application of a vacuum or is pushed up by air pressure.

Gas Monitoring in the Vadose Zone. Monitoring for gases in the vadose zone is necessary to detect the lateral movement of any landfill gases. A typical example of a vadose zone gas monitoring probe is illustrated in Fig. 11-60. In many monitoring systems, gas samples are collected from multiple depths in the vadose zone.

Groundwater Monitoring

Monitoring of the groundwater is necessary to detect changes in water quality that may be caused by the escape of leachate and landfill gases. Both down- and up-

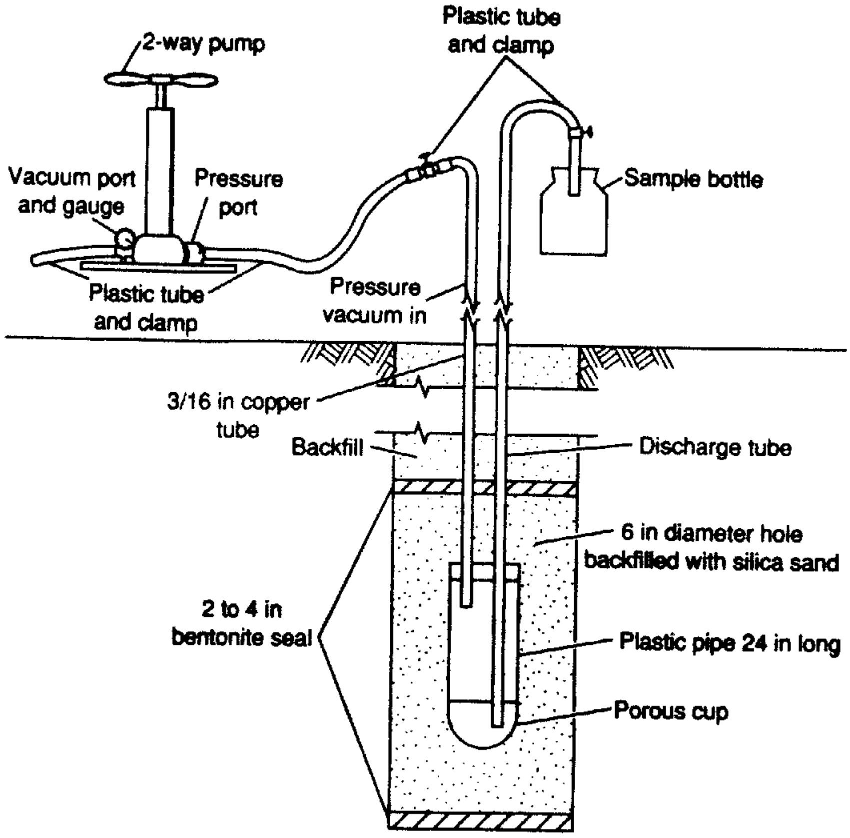


FIGURE 11-59
Porous cup suction lysimeter for the collection of liquid samples from the vadose zone. (Courtesy of California Integrated Waste Management Board.)

gradient wells are required to detect any contamination of the underground aquifer by leachate from the landfill. An example of a well used for the monitoring of groundwater is illustrated in Fig. 11-61. To obtain a representative sample, the liquid in permanent sample collection tubing, where used, must be purged before the sample is collected.

Landfill Air Quality Monitoring

Air quality monitoring at landfills involves (1) the monitoring of ambient air quality at and around the landfill site, (2) the monitoring of landfill gases extracted from the landfill, and (3) the monitoring of the off gases from any gas processing or treatment facilities.

Monitoring Ambient Air Quality. Ambient air quality is monitored at landfill sites to detect the possible movement of gaseous contaminants from the boundaries of the landfill site. Gas sampling devices can be divided into three categories: (1) passive, (2) grab, and (3) active. Passive sampling involves the collection of a gas sample by passing a stream of gas through a collection device in which the contaminants contained in the gas stream are removed for subsequent analysis.

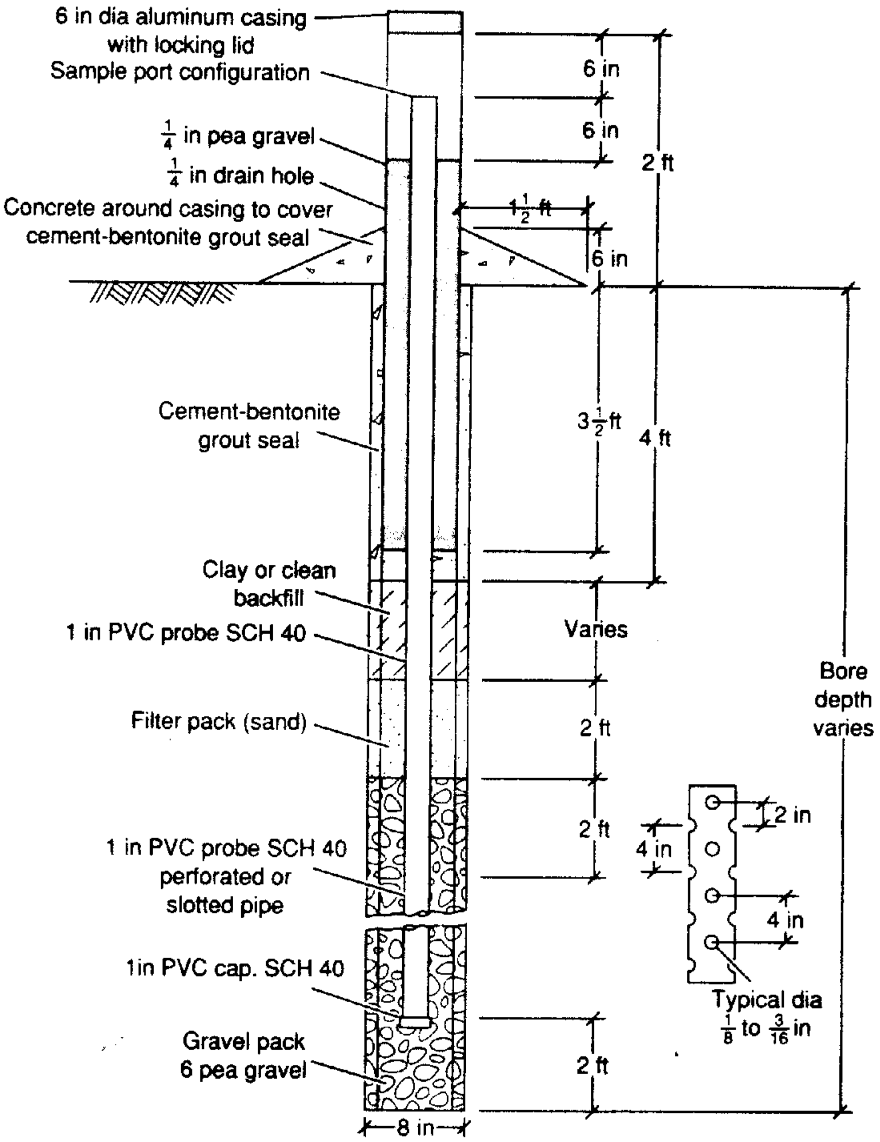


FIGURE 11-60
Vadose zone gas monitoring probe. (Courtesy of Waste Management, Inc.)

Commonly used in the past, passive sampling is seldom used today. Grab samples are collected using an evacuated flask, gas syringe, or an air collection bag made of a synthetic material (see Fig. 11-62). An active sampler involves the collection and analysis of a continuous stream of gas.

Monitoring Extracted Landfill Gas. Landfill gas is monitored to assess the composition of the gas, and to determine the presence of trace constituents that may pose a health or environmental risk.

Monitoring Off-Gases. Monitoring off-gases from treatment and energy recovery facilities is done to determine compliance with local air pollution control requirements. Both grab and continuous sampling have been used for this purpose.

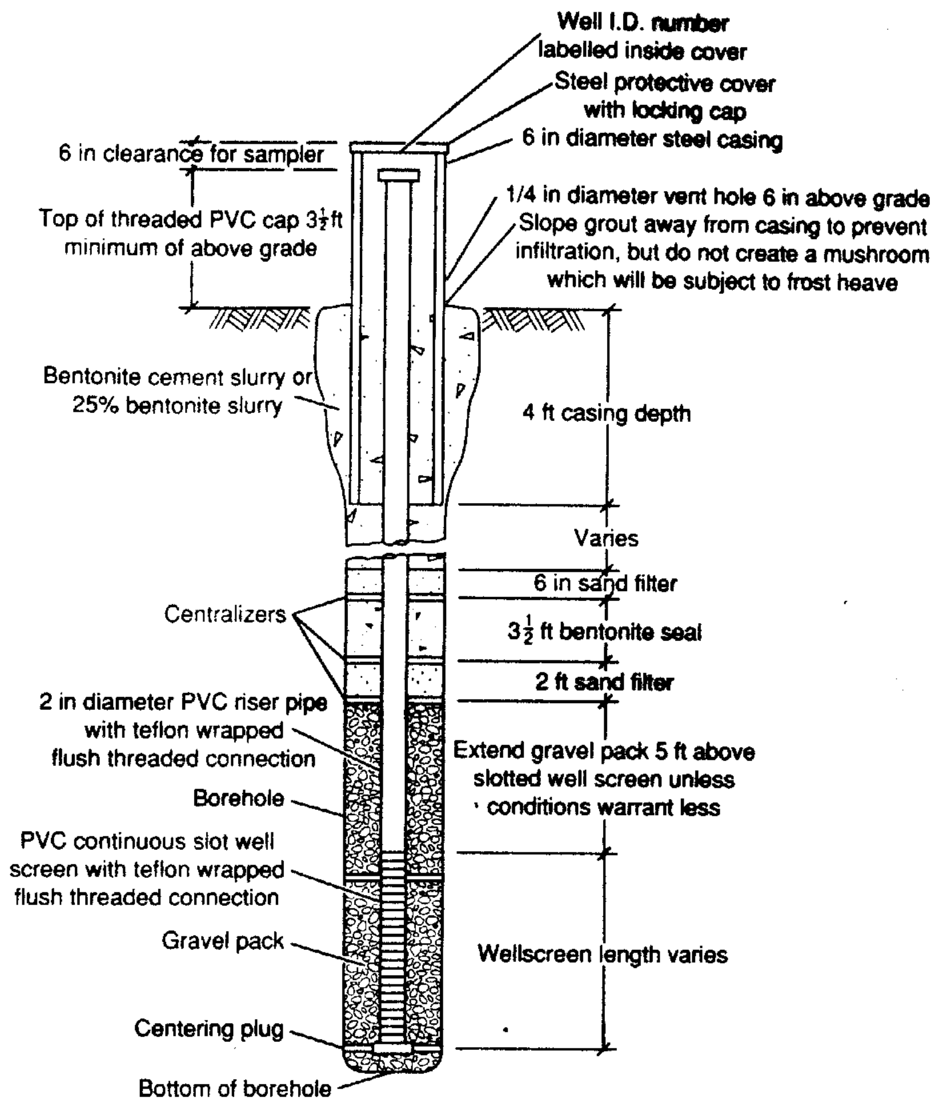


FIGURE 11-61
Typical groundwater monitoring well. (Courtesy of Waste Management, Inc.; see also Fig. 16-5.)

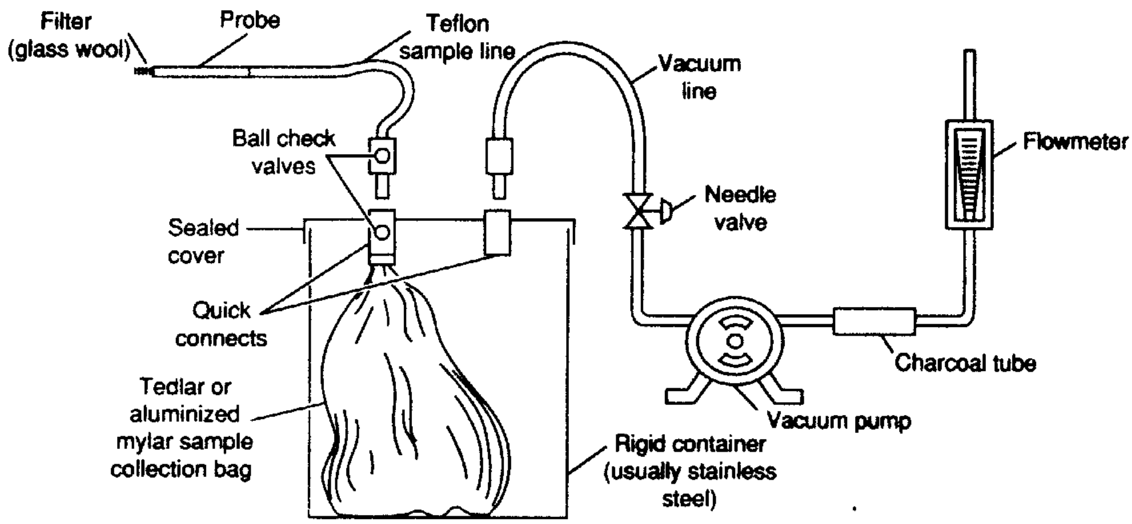


FIGURE 11-62
Sampling apparatus for the collection of air grab samples at landfills.

11-9 LAYOUT AND PRELIMINARY DESIGN OF LANDFILLS

Once the number of potential locations for landfill sites has been narrowed down on the basis of a review of the available preliminary information, it will usually be necessary to prepare a preliminary engineering design report for each site to assess the costs associated with preparation of the site for filling, placement of solid wastes, and closing of the site once filling operations have ceased. The preliminary engineering design report differs from the complete evaluation required for the final selection of a site, which includes environmental considerations.

Among the important topics that must be considered in an engineering design report, though not necessarily in the order given, are the following: (1) layout of landfill site, (2) types of wastes that must be handled, (3) the need for a convenience transfer station, (4) estimation of landfill capacity, (5) evaluation of the geology and hydrogeology of the site, (6) selection of leachate control facilities, (7) selection of landfill gas control facilities, (8) layout of surface drainage facilities, (9) aesthetic design considerations, (10) monitoring facilities, (11) determination of equipment requirements, and (12) development of an operations plan. The development of an operations plan for a landfill is considered in the following section. Closure and postclosure care is considered in Section 11-11. Important factors that must be considered in the design of landfills are reported in Table 11-23. Throughout the development of the engineering design report, careful consideration must be given to the final use or uses to be made of the completed site. Land reserved for administrative offices, buildings, and parking lots should be filled with dirt only and should be sealed against the entry of gases.

Layout of Landfill Sites

In planning the layout of a landfill site, the location of the following must be determined: (1) access roads; (2) equipment shelters; (3) scales, if used; (4) office space; (5) location of convenience transfer station, if used; (6) storage and/or disposal sites for special wastes; (7) areas to be used for waste processing (e.g., composting); (8) definition of the landfill areas and areas for stockpiling cover material; (9) drainage facilities; (10) location of landfill gas management facilities; (11) location of leachate treatment facilities, if required; (12) location of monitoring wells; and (13) plantings. A typical layout for a landfill disposal site is shown in Fig. 11-63. Because site layout is specific for each case, Fig. 11-63 is meant to serve only as a guide. However, the items identified on Fig. 11-63 can be used as a check list of the areas that must be addressed in the preliminary layout of a landfill. An aerial view of an operating landfill is shown in Fig. 11-64.

Types of Wastes

Knowledge of the types of wastes to be handled is important in the design and layout of a landfill, especially if special wastes are involved. It is usually best

TABLE 11-23
Important factors to consider in the design of landfills

Factors	Remarks
Access	Paved all-weather access roads to landfill site; temporary roads to unloading areas.
Land area	Area should be large enough to hold all community wastes for a minimum of 5 yr, but preferably 10 to 25 yr; area for buffer strips or zones must also be included.
Landfilling method	Landfilling method will vary with terrain and available cover; most common methods are excavated cell/trench, area, canyon (see Figs. 11-7, 11-8, and 11-9).
Completed landfill characteristics	Finished slopes of landfill, 3 to 1; height to bench, if used, 50 to 75 ft; slope of final landfill cover, 3 to 6%.
Surface drainage	Install drainage ditches to divert surface water runoff; maintain 3 to 6% grade on finished landfill cover to prevent ponding; develop plan to divert stormwater from lined but unused portions of landfill.
Intermediate cover material	Maximize use of onsite soil materials; other materials such as compost produced from yard waste and MSW can also be used to maximize the landfill capacity; typical waste to cover ratios vary from 5 to 1 to 10 to 1.
Final cover	Use multilayer design (see Fig. 11-53); slope of final landfill cover, 3–6%.
Landfill liner	Single clay layer (2 to 4 ft) or multilayer design incorporating the use of a geomembrane (see Figs. 11-36, 11-39, and 11-40). Cross slope for terrace type (see Fig. 11-39) leachate collection systems, 1 to 5%; maximum flow distance over terrace, 100 ft; slope of drainage channels, 0.5 to 1.0%. Slope for piped type (see Fig. 11-40) leachate collection system, 1 to 2%; size of perforated pipe, 4 in; pipe spacing, 20 ft.
Cell design and construction	Each day's wastes should form one cell; cover at end of day with 6 in of earth or other suitable material; typical cell width, 10 to 30 ft; typical lift height including intermediate cover, 10 to 14 ft; slope of working faces, 2:1 to 3:1.
Groundwater protection	Divert any underground springs; if required, install perimeter drains, well point system, or other control measures.
Landfill gas management	Develop landfill gas management plan including extraction wells (see Fig. 11-20), manifold collection system, condensate collection facilities (see Fig 11-26), the vacuum blower facilities, and flaring facilities (see Fig. 11-27) and/or energy production facilities (see Fig. 11-29). Operating vacuum at well head, 10 in of water.
Leachate collection	Determine maximum leachate flow rates and size leachate collection pipe and/or trenches; size leachate pumping facilities; select collection pipe materials to withstand static pressures corresponding to the maximum height of the landfill.
Leachate treatment	Based on expected quantities of leachate and local environmental conditions, select appropriate treatment process (see Table 11-18 and Fig. 11-46).
Environmental requirements	Install vadose zone gas and liquid monitoring facilities; install up- and downgradient groundwater monitoring facilities; locate ambient air monitoring stations.
Equipment requirements	Number and type of equipment will vary with the type of landfill (see Figs. 11-68 and 11-69) and the capacity of the landfill (see Table 11-26).
Fire prevention	Water onsite; if nonpotable, outlets must be marked clearly; proper cell separation prevents continuous burn-through if combustion occurs.

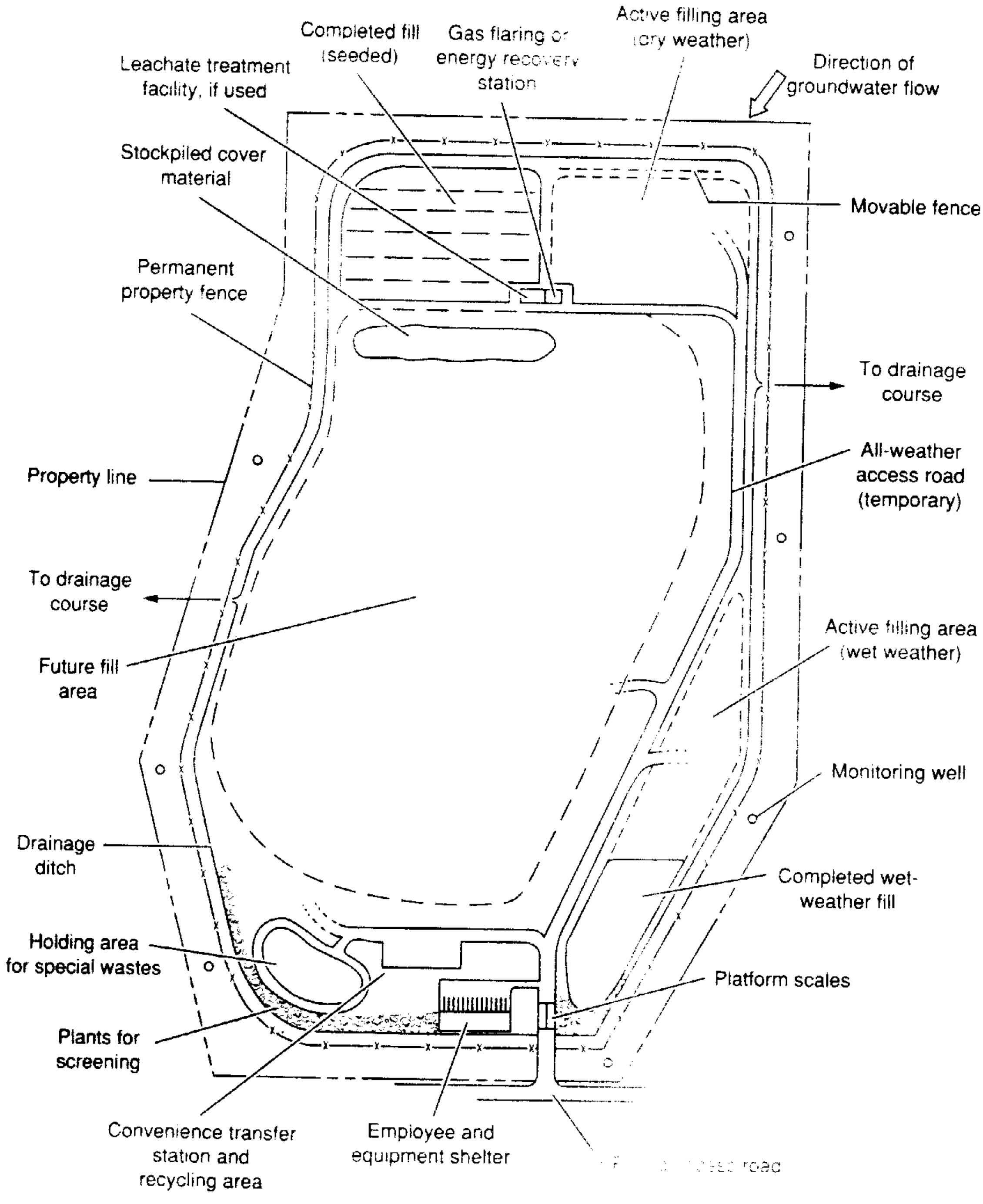


FIGURE 11-63
Typical layout of a landfill site.

to develop separate disposal sites or monofills for designated and special wastes such as asbestos because under most conditions special preparation of the site will be necessary before these wastes can be landfilled. The associated disposal costs are often significant, and it is wasteful to use this landfill capacity for wastes that do not require special precautions. If significant quantities of demolition wastes are to be handled, it may be possible to use them for embankment stabilization.

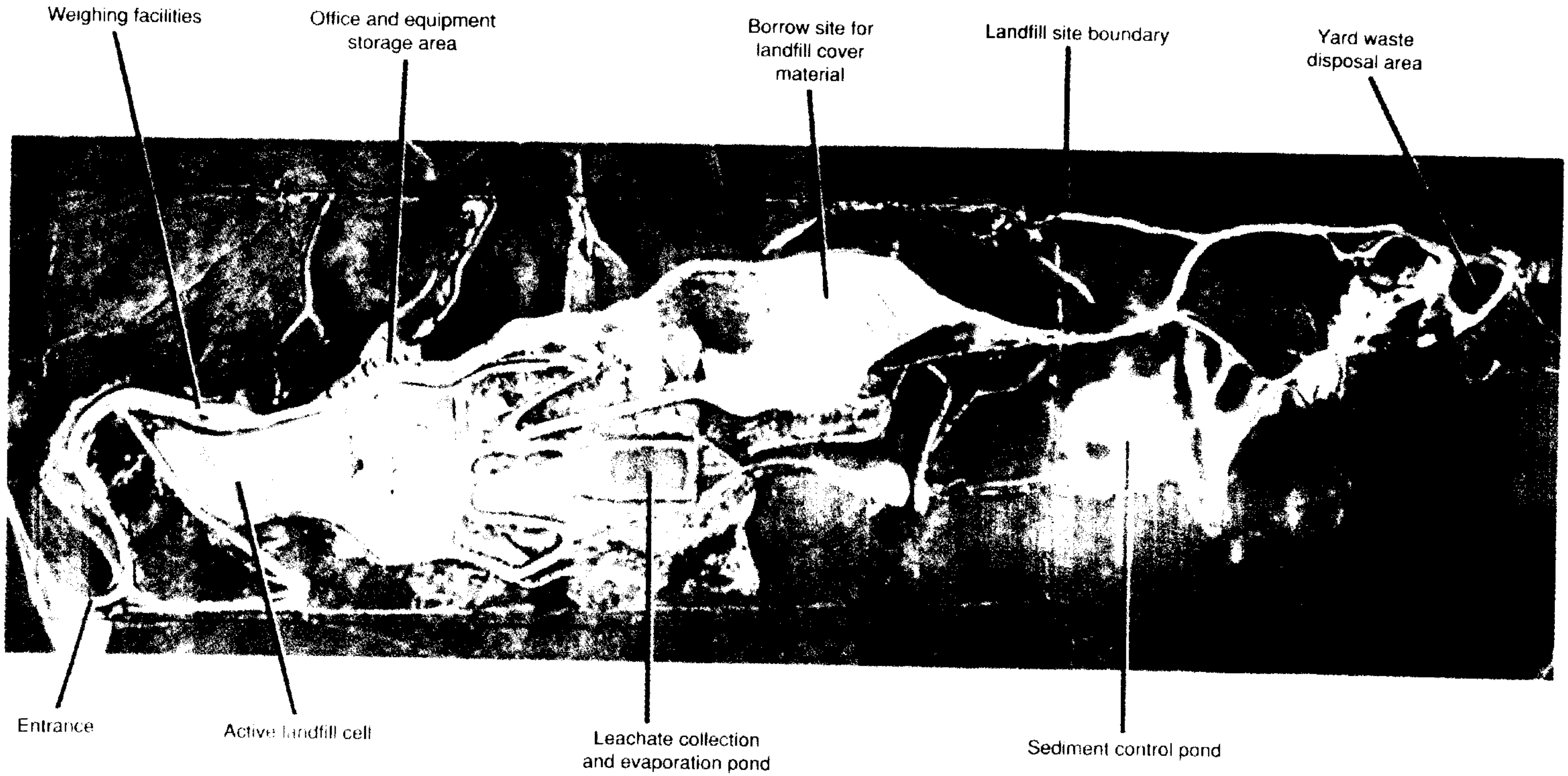


FIGURE 11-64
Aerial view of an operating landfill which receives about 80 ton/d of solid wastes. (Courtesy of Jack Scroggs, KASL Engineers.)

Need for a Convenience Transfer Station

Because of safety concerns and the many new restrictions governing the operation of landfills, many operators of landfills have constructed convenience transfer stations at the landfill site for the unloading of wastes brought to the site by individuals and small-quantity haulers (see Figs. 10-9 and 10-11). Having a separate transfer facility reduces the potential for accidents at the working face of the landfill significantly. The transfer facilities are also used for the recovery of recyclable materials. Waste materials are usually emptied into two large transfer trailers each of which is hauled to the disposal site, emptied, and returned to the transfer station. The need for a convenience transfer station will depend on the physical characteristics and the operation of the landfill and whether there is a separate location where the public can be allowed to dispose of waste safely.

Estimation of Landfill Capacity

Earlier in the chapter, an approximate method was given for determining the area requirements for landfill (see Example 11-1). In this section consideration is given to (1) the method used to estimate the nominal volume of the site, (2) the impact of the compactability of the individual solid waste components, (3) the impact of daily cover, and (4) the impact of waste decomposition and overburden height.

Determination of Nominal Landfill Volume. The nominal volumetric capacity of a proposed landfill site is determined by first laying out several different landfill configurations, taking into account appropriate design criteria (see Fig. 11-65). The next step is to determine the surface area for each lift. The nominal volume of the landfill is determined by multiplying the average area between two adjacent contours by the height of the lift and summing the volume of successive lifts. If the cover material will be excavated from the site, then the computed volume corresponds to the volume of solid waste that can be placed in the site. If the cover material has to be imported, then the computed capacity must be reduced by a factor to account for the volume occupied by the cover material. For example, if a cover to waste ratio of 1 to 5 is adopted, then the capacity reported must be multiplied by a factor of 0.833 (5/6). The determination of the nominal volume of a landfill site is considered in Example 11-7 in Section 11-12.

The nominal volumetric capacity of the landfill is used as a preliminary estimate of landfill capacity. The actual total capacity of the landfill to accept waste on a weight basis will depend on the initial specific weight at which the residual solid waste is placed in the landfill, on the subsequent compaction of the waste material due to overburden pressure, and on loss of mass as a result of biological decomposition. The impacts of these factors on the capacity of the landfill are considered in the following discussion.

Impact of Compactability of Solid Waste Components. The initial density of solid wastes placed in a landfill varies with the mode of operation of the

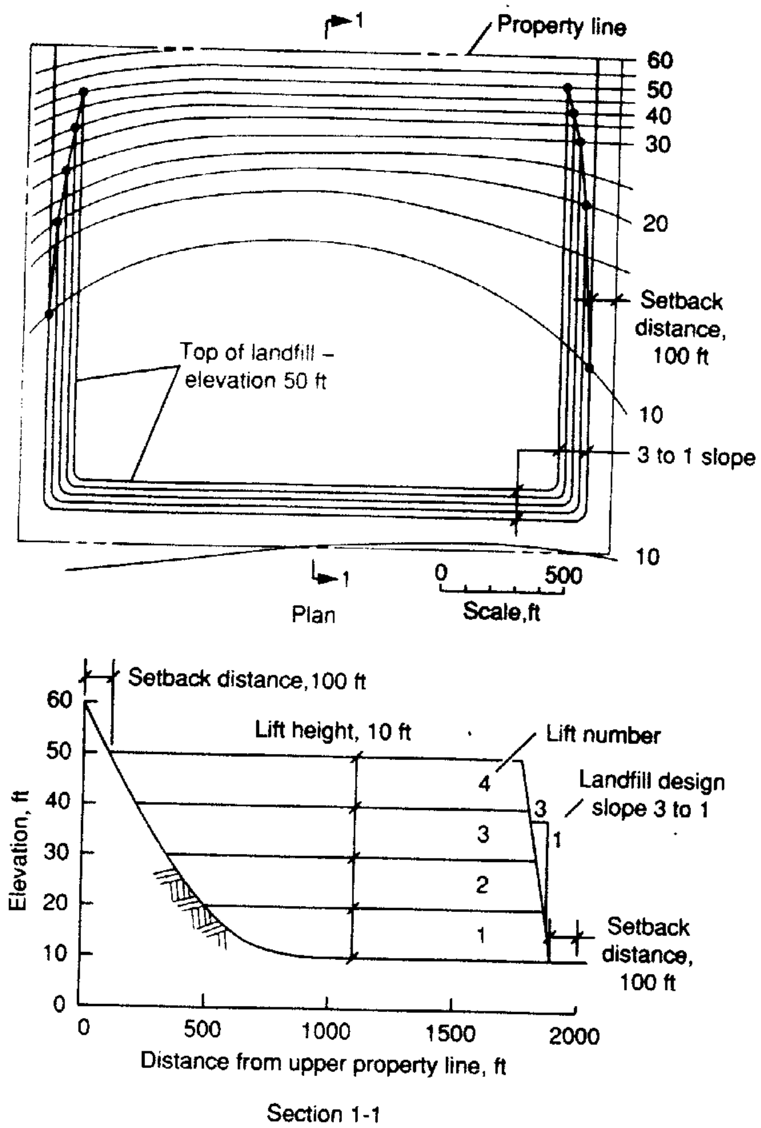


FIGURE 11-65
Layout of typical landfill for the purpose of estimating the volumetric capacity of a proposed site taking into account setback distances (100 ft), finished landfill slopes (3 to 1), and lift height (10 ft).

landfill, the compactability of the individual solid waste components, and the percentage distribution of the components. If the waste placed in the landfill is spread out in thin layers and compacted against an inclined surface, a high degree of compaction can be achieved. With minimal compaction, the initial specific weight will be somewhat less than the compacted specific weight in a collection vehicle. In general, the initial specific weight of solid waste placed in a landfill will vary from 550 to 1200 lb/yd^3, depending on the degree of initial compaction given to the waste. The diversion of waste materials before disposal will not only reduce the landfill volume requirements but will also affect the overall compactability of the remaining waste materials. Typical compactability data for the components found in MSW are reported in Table 11-24. Volume-reduction factors are given for both normally compacted and well-compacted landfills. The use of the data presented in Table 11-24 is illustrated in Example 11-5.

TABLE 11-24
Typical compaction factors for various solid waste components placed in landfills

	Compaction factors for components in landfills*		
Component	**Range**	**Normal compaction**	**Well compacted**
Organic			
Food wastes	0.2–0.5	0.35	0.33
Paper	0.1–0.4	0.2	0.15
Cardboard	0.1–0.4	0.25	0.18
Plastics	0.1–0.2	0.15	0.10
Textiles	0.1–0.4	0.18	0.15
Rubber	0.2–0.4	0.3	0.3
Leather	0.2–0.4	0.3	0.3
Garden trimmings	0.1–0.5	0.25	0.2
Wood	0.2–0.4	0.3	0.3
Inorganic			
Glass	0.3–0.9	0.6	0.4
Tin cans	0.1–0.3	0.18	0.15
Nonferrous metals	0.1–0.3	0.18	0.15
Ferrous metals	0.2–0.6	0.35	0.3
Dirt, ashes, brick, etc.	0.6–1.0	0.85	0.75

*Compaction factor = V_f / V_i where V_f = final volume of solid waste after compaction and V_i = initial volume of solid waste before compaction.

Example 11-5 Determination of density of compacted solid wastes without and with waste diversion. Determine the specific weight in a well-compacted landfill for solid wastes with the characteristics given in Table 3-4. Also determine the impact of a resource recovery program on landfill area requirements in which 50 percent of the paper and 80 percent of the glass and tin cans are recovered. Assume that the wastes have the characteristics reported in Table 3-4.

Solution

1. Set up a computation table with separate columns for (1) the weight of the individual solid waste components, (2) the volume of the wastes as discarded, (3) the compaction factors for well-compacted solid wastes, and (4) the compacted volume in the landfill. The required table, based on a total weight of 1000 lb, is given on page 475.
2. Compute the compacted specific weight of the solid wastes.

$$\text{Compacted specific weight} = \frac{1000 \text{ lb} \times 27 \text{ ft}^3/\text{yd}^3}{28.95 \text{ ft}^3}$$

$$= 933 \text{ lb/yd}^3 \ (554 \text{ kg/m}^3)$$

3. Determine the compacted specific weight of the wastes in the landfill in which 50 percent of the paper and 80 percent of the glass and tin cans are recovered.

Component	Weight of solid waste,[a] lb	Volume as discarded,[b] ft^3	Compaction factor[c]	Compacted volume in landfill, ft^3
Organic				
Food wastes	90	4.96	0.33	1.64
Paper	340	61.2	0.15	9.18
Cardboard	60	19.06	0.18	3.53
Plastics	70	17.18	0.10	1.72
Textiles	20	4.91	0.15	0.74
Rubber	5	0.61	0.3	0.18
Leather	5	0.50	0.3	0.15
Yard wastes	185	29.38	0.2	5.88
Wood	20	1.35	0.3	0.41
Inorganic				
Glass	80	6.55	0.4	2.62
Tin cans	60	10.80	0.15	1.62
Aluminum	5	0.50	0.15	0.08
Other metal	30	1.50	0.3	0.45
Dirt, ashes, brick, etc.	30	1.00	0.75	0.75
Total	1000			28.95

[a] See Table 3-4.
[b] See Table 3-9.
[c] See Table 11-23.

(*a*) Determine the weight of waste after resource recovery.

$$\text{Weight remaining} = 1000 \text{ lb} - (340 \text{ lb} \times 0.5 + 80 \text{ lb} \times 0.80 + 60 \text{ lb} \times 0.80)$$
$$= 718 \text{ lb}$$

(*b*) Determine the volume and compacted specific weight of waste after resource recovery.

$$\text{Volume remaining} = 28.95 \text{ ft}^3 - (9.18 \text{ ft}^3 \times 0.5 + 2.62 \text{ ft}^3 \times 0.80 + 1.62 \text{ ft}^3 \times 0.80) = 20.97 \text{ ft}^3$$

$$\text{Compacted specific weight} = \frac{718 \text{ lb} \times 27 \text{ ft}^3/\text{yd}^3}{20.97 \text{ ft}^3}$$
$$= 924 \text{ lb/yd}^3 \ (548 \text{ kg/m}^3)$$

Comment. The specific weight value of 933 lb/yd^3 (computed in Step 2) would then be used to determine the required landfill area. Because the specific weight computed in Step 2 is essentially the same as that computed in Step 3, the impact of the materials recovery program can be assessed on the basis of the weight reduction alone. In cases where the computed compacted specific weight changes significantly as a result of a materials recovery program, the required landfill area can also be reduced by the ratio of compacted specific weights. Large changes in the specific weight value will not be observed with materials recovery where a sizable fraction of the wastes are composed of garden trimmings.

Impact of Cover Material. Cover material, typically soil, is incorporated into a landfill at each stage of its construction. Daily cover, consisting of 6 in to 1 ft of soil, is applied to the working faces of the landfill at the close of operation each day to control disease vectors such as insects and rats, and to stop material from blowing from the working face. Interim cover is a thicker layer of daily cover material applied to areas of the landfill that will not be worked for some time. Final covers usually are 3 to 6 ft thick and include a layer of compacted clay, with other layers to enhance drainage and support surface vegetation. The quantity of cover material necessary for operation of the landfill is an important factor in determining the capacity of a landfill site. Usually, daily and interim cover needs are expressed as a waste:soil ratio, defined as the volume of waste deposited per unit volume of cover provided. Typically, waste:soil ratios range from 4:1 to 10:1.

The waste:soil ratio can be estimated by considering the geometry of a landfill cell. Cells usually are roughly parallelepipeds, with cover material on three of the six sides. The surface area of those faces depends on the slope of the working faces of the landfill, the cell volume, the lift height, and the width of the bench in which the waste is placed. Working face slopes are usually in the range of 2:1 to 3:1. The volume of the cell can be calculated by dividing the average mass of material deposited per day by the average density of the lift. Lift height and cell width should be selected to provide the lowest acceptable waste:soil ratio. The volume of daily cover should be calculated for different lift heights and bench widths, and for the minimum and maximum waste deposition rates. Calculation of waste:soil ratio is illustrated in Example 11-6.

Example 11-6 Determination of waste to soil ratio. Determine the ratio of waste to cover material (volume basis) as a function of the initial compacted specific weight for a solid waste stream of 70 tons per day to be placed in 10 ft lifts with a cell width of 15 ft. The slope of the working faces is 3:1. Assume that the waste is compacted initially to an average specific weight of 600, 800, and 1000 lb/yd³. The daily cover thickness is 6 in.

Solution

1. Determine the daily volume of the deposited solid waste.

   (*a*) For 600 lb/yd³

$$V_d = 70 \text{ ton/d} \times 2000 \text{ lb/ton} \times \frac{1 \text{ yd}^3}{600 \text{ lb}}$$

$$V_d = 233.3 \text{ yd}^3$$

   (*b*) For 800 lb/yd³

$$V_d = 175.0 \text{ yd}^3$$

   (*c*) For 1000 lb/yd³

$$V_d = 140.0 \text{ yd}^3$$

2. Determine the length of each daily cell.
   (*a*) For 600 lb/yd³

$$L = \frac{233.3 \text{ yd}^3 \times 27 \text{ ft}^3/\text{yd}^3}{10 \text{ ft} \times 15 \text{ ft}} = 41.9 \text{ ft}$$

   (*b*) For 800 lb/yd³

$$L = 31.5 \text{ ft}$$

   (*c*) For 1000 lb/yd³

$$L = 25.2 \text{ ft}$$

3. Determine cell surface areas.
   (*a*) For the top of the cell

$$A_{T600} = 41.9 \text{ ft} \times 15 \text{ ft} = 628.5 \text{ ft}^2$$

$$A_{T800} = 31.5 \text{ ft} \times 15 \text{ ft} = 472.5 \text{ ft}^2$$

$$A_{T1000} = 25.2 \text{ ft} \times 15 \text{ ft} = 378.0 \text{ ft}^2$$

   (*b*) For the face of the cell

$$A_{F600} = 41.9 \text{ ft} \times \sqrt{(10 \text{ ft})^2 + (3 \times 10 \text{ ft})^2} = 1325 \text{ ft}^2$$

$$A_{F800} = 31.5 \text{ ft} \times \sqrt{(10 \text{ ft})^2 + (3 \times 10 \text{ ft})^2} = 996 \text{ ft}^2$$

$$A_{F1000} = 25.2 \text{ ft} \times \sqrt{(10 \text{ ft})^2 + (3 \times 10 \text{ ft})^2} = 797 \text{ ft}^2$$

   (*c*) For the side of the cell

$$A_S = 15 \text{ ft} \times \sqrt{(10 \text{ ft})^2 + (3 \times 10 \text{ ft})^2} = 474 \text{ ft}^2$$

4. Determine volume of soil for daily cover.

$$V_C = 6 \text{ in} \times \frac{1 \text{ ft}}{12 \text{ in}} \times \left(A_T + A_F + A_S\right)$$

$$V_{C600} = 6 \text{ in} \times \frac{1 \text{ ft}}{12 \text{ in}} \times \left(628.5 \text{ ft}^2 + 1325 \text{ ft}^2 + 474 \text{ ft}^2\right) = 1214 \text{ ft}^3$$

$$V_{C800} = 6 \text{ in} \times \frac{1 \text{ ft}}{12 \text{ in}} \times \left(472.5\text{ft}^2 + 996 \text{ ft}^2 + 474 \text{ ft}^2\right) = 971 \text{ ft}^3$$

$$V_{C1000} = 6 \text{ in} \times \frac{1 \text{ ft}}{12 \text{ in}} \times \left(378 \text{ ft}^2 + 797 \text{ ft}^2 + 474 \text{ ft}^2\right) = 825 \text{ ft}^3$$

5. Determine ratio of waste to cover soil.
   (*a*) For 600 lb/yd³

$$R_{W:C} = \frac{233.3 \text{ yd}^3 \times 27 \text{ ft}^3/\text{yd}^3}{1214 \text{ ft}^3} = 5.19{:}1$$

(*b*) For 800 lb/yd³

$$R_{W:C} = \frac{175 \text{ yd}^3 \times 27 \text{ ft}^3/\text{yd}^3}{971 \text{ ft}^3} = 4.87{:}1$$

(*c*) For 1000 lb/yd³

$$R_{W:C} = \frac{140 \text{ yd}^3 \times 27 \text{ ft}^3/\text{yd}^3}{825 \text{ ft}^3} = 4.58{:}1$$

Comment. Note that as the initial compacted specific weight of the waste placed in the landfill increases, the ratio of the waste to cover material decreases. However, the total volume occupied by the waste that has been compacted to an initial specific weight of 1000 lb/yd³ is 0.6 times the volume occupied by the waste compacted to an initial specific weight of 600 lb/yd³.

Impact of Waste Decomposition and Overburden Height. The loss of mass through biological decomposition results in a loss of volume, which becomes available for refilling with new waste. In the preliminary assessment of site capacity, only compaction due to overburden is considered. At later stages of landfill design, the loss of landfill material to decomposition should be considered. The specific weight of the landfilled material can be estimated using Eq. (11-30). Evaluation of the impact of waste decomposition on settlement is illustrated in Example 11-13 in Section 11-12.

Evaluation of Local Geology and Geohydrology

To evaluate the geologic and hydrogeological characteristics of a site that is being considered for a landfill, core samples must be obtained. Sufficient borings should be made so that the geologic formations under the proposed site can be established from the surface to (and including) the upper portions of the bedrock or other confining layers (see Fig. 11-66). At the same time, the depth to the surface water table should be determined along with the piezometric water levels in any bedrock or confined aquifers that may be found. The resulting information is then used (1) to determine the general direction of groundwater movement under the site, (2) to determine whether any unconsolidated or bedrock aquifers are in direct hydraulic connection with the proposed landfill site, and (3) to determine the type of liner system that will be required.

Selection of Leachate Management Facilities

The principal leachate management facilities required in the design of a landfill include the landfill liner and leachate collection system and the leachate treatment facilities.

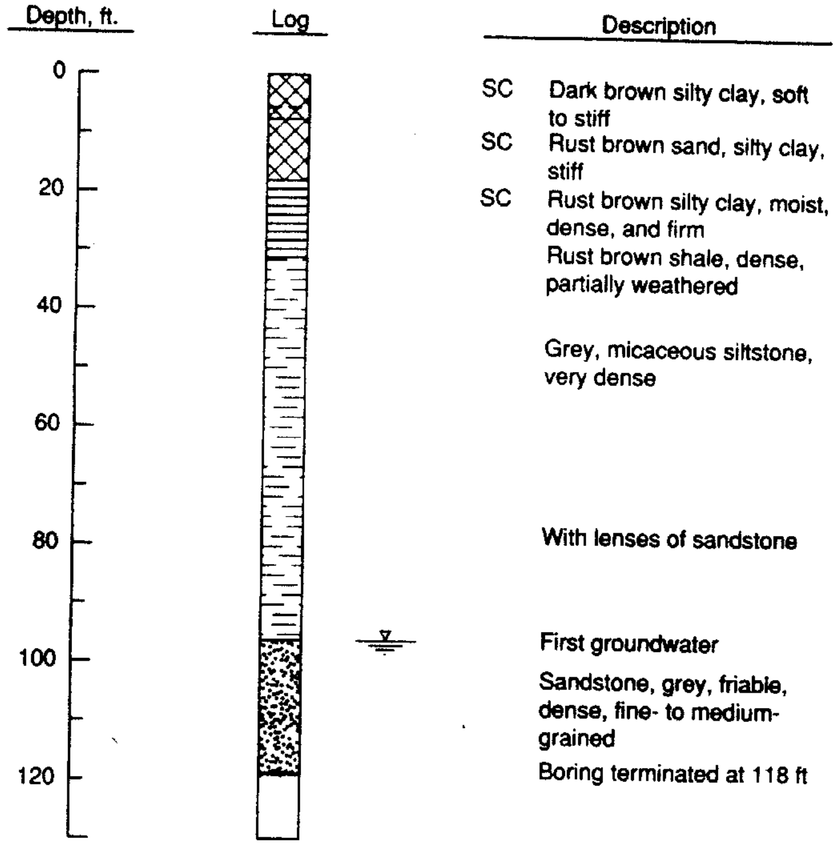


FIGURE 11-66
Typical boring log from well drilled at proposed landfill site.

Landfill Liner and Leachate Collection Facilities. The type of landfill liner used will depend on the local geology and hydrogeology. In general, landfill sites should be located where there is little or no possibility of contaminating potable water supplies. To provide assurances to the public that leachate will not contaminate underground waters, most states now require some type of liner for all landfills. Commonly used landfill liner designs are illustrated in Fig. 11-36. Typical leachate collection facilities are illustrated in Fig. 11-41 through 11-43. The current trend is toward the use of composite liners including a geomembrane and clay layer. In extremely arid areas where no possibility exists of contaminating the groundwater, it may be possible to develop a landfill without a liner. Nevertheless, the use of a liner system is a critical factor in siting new landfills. Further, the relative cost of a liner system is not great considering the potential environmental benefits. To determine the size of the leachate collection and treatment facilities required, the quantity of leachate must be estimated using the methods outlined in Section 11-5 and illustrated in Example 11-11 in Section 11-12. The selection of a liner system is illustrated in Example 11-14 in Section 11-12.

Leachate Treatment Facilities. As noted in Section 11-5, the most common alternatives that have been used to manage the leachate collected from landfills include (1) leachate recycling, (2) leachate evaporation, (3) treatment followed by disposal, and (4) discharge to municipal wastewater collection systems. The particular option used will depend on local conditions.

Selection of Gas Control Facilities

Because the uncontrolled release of landfill gas, especially methane, contributes to the greenhouse effect, and because landfill gas can migrate laterally and potentially cause explosions or kill vegetation and trees, most new landfills are equipped with gas collection and treatment facilities. To determine the size of the gas collection and processing facilities needed, the quantity of landfill gas must first be estimated using the methods outlined in Section 11-4 and illustrated in Example 11-8 in Section 11-12. Because the rate of gas production varies depending on the operating procedures (e.g., without or with leachate recycle) several rates should be analyzed. The decision to use horizontal or vertical gas recovery wells depends on the design and capacity of the landfill. The decision to flare or to recover energy from the landfill gas is determined by the capacity of the landfill site and the opportunity to sell power produced from the conversion of landfill gas to energy. In many small landfills located in remote areas, gas collection equipment is not used routinely.

Selection of Landfill Cover Configuration

As discussed previously, a landfill cover is usually composed of several layers, each with a specific function (see Fig. 11-53). The use of a geomembrane liner as a barrier layer is favored by most landfill designers to limit the entry of surface water and to control the release of landfill gases. The specific cover configuration selected will depend on the location of the landfill and the climatalogical conditions. For example, to allow for regrading, some designers favor the use of a deep layer of soil. To ensure the rapid removal of rainfall from the completed landfill and to avoid the formation of puddles, the final cover should have a slope of about 3 to 5 percent. The selection of a landfill cover is illustrated in Example 11-14 in Section 11-12.

Surface Water Drainage Facilities

An important step in the design of a landfill is to develop an overall drainage plan for the area that shows the location of storm drains, culverts, ditches, and subsurface drains as the filling operation proceeds. Depending on the location and configuration of the landfill and the capacity of the natural drainage courses, it may be necessary to install a stormwater retention basin.

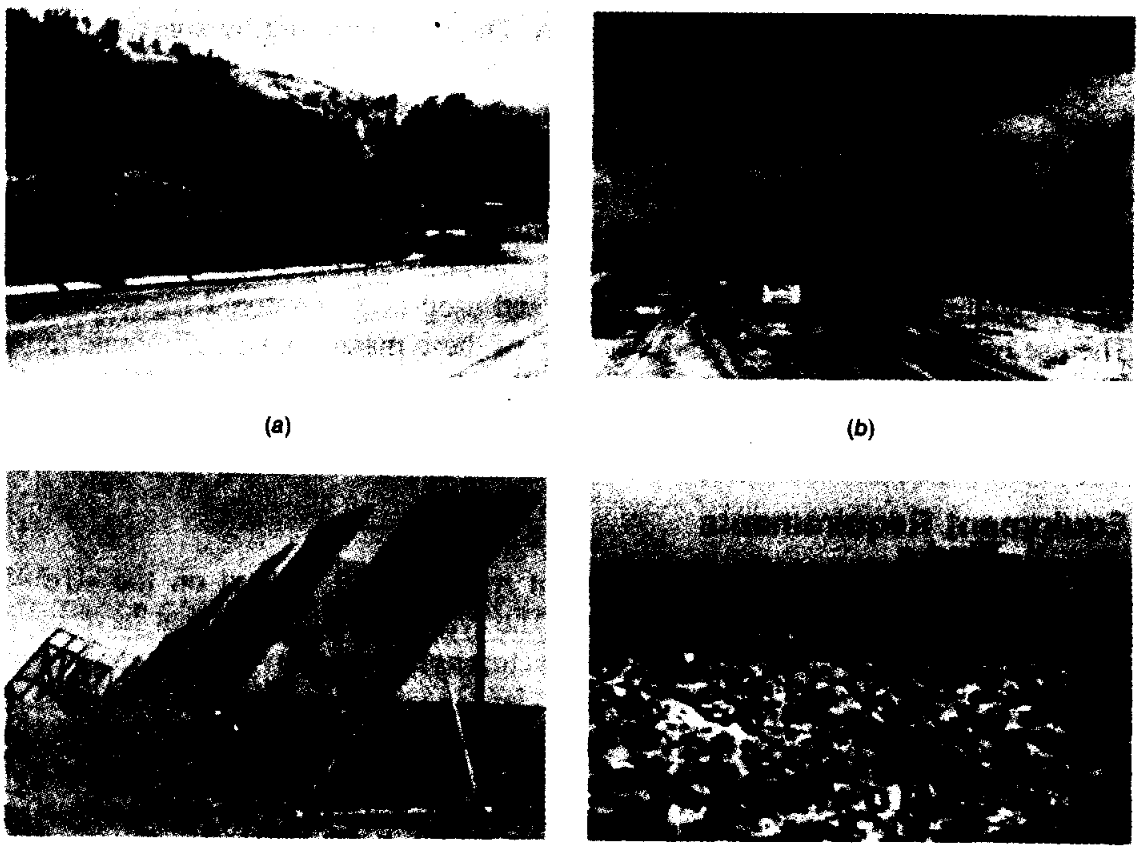
Environmental Monitoring Facilities

Monitoring facilities are required at new landfills for (1) gases and liquids in the vadose zone, (2) for groundwater quality both upstream and downstream of the landfill site, and (3) for air quality at the boundary of the landfill and from any processing facilities (e.g., flares). The specific number of monitoring stations will depend on the configuration and size of the landfill and the requirements of the local air and water pollution control agencies.

Aesthetic Design Considerations

Aesthetic design considerations relate to minimizing the impact of the landfilling operation on nearby residents as well as the public that may be passing by the landfill.

Screening of Landfilling Areas. Screening of the daily landfilling operations from nearby roads and residents with berms, plantings, and other landscaping measures is one of the most important examples of an aesthetic design consideration (see Fig. 11-67*a*). Screening of the active areas in the landfill must be incorporated in the preliminary design and layout of the landfill.



(*a*) (*b*) (*c*) (*d*)

FIGURE 11-67
Aesthetic considerations in landfill design: (*a*) view of landscaped landfill in which filling operations are not visible from nearby freeway, (*b*) overhead wire system used to control sea gulls at landfills, (*c*) wire screen used to control blowing papers and plastic, and (*d*) daily cover used to control vectors at landfills.

The Control of Birds. The presence of birds at the landfill site is not only a nuisance, but also they can cause serious problems if the landfill site is located near an airport. Techniques that have been used to control birds at landfill sites include the use of noise makers, the use of recordings of the sounds made by birds of prey, and the use of overhead wires. The use of overhead wires to keep birds out of reservoirs and fishponds dates back to the early 1930s [1, 31]. The County Sanitation Districts of Los Angeles County pioneered the use of overhead wires to control sea gulls at landfills in the early 1970s (see Fig. 11-67*b*). Because sea gulls descend in a circular pattern when landing, it appears that the wires may interfere with the birds' guidance mechanism. The poles are usually spaced 50 to 75 ft apart, with line spans from 500 to 1200 ft [30]. Crisscrossing improves the effectiveness of the wire system. Typically, 100 lb test monofilament fish line is used, although stainless steel wire has also been used.

The Control of Blowing Materials and Dust. Depending on the location, wind-blown paper, plastics, and other debris can be a problem at some landfills. The most common solution is to use portable screens near the operating face of the landfill (see Fig. 11-67*c*). To avoid problems with vectors, the material accumulated on the screens must be removed daily. Dust is controlled by spraying water on the approach and internal access roads (see Fig. 11-69*e*).

The Control of Pests and Vectors. The principal vectors of concern in the design and operation of landfills are pests including mosquitos and flies and rodents such as rats and other burrowing animals. Flies and mosquitos are controlled by the placement of daily cover and by the elimination of standing water. The latter can be a problem in areas where white goods and used tires are stored for recycling. The use of covered facilities for the storage of these materials will eliminate most problems. Rats and other burrowing animals are controlled by the use of daily cover (see Fig. 11-67*d*).

Equipment Requirements

The type, size, and amount of equipment required will depend on the size of the landfill and the method of operation. The types of equipment that have been used at sanitary landfills include crawler tractors, scrapers, compactors, draglines, and motorgraders (see Figs. 11-68 and 11-69). Of these, crawler tractors are most commonly used. Properly equipped tractors can be used to perform all the necessary operations at a sanitary landfill, including spreading, compacting, covering, trenching, and even hauling cover materials [26]. Some generalized information on the performance of landfill equipment is summarized in Table 11-25. Typical cost information for landfill equipment may be found in Appendix E. The size and amount of equipment will depend primarily on the size of the landfill operation. Local site conditions will also influence the size of the equipment. Equipment requirements that may be used as a guide for landfill operations are reported in Table 11-26.

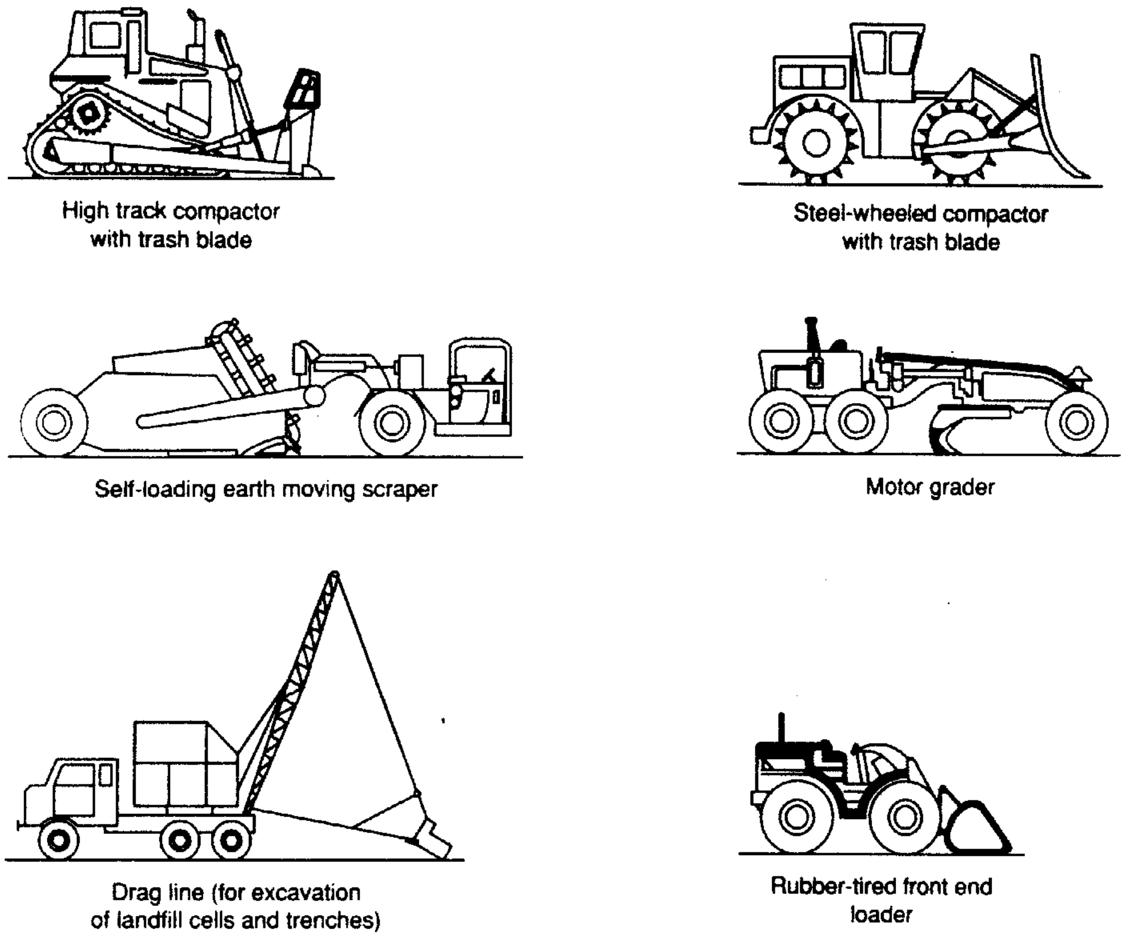


FIGURE 11-68
Typical equipment used at landfills for the placement and covering of solid waste.

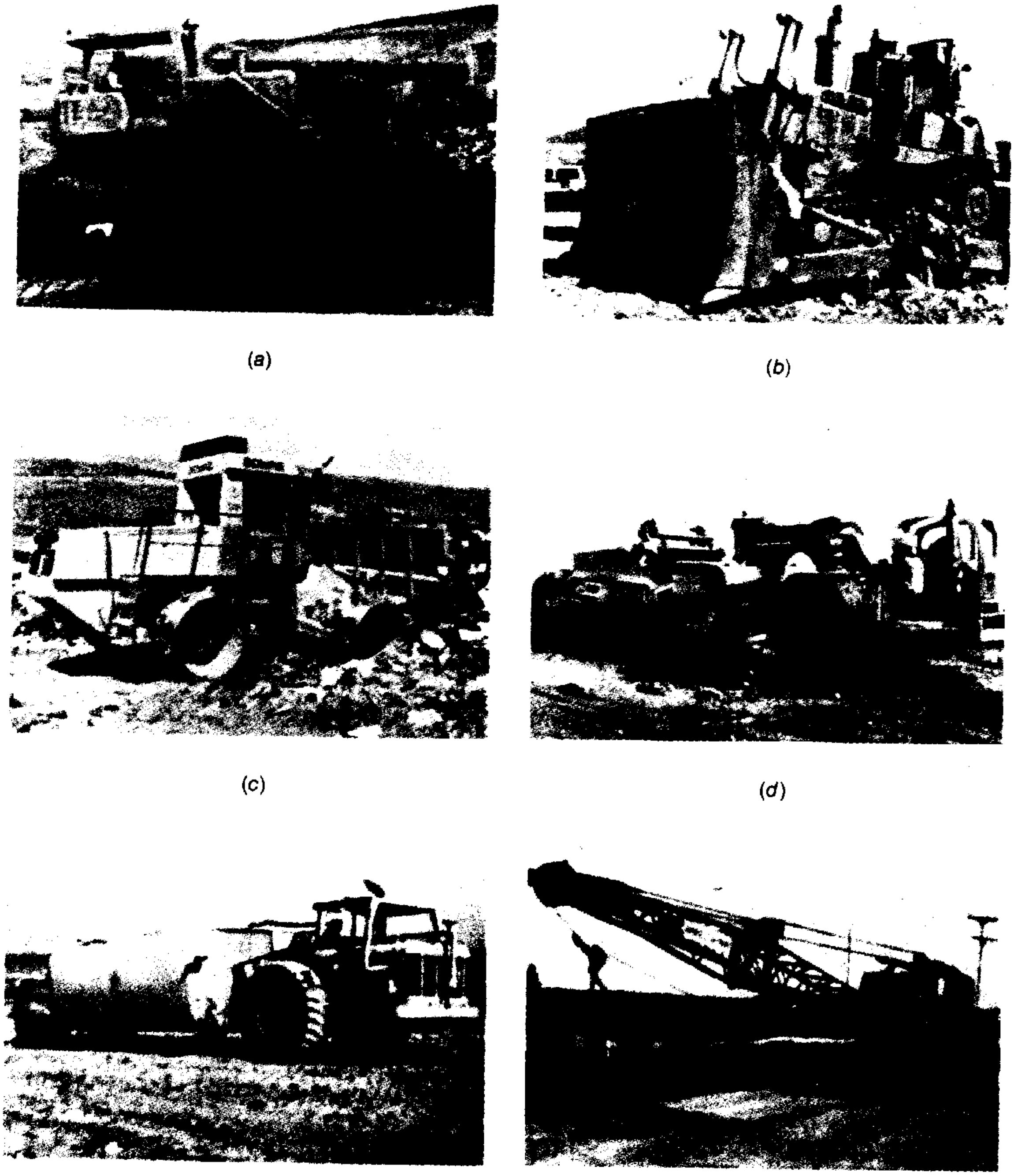
TABLE 11-25
Perfomance characteristics of landfill equipment[a,b]

	Solid waste		Cover material			
Equipment	**Spreading**	**Compacting**	**Excavating**	**Spreading**	**Compacting**	**Hauling**
Crawler tractor	E[c]	G	E	E	G	NA
Wheeled compactor	E	E	P	F–G	E	NA
Scraper	NA	NA	G	E	NA	E

[a] From Ref. 4.

[b] Basis of evaluation: easily workable soil and cover material haul distance greater than 1000 ft.

[c] Rating key: E, excellent; G, good; F, fair; P, poor; NA, not applicable.



(*a*) (*b*)

(*c*) (*d*)

(*e*) (*f*)

FIGURE 11-69
Views of equipment used at landfills: (*a*) crawler tractor with dozer blade, (*b*) high track crawler tractor with trash blade, (*c*) steel wheel compactor with trash blade—engine in this unit is air cooled, (*d*) self-loading scraper, (*e*) water wagon used for dust control, and (*f*) drag line.

TABLE 11-26
Typical equipment requirements for sanitary landfills

Approximate population	Daily wastes, tons	Equipment			Accessory[a]
		Number	Type	Equipment weight, lb	
0–20,000	0–50	1	Tractor, crawler	10,000–30,000	Dozer blade Front-end loader (1 to 2 yd^3) Trash blade
20,000–50,000	50–150	1	Tractor, crawler	30,000–60,000	Dozer blade Front-end loader (2 to 4 yd^3) Bullclam Trash blade
		1	Scraper or dragline		
		1	Water truck		
50,000–100,000	150–300	1–2	Tractor, crawler	30,000+	Dozer blade Front-end loader (2 to 5 yd^3) Bullclam Trash blade
		1	Scraper or dragline[b]		
		1	Water truck		
>100,000	300[c]	1–2	Tractor, crawler	45,000+	Dozer blade Front-end loader (2 to 5 yd^3) Bullclam Trash blade
		1	Steel wheel compactor		
		1	Scraper or dragline[b]		
		1	Water truck		
		—[a]	Road grader		

[a] Optional, depends on individual needs.
[b] The choice between a scraper or dragline will depend on local conditions.
[c] For each 500-ton increase add one more of each piece of equipment.

11-10 LANDFILL OPERATION

The development of a workable operating schedule, a filling plan for the placement of solid wastes, landfill operating records and billing information, a load inspection plan for hazardous wastes, and site safety and security plans are important elements of a landfill operation plan. Other factors that must be considered in the operation of a landfill are reported in Table 11-27.

Landfill Operating Schedules

Factors that must be considered in developing operating schedules include (1) arrival sequences for collection vehicles, (2) traffic patterns at the site, (3) the time

TABLE 11-27
Important factors that must be considered in the operation of landfills

Factors	Remarks
Days and hours of operation	Usual practice is 5 to 6 d/wk and 8 to 10 h/d
Communications	Telephone for emergencies
Employee facilities	Restrooms and drinking water should be provided
Equipment maintenance	A covered shed should be provided for field maintenance of equipment
Litter control	Use movable fences at unloading areas; crews should pick up litter at least once per month or as required
Operation plan	With or without the codisposal of treatment plant sludges and the recovery of gas
Operational records	Tonnage, transactions, and billing if a disposal fee is charged
Salvage	No scavenging; salvage should occur away from the unloading area
Scales	Essential for record keeping if collection trucks deliver wastes; capacity to 100,000 lb
Security	Provide locked gates and fencing; lighting of sensitive areas
Spread and compaction	Spread and compact waste in layers less than 2 ft thick to achieve optimum compaction
Unloading area	Keep small, generally under 100 ft on a side; operate separate unloading areas for automobiles and commercial trucks

sequence to be followed in the filling operations, (4) effects of wind and other climatic conditions, and (5) commercial and public access. For example, because of heavy truck traffic early in the morning, it may be necessary to restrict public access to the site until later in the morning.

Solid Waste Filling Plan

Once the general layout of the landfill site has been established, it will be necessary to select the placement method to be used and to lay out and design the individual solid waste cells. The specific method of filling will depend on the characteristics of the site, such as the amount of available cover material, the topography, and the local hydrology and geology. Details on the various filling methods were presented in Section 11-2. To assess future development plans, it will be necessary to prepare a detailed plan for the layout of the individual solid waste cells. The filling sequence should be established so that the landfill operations are not impeded by unusual weather or adverse winter conditions. A typical example of such a plan is shown in Fig. 11-70.

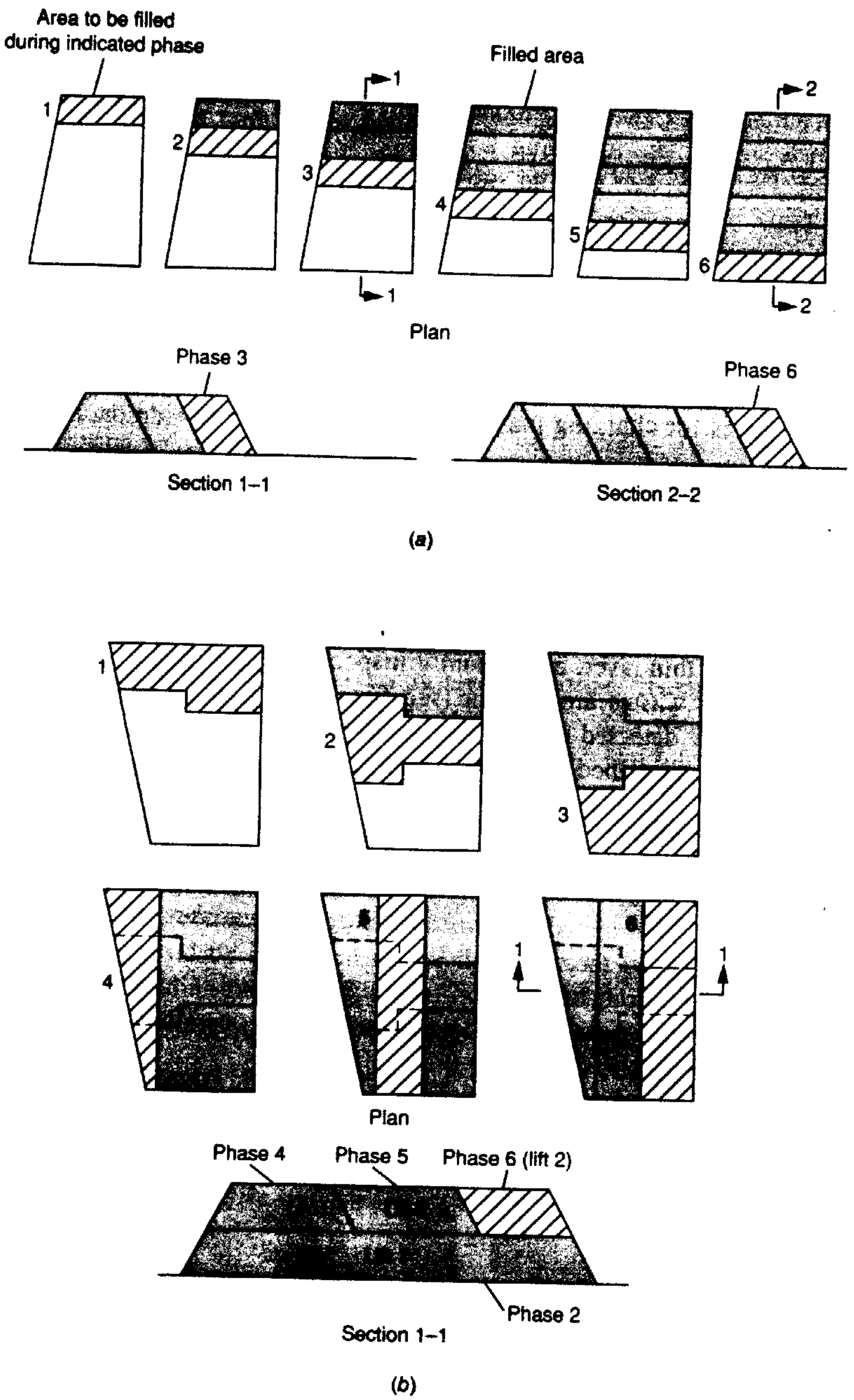


FIGURE 11-70
Typical examples of solid waste filling plans: (*a*) filling plan for single-lift landfill and (*b*) filling plan for a multilift landfill.

Landfill Operating Records

To determine the quantities of waste that are disposed, an entrance scale and gatehouse will be required. The gatehouse would be used by personnel who are responsible for weighing the incoming and outgoing trucks. The sophistication of the weighing facilities will depend on the number of vehicles that must be processed per hour and the size of the landfill operation. (For example, in some larger landfills, weigh stations are equipped with radiation detectors to detect the presence of radioactive substances in the incoming wastes.) Some examples of weighing facilities are shown in Fig. 11-71. If the weight of the solid wastes delivered is known, then the in-place density of the wastes can be determined and the performance of the operation can be monitored. The weight records would also be used as a basis for charging participating agencies and private haulers for their contributions.

Load Inspection for Hazardous Waste

Load inspection is the term used to describe the process of unloading the contents of a collection vehicle near the working face or in some designated area, spreading the wastes out in a thin layer, and visually inspecting the wastes to determine whether any hazardous wastes are present (see Fig. 11-72). The presence of radioactive wastes can be detected with a hand-held radiation measuring device or at the weigh station, as described above. If hazardous wastes are found, the waste collection company is responsible for removing them. In the operation of some landfills, if a company is caught bringing in hazardous wastes a second time, a high fine is levied. If caught a third time, the company is banned from discharging wastes at the landfill.

(*a*) (*b*)

FIGURE 11-71
Typical truck weighing facilities: (*a*) at small landfill and (*b*) at large landfill.

(a) (b)

FIGURE 11-72
Inspection of solid waste for the presence of hazardous wastes at the Frank R. Bowerman landfill in Orange Co., CA: (a) residential load and (b) commercial load.

Public Health and Safety

Public health and safety issues are related to worker health and safety and to the health and safety of the public.

Health and Safety of Workers. The health and safety of the workers at landfills is critical in the operation of a landfill. The federal government through OSHA regulations and states through OSHA-type programs have established requirements for a comprehensive health and safety program for the workers at landfill sites. Because the requirements for these programs change continually, the most recent regulations should be consulted in the development of worker health and safety programs. Attention must be given to the types of protective clothing and boots, air-filtering head gear, and punctureproof gloves supplied to the workers.

Safety of the Public. As noted previously, safety concerns and the many new restrictions governing the operation of landfills have forced landfill operators to reexamine past operational practices with respect to public safety and site security. As a result, the use of a convenience transfer station at the landfill site, to minimize the public contact with the working operations of the landfill, is gaining in popularity.

Site Safety and Security

The increasing number of law suits over accidents at landfill sites has caused landfill operators to improve security at landfill sites significantly. Most sites now have restricted access and are fenced and posted, with no trespassing and other warning signs. In some locations, television cameras are used to monitor landfill operations and landfill access.

11-11 LANDFILL CLOSURE AND POSTCLOSURE CARE

Landfill closure and *postclosure care* are the terms used to describe what is to happen to a completed landfill in the future. To ensure that completed landfills will be maintained 30 to 50 years into the future, many states have passed legislation that requires the operator of a landfill to put aside enough money so that when the landfill is completed the amount of money that has been set aside will be sufficient to maintain the closed site into perpetuity.

Development of Long-Term Closure Plan

Perhaps the most important element in the long-term maintenance of a completed landfill is the availability of a closure plan in which the requirements for closure are delineated clearly. A closure plan must include a design for the landfill cover and the landscaping of the completed site. Closure must also include long-term plans for the control of runoff, erosion control, gas and leachate collection and treatment, and environmental monitoring.

Cover and Landscape Design. The landfill cover must be designed to divert surface runoff and snowmelt from the landfill site and to support the landscaping design selected for the landfill. Increasingly, the final landscaping design is based on local plant and grass species as opposed to nonnative plant and grass species. In many arid locations in the Southwest, a desert type of landscaping is favored. The subject of landscaping is considered further in Chapter 16.

Control of Landfill Gases. The control of landfill gases is a major concern in the long-term maintenance of landfills. Because of the concern over the uncontrolled release of landfill gases, a gas control system is now installed before most modern landfills are completed. Older completed landfills without gas collection systems are being retrofitted with gas collection systems. The retrofitting of older landfills with gas collection facilities is considered in Chapter 17, along with the remedial actions that may be required at abandoned disposal sites.

Collection and Treatment of Leachate. As with the control of landfill gas, the control of leachate discharges is another major concern in the long-term maintenance of landfills. Again, most modern landfills have some sort of leachate control system as discussed above. Older completed landfills without leachate collection systems are being retrofitted with leachate collection systems (see Chapter 17).

Environmental Monitoring Systems. To be able to conduct long-term environmental monitoring after a landfill has been completed, monitoring facilities must be installed. The monitoring required at completed landfills usually involves (1) vadose zone monitoring for gases and liquids, (2) groundwater monitoring, and (3) air quality monitoring. The required facilities have been described previously.

Postclosure Care

Postclosure care involves the routine inspection of the completed landfill site, maintenance of the infrastructure, and environmental monitoring. These subjects are considered briefly below and in more detail in Chapter 16.

Routine Inspections. A routine inspection program must be established to monitor continually the condition of the completed landfill. Criteria must be established to determine when a corrective action(s) must be taken. For example, how much settlement will be allowed before regrading must be undertaken?

Infrastructure Maintenance. Infrastructure maintenance typically involves the continued maintenance of surface water diversion facilities; landfill surface grades; the condition of liners, where used; revegetation; and maintenance of landfill gas and leachate collection equipment. The amount of regrading that will be required will depend on the amount of settlement. In turn, the rate of settlement will depend on the rate of gas formation and the degree of initial compaction achieved in the placement of the waste materials in the landfill. The amount of equipment that must be available at the site will depend on the extent and capacity of the landfill and the nature of the facilities that must be maintained.

Environmental Monitoring Systems. Long-term environmental monitoring is conducted at completed landfills to ensure that there is no release of contaminants from the landfill that may affect health or the surrounding environment. The kinds of systems needed have already been enumerated. The number of samples collected for analysis and the frequency of collection will usually depend on the regulations of the local air pollution and water pollution control agencies. EPA has developed a baseline procedure for sampling of groundwater that should be reviewed (40 CFR 258).

11-12 LANDFILL PROCESS COMPUTATIONS

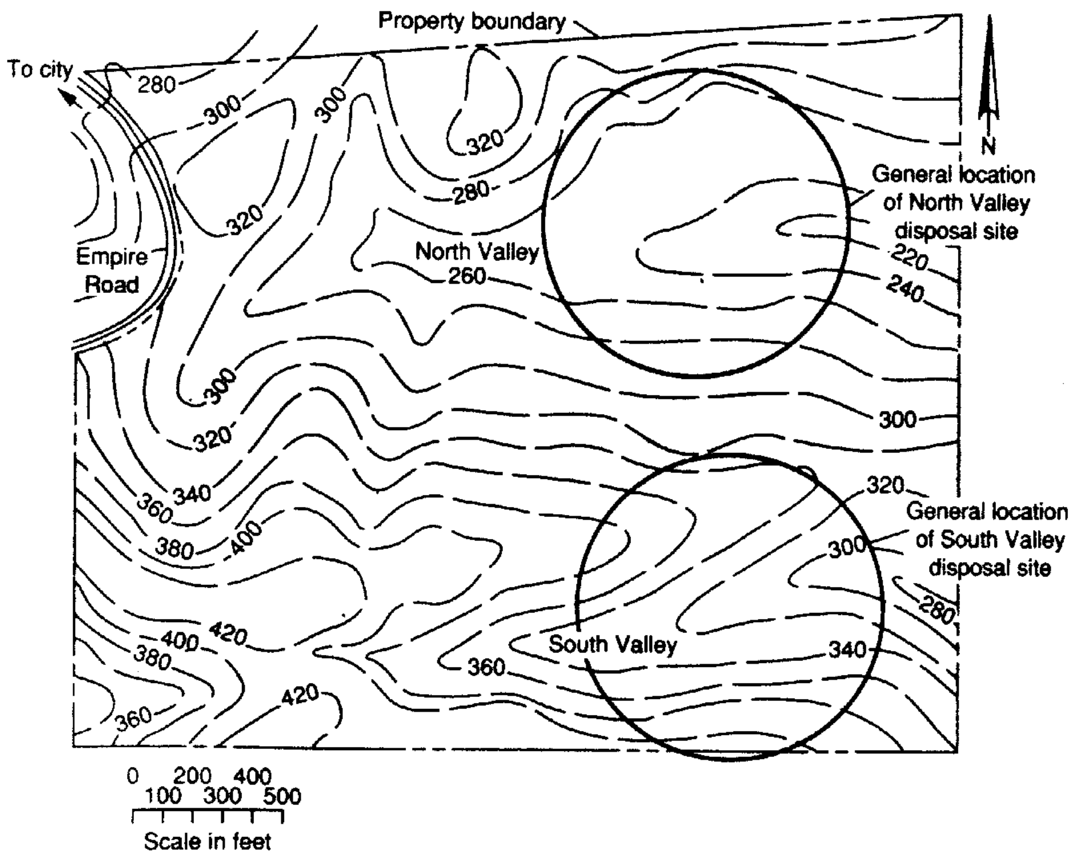
The general features of a sanitary landfill have been presented and described in this chapter. The purpose of this section is to illustrate the basic process computations involved in the development of a landfill site. Process computations are used to identify the quantities required for assessing the suitability of a site (e.g., volumetric capacity) and for sizing of the physical facilities (e.g., leachate collection pipes). The principal process and design computations to be considered in the following discussion include:

- 11-7 Determination of landfill capacity and useful life
- 11-8 Landfill gas generation
- 11-9 Analysis of landfill gas recovery system
- 11-10 Determination of the amount of water vapor collected in a landfill gas recovery system

11-11 Landfill leachate production
11-12 Estimation of water percolation rates through a landfill cover
11-13 Landfill compaction during operation and long-term compaction/consolidation
11-14 Selection of a landfill leachate collection system and cover configuration

These design computations have been grouped together so as not to break up the text discussion and to provide a more coherent presentation of the computations involved in designing a landfill. Wherever possible, the computations presented in the following examples have been set up to be solved using a spreadsheet. In addition, spreadsheet formats have been used for data presentation.

Example 11-7 Determination of landfill capacity and useful life. Determine the capacity and the expected useful life of the South Valley landfill site shown in the accompanying figure. The assumptions to be used in determining the capacity and useful life of the landfill are given below along with data on the expected population and daily waste quantities to be landfilled.



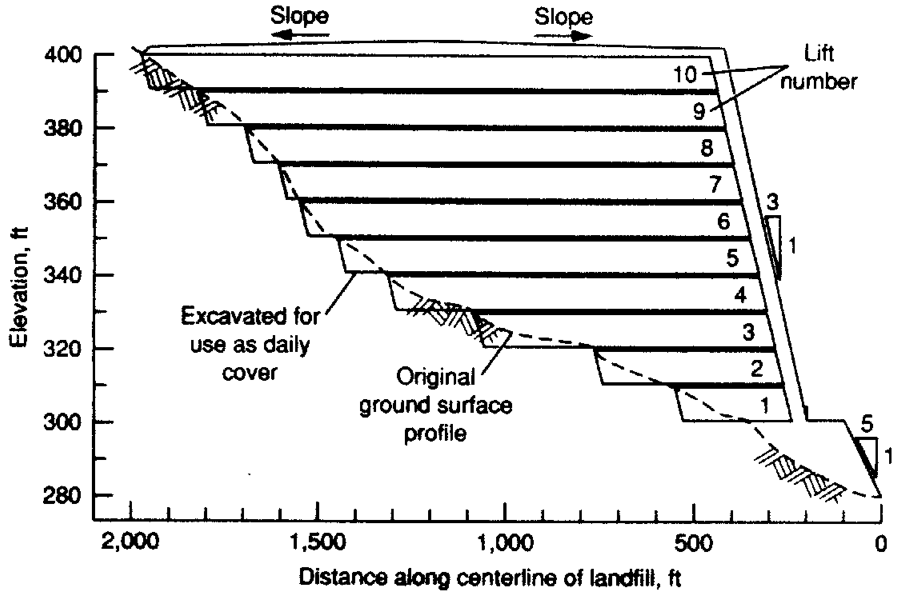
Height of individual landfill lift including the cover material = 10 ft
Slope of front face of landfill = 3 to 1 (see Table 11-23)
Specific weight of compacted solid waste in the landfill = 900 lb/yd^3
Maximum elevation of landfill = 400 ft

Year	Projected end-of-year population (×1000)	Waste quantities, lb/capita · d
1995	38	4.8
1996	40	4.5
1997	42	4.2
1998	44	3.9
1999	46	3.7
2000	48	3.6
2001	50	3.5
2002	51	3.4
2003	52	3.3
2004	53	3.2
2005	54	3.1
2006	55	3.0
2007	56	3.0
2008	57	3.0
2009	58	3.0
2010	59	3.0

Solution

1. Develop a ground surface profile through the proposed landfill site.

   The profile of the south site, taken coincident with the flow line, is shown in the following figure. The ground surface profile is drawn by measuring, using the graphic scale provided, the distance along the flow line to the point where each contour line crosses the flow line. In preparing the profile through the landfill, an expanded vertical scale is used to allow for the superposition of alternative landfill configurations.

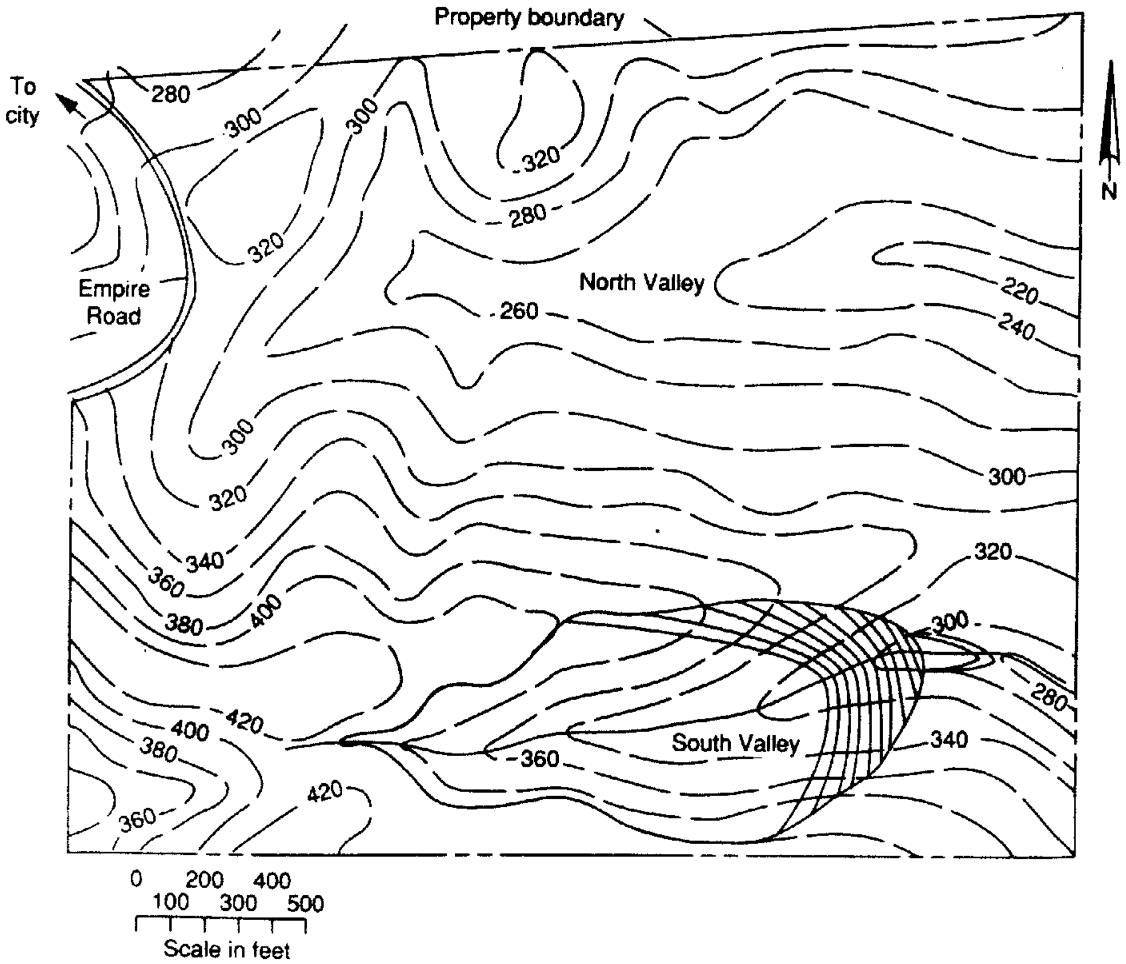


2. Develop a profile of the completed landfill.

   For operating lifts of 10 ft and a 3 to 1 slope for the front face of the landfill, a typical landfill profile is shown on the profile developed in Step 1 above. As shown, the maximum elevation of the landfill is 400 ft and a total of 10 lifts are to be used.

3. Develop a plan map of the completed landfill showing the 10 ft contours corresponding to the individual lifts.

Developing a plan of the proposed landfill involves transferring information from the landfill profile developed in Step 2 to the location map. The plan view of the proposed landfill is shown in the following figure. From the profile map (see Step 2) there is a 10 ft vertical rise for each 30 ft of horizontal distance measured along the flow line. The locations where the 10 ft contours, corresponding to each lift, cross the flow line are marked off every 30 ft along the flow line. The method used to connect the contour intervals to the existing ground contours depends on the design of the front face of the landfill. For example, if the front face of the landfill is to be a flat inclined plane, then straight lines are passed through the contour intervals marked off along the flow line. Alternatively, if the front face of the completed landfill is to be curved, then the landfill might look as shown in the following figure.



4. Determine the capacity of the proposed landfill.

(*a*) The volumetric capacity of the South Valley landfill site in cubic yards is computed by determining the volume between contour intervals. The areas of the two adjacent contours are averaged, and the average value is multiplied by 10 ft (the lift height) and divided by 27 ft^3/yd^3 to convert to cubic yards. The necessary computations are presented in the table below. The area at each contour interval is obtained from the contour map developed in Step 3 using a planimeter. Alternatively, the surface area corresponding to each contour can be determined by tracing on a see-through grid the area enclosed by each contour and counting the squares. As computed, the total capacity of the landfill is 1,118,250 yd³. Because the site will be excavated to obtain the necessary cover material, the capacity of the site is equal to the volume of the site.

Lift number	Elevation	Area, ft²: At contour, interval[a]	Area, ft²: Average between contours	Capacity between contours,[b] yd³
	300	11,360		
1			28,405	10,520
	310	45,450		
2			79,540	29,460
	320	113,635		
3			136,360	50,500
	330	159,090		
4			193,180	71,550
	340	227,270		
5			255,680	94,700
	350	284,090		
6			321,500	115,740
	360	340,910		
7			423,865	156,990
	370	506,820		
8			526,135	194,860
	380	545,450		
9			537,495	199,070
	390	529,540		
10			526,135	194,860
	400	522,730		
Total capacity, yd³				1,118,250

[a] From the figure given in Step 3.

[b] Volume = (average area, ft) × (10 ft)/(27 ft³/yd³)

(*b*) If cover material has to be brought to the site, then the volume of solid wastes determined in the above table must be multiplied by a factor to account for the cover material. For a cover to waste ratio of 1 to 5, the capacity of the proposed landfill is 931,875 yd³.

5. Determine the useful life of the proposed landfill.

(*a*) Determine the expected daily, yearly, and cumulative yearly total waste quantities. These totals are summarized in the following table. The daily and yearly waste quantities were computed on the basis of the projected end-of-year population. This procedure is recommended even though it is on the conservative side. The volume was computed using an assumed value of 900 lb/yd³ for the in-place compacted specific weight of the solid wastes. The computed values can be scaled for any other assumed specific weight values.

Year	Projected end-of-year population (×1000)	Waste quantities, lb/capita · d	Waste quantities, yd^3		
			Daily volume	Yearly volume	Cumulative total
1995	38	4.8	202.7	73,986	73,986
1996	40	4.5	200.0	73,000	146,986
1997	42	4.2	196.0	71,540	218,526
1998	44	3.9	190.7	69,606	288,132
1999	46	3.7	189.1	69,022	357,154
2000	48	3.6	192.0	70,080	427,234
2001	50	3.5	194.4	70,956	498,190
2002	51	3.4	192.7	70,336	568,526
2003	52	3.3	190.7	69,606	638,132
2004	53	3.2	186.0	67,890	706,022
2005	54	3.1	186.0	67,890	773,912
2006	55	3.0	183.3	66,905	840,817
2007	56	3.0	186.7	68,146	908,963
2008	57	3.0	190.0	69,350	978,313
2009	58	3.0	193.3	70,555	1,048,868
2010	59	3.0	196.7	71,796	1,120,664

(*b*) When the waste quantities given in the above table are compared to the available capacity determined in Step 4, the useful life of the South Valley landfill site is found to be about 16 yr (1995 to 2010). At that time it would be necessary to develop the North Valley landfill site.

Comment. To start the landfill operation, the topsoil would be stripped away in the lower portions of the South Valley and stockpiled at the eastern end of the landfill site. The stockpile serves as a dam to capture and divert stormwater runoff as well as a site for topsoil storage. The computations performed in this example could also be performed using computer-aided design (CAD) software on a microcomputer or an engineering workstation.

Example 11-8 Landfill gas generation. Determine the distribution of gas production over time for a landfill with a useful life of five years based on the following data and assumptions:

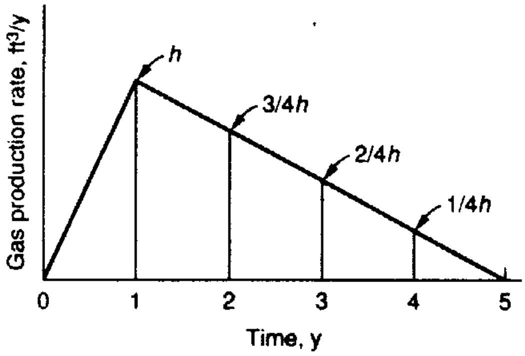
1. Landfill life = 5 yr
2. The composition of the waste is as described in Table 3-4 for residential and commercial MSW, of which 79.5 percent is organic and 20.5 percent is inert.
3. The organic fraction (79.5 percent) is composed of 7 percent plastic (considered to be inert), 60.1 percent rapidly biodegradable material, and 12.4 percent slowly biodegradable material (see Example 11-2). The corresponding values for rapidly and slowly biodegradable material based on dry weight are 44.8 and 7.3 percent, respectively.
4. Of the rapidly biodegradable organic waste, 75 percent is available for degradation (i.e., some organic waste materials in plastic bags will not be degraded, some of the material will be too dry to support biological activity).
5. Of the slowly biodegradable organic waste, 50 percent is available for degradation (for the same reasons cited above).

6. The total amount of landfill gas produced from the biodegradable fraction of the rapidly and slowly biodegradable organic materials deposited each year is 14 and 16 ft^3/lb dry solids, respectively (see Example 11-2).
7. Time period for total decomposition of rapidly decomposable organic material is 5 yr.
8. Time period for total decomposition of slowly decomposable organic material is 15 yr.

Assume the yearly rate of decomposition for rapidly and slowly decomposable material is based on a triangular gas production model in which the peak rate of gas production occurs 1 and 5 years, respectively, after gas production starts. Gas production is assumed to start at the end of the first full year of operation.

Solution

1. Determine the amount of gas that has been produced at the end of each year from one pound of the rapidly and slowly biodegradable organic waste material as these materials decompose over a 5- and 15-year period, respectively.
   (*a*) Rapidly biodegradable waste (RBW):
      i. If one uses a triangular gas production model, the gas production over the five-year period can be illustrated graphically as shown in the following figure.



      ii. Because the area of the triangle is equal to one half the base times the altitude, the total amount of gas produced is equal to

Total gas produced, ft^3

$$= 1/2 \text{ (base, yr)} \times \text{(altitude, peak rate of gas production, ft}^3\text{/yr)}$$

      iii. If the total amount of gas produced from one pound of RBW is equal to 14.0 ft^3, then the peak rate of gas production, which occurs at the end of the first year that gas is produced, is equal to

$$\text{Peak rate of gas production, ft}^3\text{/yr} = 14.0 \text{ ft}^3 \times (2/5 \text{ yr})$$
$$= 5.6 \text{ ft}^3\text{/yr}$$

      iv. The amount of gas produced during the first year that gas is produced is equal to

$$\text{Gas produced during the first year, ft}^3 = 1/2\ (1.0 \text{ yr}) \times (5.6 \text{ ft}^3\text{/yr})$$
$$= 2.8 \text{ ft}^3$$

      v. The rate of gas production during the second year that gas is produced is

$$\text{Rate of gas production, ft}^3\text{/yr} = (5.6 \text{ ft}^3\text{/yr} + (3/4)\ 5.6 \text{ ft}^3\text{/yr})/2$$
$$= 4.9 \text{ ft}^3\text{/yr}$$

vi. The amount of gas produced during the second year that gas is produced is

$$\text{Gas produced during the second year, ft}^3 = [(5.6\ \text{ft}^3/\text{yr} + 5.6\ \text{ft}^3/\text{yr} \times 3/4) \times 1.0\ \text{yr}]/2 = 4.9\ \text{ft}^3$$

vii. The rate and amount of gas produced during the third, fourth, and fifth years are determined in a similar manner.

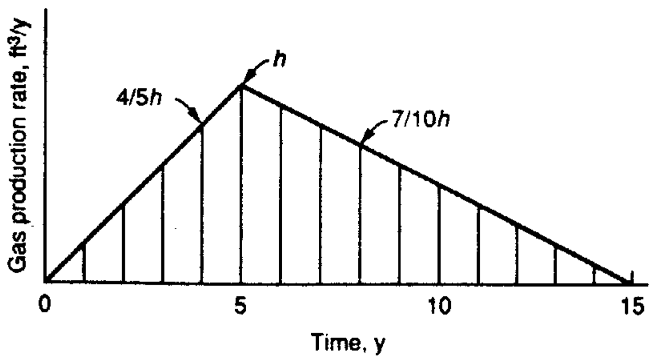
viii. Summarize the yearly gas production quantities.

End of year	Rate of gas production, ft³/yr	Gas production, ft³
1	0.0	
		2.8
2	5.6	
		4.9
3	4.2	
		3.5
4	2.8	
		2.1
5	1.4	
		0.7
6	0.0	
Total		14.0

(*b*) Slowly biodegradable waste (SBW):

Determine the amount of gas produced at the end of each year from one pound of the slowly decomposable biodegradable organic material as it decomposes during the 15-year period.

i. Using a triangular gas production model, the gas production over the 15-year period can be shown graphically in the following figure.



ii. If the total amount of gas produced from one pound of SBW is equal to 16.0 ft³, then the peak rate of gas production is equal to

$$\text{Peak rate of gas production, ft}^3/\text{yr} = 16.0\ \text{ft}^3 \times (2/15\ \text{yr}) = 2.133\ \text{ft}^3/\text{yr}$$

iii. The rate of gas production during the first year that gas is produced is

$$\text{Rate of gas production, ft}^3/\text{yr} = 1/5 \times 2.133\ \text{ft}^3/\text{yr} = 0.427\ \text{ft}^3/\text{yr}$$

2.

iv. The amount of gas produced during the first year that gas is produced is

$$\text{Gas produced during the first year, ft}^3 = 1/2\ (1.0\ \text{yr}) \times (0.427\ \text{ft}^3/\text{yr}) = 0.213\ \text{ft}^3$$

v. The amount of gas produced during the second year that gas is produced is

Gas produced during the second year, ft^3

$$= \left\{\left[\left(2.13\ \text{ft}^3/\text{yr} \times 1/5\right) + \left(2.13\ \text{ft}^3/\text{yr} \times 2/5\right)\right] \times 1.0\ \text{yr}\right\} /2$$

$$= 0.64\ \text{ft}^3$$

vi. The amount of gas produced during the remaining thirteen years is determined in a similar manner.

vii. Summarize the yearly gas production quantities.

End of year	Rate of gas production, ft^3/yr	Gas production, ft^3
1	0.000	
		0.213
2	0.427	
		0.640
3	0.853	
		1.067
4	1.280	
		1.493
5	1.706	
		1.920
6	2.133	
		2.027
7	1.920	
		1.813
8	1.706	
		1.600

End of year	Rate of gas production, ft^3/yr	Gas production, ft^3
9	1.493	
		1.387
10	1.280	
		1.173
11	1.066	
		0.960
12	0.853	
		0.747
13	0.640	
		0.534
14	0.427	
		0.320
15	0.213	
		0.107
16	0.000	
Total		16.001

2. Determine the yearly gas production rates from the rapidly and slowly biodegradable organic material per pound of total waste. The computed values will be used to prepare a spreadsheet computation table to determine total quantity of gas produced per pound of total waste deposited in the landfill.

(*a*) Determine the distribution of gas produced from the rapidly and slowly biodegradable organic material per pound of total waste deposited.

i. Determine the fraction of the total waste that is rapidly biodegradable, based on dry weight.

$$(0.448)(0.75) = 0.336\ \text{lb RBW/lb total waste}$$

ii. Determine the fraction of the total waste that is slowly biodegradable, based on dry weight.

$$(0.073)(0.50) = 0.0365\ \text{lb SBW/lb total waste}$$

iii. Determine the total amount of gas produced per pound of RBW.

$$\text{Gas}_{\text{RB}} = 0.336\ \text{lb RBW/lb waste} \times 14\ \text{ft}^3/\text{lb RBW} = 4.7\ \text{ft}^3/\text{lb waste}$$

iv. Determine the total amount of gas produced per pound of SBW.

$$\text{Gas}_{\text{SB}} = 0.0365 \text{ lb SBW/lb waste} \times 16 \text{ ft}^3\text{/lb SBW}$$
$$= 0.584 \text{ ft}^3\text{/lb waste}$$

(*b*) Determine the rapidly and slowly biodegradable waste gas generated based on total waste.

Determine the amount of gas produced at the end of each year from one pound of total waste as it decomposes during the five-year period. For rapidly decomposable waste, multiply the gas production per year values determined in Part 1 by 0.336 lb/lb; for slowly decomposable waste, multiply the gas productions per year determined in Step 1 by 0.0365 lb/lb (see Step 2*a*). The yearly gas production quantities are summarized as follows.

	Rapidly biodegradable		Slowly biodegradable		Total (rapid + slow)	
End of year	Rate of generation, ft³/yr	Volume of gas, ft³	Rate of generation, ft³/yr	Volume of gas, ft³	Rate of generation, ft³/yr	Volume of gas, ft³
0	0.000		0.000		0.000	
		0.000		0.000		0.000
1	0.000		0.000		0.000	
		0.941		0.008		0.949
2	1.882		0.016		1.898	
		1.646		0.023		1.669
3	1.411		0.031		1.442	
		1.176		0.039		1.215
4	0.941		0.047		0.988	
		0.706		0.055		0.761
5	0.470		0.062		0.532	
		0.235		0.070		0.305
6	0.000		0.078		0.078	
		0.000		0.074		0.074
7	0.000		0.070		0.070	
				0.066		0.066
8			0.062		0.062	
				0.058		0.058
9			0.055		0.055	
				0.051		0.051
10			0.047		0.047	
				0.043		0.043
11			0.039		0.039	
				0.035		0.035
12			0.031		0.031	
				0.027		0.027
13			0.023		0.023	
				0.019		0.019
14			0.016		0.016	
				0.012		0.012
15			0.008		0.008	
				0.004		0.004
16			0.000		0.000	
Total		4.704		0.584		5.288

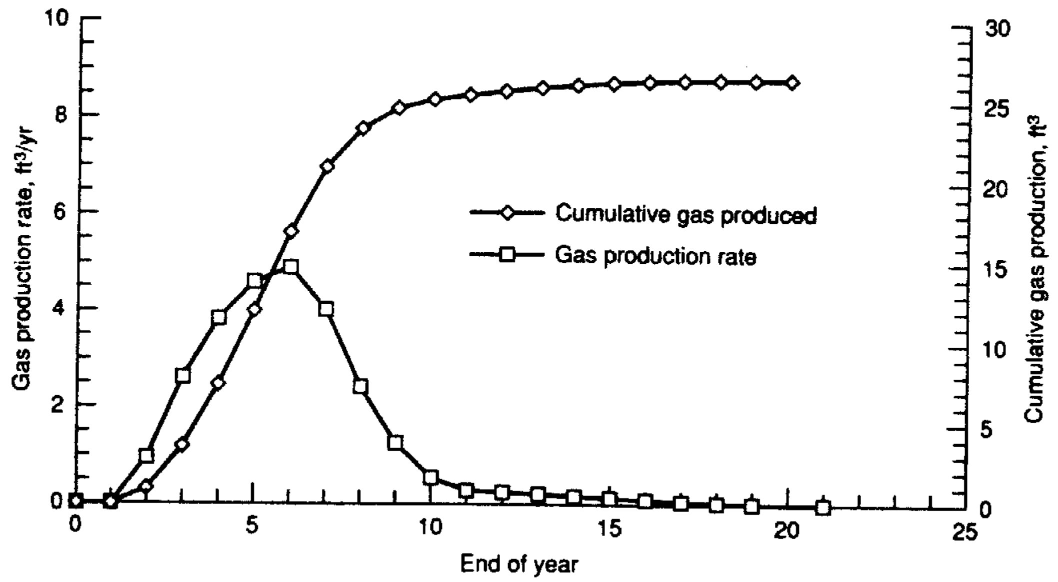
3. Using the gas production data determined in Step 2, prepare a spread sheet computation table to determine total quantity of gas produced. Assume that equal amounts of waste will be deposited each of the five years that the landfill is used. For illustration purposes, in the following spreadsheet computation table 1 lb of waste is assumed to be deposited each year. Column 1 is the time since wastes were first accepted at the landfill. The yearly columns correspond to the total rate of gas production from the waste material deposited in the indicated year.

Landfill gas as produced from waste deposited over a period of five years

End of year	Rate of landfill gas generation from waste deposited in indicated year, ft³/yr[a]						Gas, ft³	Cumulative production, ft³
	Year 1	Year 2	Year 3	Year 4	Year 5	Total		
0	0.000					0.000		
							0.000	0.000
1	0.000	0.000				0.000		
							0.949	0.949
2	1.897	0.000	0.000			1.897		
							2.618	3.567
3	1.442	1.897	0.000	0.000		3.340		
							3.833	7.400
4	0.988	1.442	1.897	0.000	0.000	4.327		
							4.593	11.993
5	0.533	0.988	1.442	1.897	0.000	4.860		
							4.899	16.892
6	0.078	0.533	0.988	1.442	1.897	4.938		
							4.024	20.916
7	0.070	0.078	0.533	0.988	1.442	3.111		
							2.420	23.336
8	0.062	0.070	0.078	0.533	0.988	1.730		
							1.264	24.600
9	0.055	0.062	0.070	0.078	0.533	0.797		
							0.544	25.154
10	0.047	0.055	0.062	0.070	0.078	0.311		
							0.292	25.446
11	0.039	0.047	0.055	0.062	0.070	0.273		
							0.253	25.699
12	0.031	0.039	0.047	0.055	0.062	0.234		
							0.214	25.913
13	0.023	0.031	0.039	0.047	0.055	0.195		
							0.175	26.088
14	0.016	0.023	0.031	0.039	0.047	0.156		
							0.136	26.224
15	0.008	0.016	0.023	0.031	0.039	0.117		
							0.097	26.321
16	0.000	0.008	0.016	0.023	0.031	0.078		
							0.062	26.383
17		0.000	0.008	0.016	0.023	0.047		
							0.035	26.418
18			0.000	0.008	0.016	0.023		
							0.016	26.434
19				0.000	0.008	0.008		
							0.004	26.438
20					0.000	0.000		

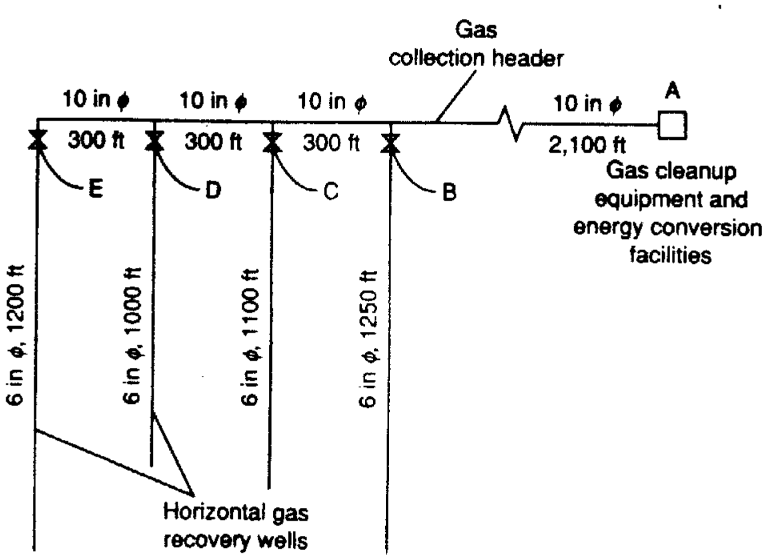
[a] Total waste deposited = 1 lb/year for five years.

4. Prepare a plot of the total yearly gas production rates and the cumulative amount of gas produced from the RBW and SBW deposited in the landfill over a five-year period.



Comment. In developing the total gas production curve in this example, a triangular gas production function was used. Note that any type of gas production function can be used if better information is available.

Example 11-9 Analysis of landfill gas recovery system. Determine the head loss in the landfill gas recovery system shown in the accompanying figure. Also determine the required blower capacity. The analysis is to be based on the following data and assumptions:



1. Diameter of horizontal gas extraction wells = 6 in
2. Diameter of header used to collect gas from the horizontal landfill gas recovery wells = to be determined

3. Absolute roughness for the plastic pipe used for the gas collection header, e = 0.00005 ft
4. Allowance for minor losses in header between extraction wells = 0.1 in H_2O
5. Allowance for minor losses in header between last extraction well and blower = 0.5 in H_2O
6. Estimated gas flow per horizontal gas extraction well = 200 ft^3/min (60°F, 14.7 lb/in^2)
7. Gas composition (by volume) = CH_4, 50%; CO_2, 50%
8. Temperature of landfill gas at the wellhead = 130°F
9. Temperature loss in manifold section between extraction wells = 5°F
10. Temperature of landfill gas at the blower station = 90°F
11. Landfill gas is saturated in water vapor at the wellhead.
12. Vacuum to be maintained at the wellhead of the farthermost horizontal gas extraction well (Point E) = 10 in H_2O
13. Vacuum at blower = to be determined, in H_2O

Solution

1. Determine the head loss in the header used to collect gas from the individual horizontal gas extraction wells starting at point E.
   Determine the headloss per 100 ft of header. Assume a 10 in header will be used. If the head loss using a 10 in header is too large, the size of the header is increased and the head loss computations are repeated. Friction losses in the gas piping can be calculated using the Darcy-Weisbach equation as given below (see Appendix I).

$$h_L = f\frac{L}{D}h_i$$

where h_L = friction loss, in of water
f = dimensionless friction factor obtained from Moody diagram (see Fig. I-1 in Appendix I)
L = length of pipe, ft
D = diameter of pipe, ft
h_i = velocity head of air, in of water

(a) Determine the velocity of flow of landfill gas in the 10 in header from point E to D. Using the perfect gas law, determine the volumetric flow rate at the average temperature in the header between the first and second extraction wells. Assume the temperature falls linearly with distance. Thus, the temperature at point D is 125°F. The volumetric flow rate of landfill gas at an average temperature of 127.5°F and 10 in H_2O vacuum can be determined as follows:

$$\left(\frac{PV}{T}\right)_1 = \left(\frac{PV}{T}\right)_2$$

P_1 = 14.7 lb/in^2 = 2116.8 lb/ft^2 = 33.9 ft of H_2O

V_1 = 200 ft^3/min

T_1 = 460 + 60 = 520°R

P_2 = 2116.8 lb/ft^2 − [(10 in/12 in/ft) × 61.60 lb/ft^3] = 2065.5 lb/ft^2

$$V_2 = \text{?}\ \text{ft}^3/\text{min}$$

$$T_2 = 460 + 127.5 = 587.5°\text{R}$$

$$V_2 = \frac{2116.8 \times 200}{520} \times \frac{587.5}{2065.5} = 231.6\ \text{ft}^3/\text{min}$$

The velocity of flow is given by

$$v = q/A$$

v = velocity of flow, ft/min

q = volumetric landfill gas flow rate, ft^3/min

A = cross-sectional area of 10 in diameter pipe, ft^2 = 0.545 ft^2

Thus:

$$v = (231.6\ \text{ft}^3/\text{min})/0.545\ \text{ft}^2 = 425.0\ \text{ft/min}$$

(*b*) Determine the value of the friction factor f in the Darcy-Weisbach equation using the Moody diagram given in Appendix I. The Reynolds number, N_R, may be computed using the following relationship:

$$N_R = \frac{dv\rho_{\text{gas}}}{\mu_{\text{gas}}} = \frac{dv\gamma_{\text{gas}}}{g\,\mu_{\text{gas}}}$$

where d = inside diameter of pipe, ft
v = velocity of gas flow in collection pipe = ft/s
ρ_{gas} = density of gas, slug/ft^3
μ_{gas} = viscosity of air, lb · s/ft^2
γ_{gas} = specific weight of landfill gas at the operating temperature, lb/ft^3
g = acceleration due to gravity, ft/s^2

The specific weight of the landfill gas at a temperature of 127.5°F and a pressure of 2065.5 lb/ft^2 can be computed using the perfect gas law as given below (note that the specific volume is inversely proportional to the specific weight):

$$\gamma_{\text{gas}} = \frac{1}{V} = \frac{P}{RT}$$

where R = gas constant for the landfill gas, ft · lb/(lb-landfill gas) · °R
P = pressure at operating temperature, lb/ft^2

The gas constant for landfill gas is obtained by dividing the universal gas constant [1543 ft · lb/(lb · mole) · °R] by the number of lb/lb · mole in the landfill gas. The lb/lb · mole of landfill gas, based on the given composition of the landfill gas, is calculated as

$$\text{lb/lb} \cdot \text{mole} = (0.50\ CH_4 \times 16) + (0.50\ CO_2 \times 44) = 30.0$$

The gas constant for the landfill gas is

$$R_{\text{landfill gas}} = [1543\ \text{ft} \cdot \text{lb/(lb} \cdot \text{mole)} \cdot °\text{R}]/(30.0\ \text{lb/lb} \cdot \text{mole landfill gas})$$

$$= 51.43\ \text{ft} \cdot \text{lb/(lb-landfill gas)} \cdot °\text{R}$$

Thus, the specific weight of the landfill gas is equal to

$$\gamma_{gas} = \frac{2065.5 \text{ lb/ft}^2}{\left[\dfrac{51.43 \text{ ft}\cdot\text{lb}}{(\text{lb-landfill gas})\cdot{}^\circ\text{R}}\right][(460 + 127.5)^\circ\text{R}]} = 0.068 \text{ lb/ft}^3$$

The viscosity of the landfill gas, μ_{gas}, at 127.5°F can be approximated, with sufficient accuracy for most practical purposes, using the following relationship:

$$\mu_{gas} = (0.0137) \times \mu_{\text{water at } 68^\circ\text{F}} \text{ (see Appendix I)}$$

$$\mu_{\text{water at } 68^\circ\text{F}} = 1.009 \text{ centipoise} = 2.11 \times 10^{-5} \text{ lb}\cdot\text{s/ft}^2$$

The Reynolds number at a temperature of 127.5°F is

$$N_R = \frac{dv\gamma_{gas}}{g\mu_{gas}} = \frac{(10/12)(425.3/60)(0.068)}{(32.17)(0.0137 \times 2.11 \times 10^{-5})} = 0.432 \times 10^5$$

Using an e/D value of 0.00006 (e = 0.00005 ft) and a Reynolds number of 0.432×10^5, the friction factor f from Fig. I-1 is found to be be equal to 0.020.

(*c*) The velocity head h_i in inches of water at a temperature of 127.5°F and a pressure of 2065.5 lb/ft² can be computed as follows:

$$h_i = \frac{(v, \text{ ft/min})^2}{2(32.17 \text{ ft/s}^2)}\left(\frac{1}{(60 \text{ s/min})^2}\right)\left(\gamma_{gas}, \frac{\text{lb-landfill gas}}{\text{ft}^3}\right)\left(\frac{1}{\gamma_w, \text{ lb/ft}^3}\right)\left(\frac{12 \text{ in}}{\text{ft}}\right)$$

where v = gas velocity, ft/min

γ_{gas} = specific weight of landfill gas at the operating temperature and pressure, lb/ft³

γ_w = specific weight of water, at the operating temperature, lb/ft³

The velocity head is

$$h_i = \frac{(425.0 \text{ ft/min})^2}{2(32.17 \text{ ft/s}^2)}\left(\frac{1}{(60 \text{ s/min})^2}\right)(0.068 \text{ lb/ft}^3)\left(\frac{1}{61.60 \text{ lb/ft}^3}\right)\left(\frac{12 \text{ in}}{\text{ft}}\right)$$

$$= 0.010 \text{ in of water}$$

(*d*) The head loss per 100 ft of 10 in pipe is

$$h_L = 0.020\left(\frac{100 \text{ ft}}{10 \text{ in}/(12 \text{ in/ft})}\right)0.010 \text{ in } H_2O = 0.024 \text{ in } H_2O$$

2. Set up a computation table to determine the head loss in the remaining portions of the manifold system. The computations for each section of the manifold are completed as outlined above. A new gas temperature must be computed at the point where each extraction well joins the manifold. The summary computation table is presented below.

Section	Pipe diameter, in	Pipe length, ft	Gas velocity, ft/min	Average gas temp., °F	Velocity head, h_i, in of H_2O	Friction factor, f	Friction loss, in/100 ft
E–D	10	300	425	127.5	0.010	0.020	0.024
D–C	10	300	850	125.0	0.041	0.018	0.089
C–B	10	300	1275	122.5	0.093	0.017	0.190
B–A	10	2100	1700	106.3	0.164	0.016	0.315

Section	Total friction loss, in of H_2O	Minor head loss, in of H_2O	Total head loss, in of H_2O
E–D	0.072[a]	0.1	0.172
D–C	0.267	0.1	0.367
C–B	0.570	0.1	0.670
B–A	6.615	0.5	7.115
Pipe loss in inches of H_2O			8.320
Vacuum at point E in inches of H_2O			10.000
Total			18.320

[a]0.024 in × (300 ft/100 ft) = 0.072 in

In the above computations the change in the gas volume due to the increased vacuum has not been considered. If the change in vacuum is significant, then successive computations must be conducted to account for the change in vacuum. In most cases, the change in temperature will offset the difference in vacuum. The total vacuum that must be supplied at the inlet of the vacuum blower, as computed above, is 18.32 in of H_2O at a gas flow of 893 ft^3/min. Typical vacuum levels at the blower inlet for landfill gas recovery systems vary from about 18 to 60 in of H_2O. The total pressure that the vacuum blower must overcome depends on the nature of the discharge facilities including meters, silencers, and check valves.

Comment. For the purposes of this example, the given values for the minor head losses were used. If assumed values for minor head losses are not used, the loss of head due to the presence of elbows, tees, valves, and so forth can be computed as a fraction of velocity head using the K values given in Appendix I of this text or in standard fluid mechanics texts. As noted in Appendix I, the minor losses due to fittings can also be expressed in terms of equivalent diameters of straight pipe that would result in the same loss of head. Meter losses can be estimated as a fraction of the differential head, depending on the type of meter. Losses owing to vacuum blower silencers and check valves should be obtained from equipment manufacturers.

Example 11-10 Determination of the amount of water vapor collected in a landfill gas recovery system. Determine the amount of condensed water vapor that must be removed daily from a landfill gas recovery system based on the following data and assumptions:

1. Total gas flow = 2.5×10^6 ft^3/d (60°F, 14.7 lb/in^2)
2. Temperature of landfill gas as it exits the landfill = 130°F
3. Temperature of landfill gas at the blower station = 90°F
4. Vacuum at well head = 10 in H_2O
5. Vacuum at blower = 75 in H_2O
6. Landfill gas is saturated in water vapor at the well head

Solution

1. **Determine the total pounds of water present in the water vapor in the saturated landfill gas at the well head.**

(*a*) Determine the volume of gas at the well head relative to the volume at standard conditions (60°F, 14.7 lb/in²).

$$\left(\frac{PV}{T}\right)_1 = \left(\frac{PV}{T}\right)_2$$

$$P_1 = 14.7 \text{ lb/in}^2 = 33.9 \text{ ft } H_2O$$

$$V_1 = 2.5 \times 10^6 \text{ ft}^3/\text{d}$$

$$T_1 = 460 + 60 = 520°\text{R}$$

$$P_2 = 33.9 \text{ ft } H_2O - [10 \text{ in}/(12 \text{ in}/1 \text{ ft})] = 33.07 \text{ ft } H_2O$$

$$V_2 = ?\ \text{ft}^3/\text{d}$$

$$T_2 = 460 + 130 = 590°\text{R}$$

$$V_2 = \frac{34 \times (2.5 \times 10^6)}{520} \times \frac{590}{33.07} = 2.92 \times 10^6 \text{ ft}^3/\text{d}$$

(*b*) Determine the moles of water vapor present in the landfill gas at the well head using the universal gas law.

$$p_v V = nRT$$

$$p_v = \text{vapor pressure of } H_2O \text{ at } 130°\text{F}$$

$$= 2.22 \text{ lb/in}^2 \text{ (see Appendix C)} = 319.7 \text{ lb/ft}^2$$

$$V = 2.92 \times 10^6 \text{ ft}^3/\text{d}$$

$$R = \text{universal gas constant} = 1543 \text{ ft} \cdot \text{lb/(lb} \cdot \text{mole)} \cdot °\text{R}$$

$$T = 460 + 130 = 590°\text{R}$$

$$n = \frac{p_v V}{RT} = \frac{319.7 \times (2.92 \times 10^6)}{1543 \times 590} = 1025.4 \text{ lb} \cdot \text{mole/d}$$

(*c*) Determine the pounds of water vapor present in the landfill gas at the well head.

$$\text{lb } H_2O = (1025.4 \text{ lb} \cdot \text{mole/d}) \times (18 \text{ lb } H_2O/\text{lb} \cdot \text{mole}) = 18{,}457.2 \text{ lb/d}$$

2. Determine the total pounds of water present as water vapor in the landfill gas at the blower.

(*a*) Determine the volume of landfill gas at the blower.

$$P_1 = 33.07 \text{ ft } H_2O$$

$$V_1 = 2.92 \times 10^6 \text{ ft}^3/\text{d}$$

$$T_1 = 460 + 130 = 590°\text{R}$$

$$P_2 = 33.9 \text{ ft } H_2O - [75 \text{ in}/(12 \text{ in/ft})] = 27.65 \text{ ft } H_2O$$

$$V_2 = ?\ \text{ft}^3/\text{d}$$

$$T_2 = 460 + 90 = 550°\text{R}$$

$$V_2 = \frac{33.07 \times (2.92 \times 10^6)}{590} \times \frac{550}{27.65} = 3.26 \times 10^6 \text{ ft}^3/\text{d}$$

(*b*) Determine the moles of water vapor present in the landfill gas at the blower.

$$p_v = \text{vapor pressure of } H_2O \text{ at } 90°F$$
$$= 0.70 \text{ lb/in}^2 \text{ (see Appendix B)} = 100.8 \text{ lb/ft}^2$$
$$V = 3.26 \times 10^6 \text{ ft}^3\text{/d}$$
$$R = 1543 \text{ ft} \cdot \text{lb/(lb} \cdot \text{mole)} \cdot °R$$
$$T = 460 + 90 = 550°R$$
$$n = \frac{p_v V}{RT} = \frac{100.8 \times (3.26 \times 10^6)}{1543 \times 550} = 387.2 \text{ lb} \cdot \text{mole/d}$$

(*c*) Determine the pounds of water vapor present in the landfill gas at the blower.

$$\text{lb } H_2O\text{/d} = (387.2 \text{ lb} \cdot \text{mole/d}) \times (18 \text{ lb } H_2O\text{/lb} \cdot \text{mole}) = 6969.6 \text{ lb/d}$$

3. Determine the amount of condensed water vapor that must be removed daily.

$$\text{Total water vapor condensed} = \text{lb } H_2O \text{ at well head} - \text{lb } H_2O \text{ at vacuum blower}$$
$$= 18{,}457.2 \text{ lb/d} - 6969.6 \text{ lb/d}$$
$$= 11{,}487.6 \text{ lb/d}$$
$$= 1377.4 \text{ gal/d}$$

Comment. Because significant amounts of water can be removed with the landfill gas, the capacity of the condensate traps should be constructed to handle at least two days of condensate flow. Depending on the location of the landfill and treatment facilities, larger condensate traps may be required.

Example 11-11 Landfill leachate production. Given the following information, calculate the yearly quantity of leachate produced from a landfill that is to be operated for a period of five years. The calculations should continue until the landfill reaches equilibrium; that is, the amount of water that enters the landfill will equal the amount of water that leaches out. Plot a curve of the yearly leachate production for the landfill. To simplify the calculations, determine the quantity of leachate produced for a surface area of one square yard, then convert the solution to account for the total quantity of waste deposited in the landfill.

1. Waste quantities
   (*a*) Waste deposited per day = 1000 tons
   (*b*) Number of operating days = 300
   (*c*) Waste deposited per year = 6×10^8 lb
2. Waste characteristics
   (*a*) Compacted specific weight of the waste = 1000 lb/yd^3
   (*b*) Initial moisture content of the waste = 20% by mass
   (*c*) The distribution of rapidly and slowly decomposable organic materials in the waste stream is as in Examples 11-2 and 11-6.
   (*d*) Assume no sludge will be deposited with the waste.

3. Landfill characteristics
   (*a*) General
      i. Lift height = 10 ft
      ii. Waste to cover ratio = 5:1 by volume
      iii. Number of lifts = 5 (one corresponding to each year)
   (*b*) Cover material
      i. Soil specific weight = 3000 lb/yd^3 (including moisture)
      ii. Moisture content of the soil is assumed to be at field capacity
   (*c*) Gas production
      i. Gas production: Use the following gas production data to estimate the total quantity of gas produced per lb of total waste deposited from each lift.

	Gas production, ft^3/lb		
End of year	Rapidly decomp.	Slowly decomp.	Total[a]
1	0.000	0.000	0.000
2	0.941	0.008	0.949
3	1.646	0.023	1.669
4	1.176	0.039	1.215
5	0.706	0.055	0.761
6	0.235	0.070	0.305
7	0.000	0.074	0.074
8	0.000	0.066	0.066
9	0.000	0.058	0.058
10	0.000	0.051	0.051
11	0.000	0.043	0.043
12	0.000	0.035	0.035
13	0.000	0.027	0.027
14	0.000	0.019	0.019
15	0.000	0.012	0.012
16	0.000	0.004	0.004
17	0.000	0.000	0.000
Total	4.704	0.584	5.288

[a] Based on a distribution of rapidly and slowly decomposable materials in the waste stream as given in Example 11-6.

      ii. Water consumed in the formation of landfill gas = 0.01 lb/ft^3 of gas produced
      iii. Water present as water vapor in landfill gas = 0.001 lb/ft^3 of gas produced
      iv. Specific weight of landfill gas = 0.0836 lb/ft^3
   (*d*) Field capacity

Field capacity as a function of the overburden mass is expressed as

$$FC = 0.6 - 0.55\left[\frac{W}{10{,}000 + W}\right]$$

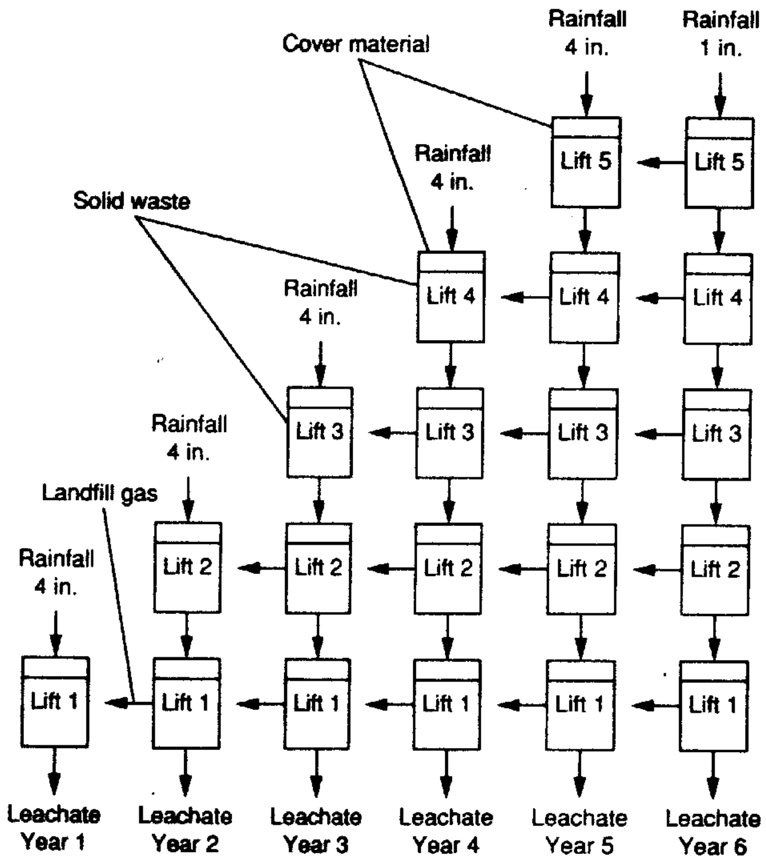
FC = fraction of water in the waste based on dry weight

W = overburden weight calculated at the midheight of the waste in the lift in question, lb

4. Rainfall quantities
   (*a*) Rainfall that infiltrates the daily cover during the first five years of operation = 4 in/yr
   (*b*) Rainfall that infiltrates the final cover after five years = 1 in/yr

Solution—Part 1: for years 1 through 5

1. Define the elements of the water balance for the first lift. The pertinent definition sketch for the problem follows.



(*a*) Determine the weight of cover material and solid waste in each lift.

Weight of cover material = [3000 lb/yd^3 × (10 ft × 1/6) × 1.0 yd^2]/(3 ft/yd)
= 1666.7 lb

Weight of solid waste = [1000 lb/yd^3 × (10 ft × 5/6) × 1.0 yd^2]/(3 ft/yd)
= 2777.8 lb

Total weight of lift = (1666.7 lb + 2777.8 lb)
= 4444.5 lb

(*b*) Dry weight of solid waste = 2777.8 lb × 0.80 = 2222.2 lb

(*c*) Moisture content in solid waste = 2777.8 lb × 0.20 = 555.6 lb (*d*) Weight of rainfall entering landfill during each of the first five years

$$\text{Rainfall weight} = [4 \text{ in}/(12 \text{ in/ft})] \times 1.0 \text{ yd}^2 \times (9 \text{ ft}^2/\text{yd}^2) \times (62.4 \text{ lb/ft}^3)$$
$$= 187.2 \text{ lb}$$

(*e*) Total weight of lift = 2777.8 lb + 1666.7 lb + 187.2 lb = 4631.7 lb

2. Prepare a water balance for lift 1 at the end of year 1 and determine the quantity of leachate to be expected from lift 1. The pertinent definition sketch for the first lift is shown above (see Step 1).

(*a*) Determine the amount and weight of gas produced from lift 1 during year 1. Note that gas production does not begin until the end of year 1, that is, it is assumed that no gas is produced in the first year.

$$\text{Gas produced} = 2777.8 \text{ lb} \times 0.0 \text{ ft}^3/\text{lb of waste deposited in lift 1}$$
$$= 0.0 \text{ ft}^3$$

$$\text{Weight of gas produced} = 0.0 \text{ ft}^3 \times 0.0836 \text{ lb/ft}^3$$
$$= 0.0 \text{ lb}$$

(*b*) Determine the weight of water consumed in the production of the landfill gas.

$$\text{Weight of water consumed} = 0.0 \text{ ft}^3 \times 0.01 \text{ lb/ft}^3 = 0.0 \text{ lb}$$

(*c*) Determine the weight of water vapor in the gas.

$$\text{Weight of water vapor} = 0.0 \text{ ft}^3 \times 0.001 \text{ lb/ft}^3 = 0.0 \text{ lb}$$

(*d*) Determine the weight of water in the solid waste in lift 1.

$$\text{Weight of water} = 555.6 \text{ lb} + 187.2 \text{ lb (from rainfall)} = 742.8 \text{ lb}$$

(*e*) Determine the dry weight of solid waste remaining in lift 1 at the end of year 1.

$$\text{Dry weight of solid waste} = 2222.2 \text{ lb} - [0.0 \text{ lb (landfill gas)} - 0.0 \text{ lb (water consumed in conversion reaction)}]$$
$$= 2222.2 \text{ lb}$$

(*f*) Determine the average weight on the waste plaçed in lift 1. (Note: the average weight in lift 1 will occur at the midpoint of the waste in lift 1.)

$$\text{Average weight} = 0.5 \times (2222.2 \text{ lb} + 742.8 \text{ lb}) + 1666.7 \text{ lb} = 3149.2 \text{ lb}$$

(*g*) Determine the field capacity factor using the following equation:

$$FC = 0.6 - 0.55\frac{W}{10{,}000 + W}$$

$$FC = 0.6 - 0.55\frac{3149.2}{10{,}000 + 3149.2} = 0.486$$

(*h*) Determine the amount of water that can be held in the solid waste.

$$\text{Water held in solid waste in lift 1} = 0.486 \times 2222.2 \text{ lb} = 1040 \text{ lb}$$

(*i*) Determine amount of leachate formed.

Leachate formed = actual water in solid waste − field capacity of solid waste

Leachate formed = 742.8 lb − 1040 lb = −297.2 lb

Because the field capacity of the waste is greater than the actual amount of water present in the waste, no leachate will form.

(*j*) Determine the amount of water remaining in lift 1 at the end of year 1.

Water remaining = 742.8 − 0 = 742.8 lb

(*k*) Determine the total weight of lift 1 at the end of year 1.

Total weight of lift = dry waste + water remaining + cover

= 2222.2 lb + 742.8 lb + 1666.7 lb = 4631.7 lb

3. Prepare a water balance for lifts 1 and 2 at the end of year 2 and determine the quantity of leachate to be expected from the first lift. The pertinent definition sketch for lifts 1 and 2 is shown above (see Step 1). Note that the computations for lift 2 in year 2 = the computations for lift 1 in year 1.

(*a*) Determine the amount and weight of gas produced from lift 1 during year 2.

Gas produced = 2777.8 lb (from Step 2*e*) × 0.949 ft^3/lb of waste deposited in lift 1

= 2636.1 ft^3

Weight of gas produced = 2636.1 ft^3 × 0.0836 lb/ft^3 = 220.4 lb

(*b*) Determine the weight of water consumed in the production of the landfill gas. Also note that the weight of solid waste that is consumed in the reaction is included in the weight of the gas determined in Step 3*a* above.

Weight of water consumed = 2636.1 ft^3 × 0.01 lb/ft^3 = 26.4 lb

(*c*) Determine the weight of water vapor in the gas.

Weight of water vapor = 2636.1 ft^3 × 0.001 lb/ft^3 = 2.6 lb

(*d*) Determine the weight of water in the solid waste in lift 1 at the end of year 2.

Weight of water = 742.8 lb − 26.4 lb − 2.6 lb = 713.8 lb

(*e*) Determine the dry weight of solid waste remaining in lift 1 at the end of year 2.

Dry weight of solid waste = 2222.2 lb − (220.4 lb − 26.4 lb)

= 2028.2 lb

(*f*) Determine the average weight on the waste placed in lift 1.

Average weight = 4631.7 lb (lift 2) + 0.5 × (2028.2 lb + 713.8 lb) + 1666.7 lb

= 7669.4 lb

(*g*) Determine the field capacity factor.

$$FC = 0.6 - 0.55\frac{7669.4}{10{,}000 + 7669.4} = 0.361$$

(*h*) Determine the amount of water that can be held in the solid waste.

$$\text{Water held in solid waste in lift 1} = 0.361 \times 2028.3 \text{ lb} = 732.8 \text{ lb}$$

(*i*) Determine amount of leachate formed.

$$\text{Leachate formed} = 713.8 \text{ lb} - 732.8 \text{ lb} = -18.9 \text{ lb}$$

Because the field capacity of the waste is greater than the actual amount of water present in the waste, no leachate will form.

(*j*) Determine the amount of water remaining in lift 1 at the end of year 2.

$$\text{Water remaining} = 713.8 - 0 = 713.8 \text{ lb}$$

(*k*) Determine the total weight of lift 1 at the end of year 2.

$$\text{Total weight of lift} = \text{dry waste} + \text{water remaining} + \text{cover}$$
$$= 2028.2 \text{ lb} + 713.8 \text{ lb} + 1666.7 \text{ lb} = 4408.8 \text{ lb}$$

4. Prepare a water balance for lifts 1, 2, and 3 at the end of year 3 and determine the quantity of leachate to be expected from lift 1. The pertinent definition sketch for lifts 1, 2, and 3 is shown above (see Step 1). Note that lift 3 = lift 2 and lift 2 = lift 1 in year 2.

(*a*) Determine the amount and weight of gas produced from lift 1 at the end of year 3.

$$\text{Gas produced} = 2777.8 \text{ lb} \times 1.67 \text{ ft}^3/\text{lb of waste deposited in lift 1}$$
$$= 4638.9 \text{ ft}^3$$
$$\text{Weight of gas produced} = 4638.9 \text{ ft}^3 \times 0.0836 \text{ lb/ft}^3 = 387.8 \text{ lb}$$

(*b*) Determine the weight of water consumed in the production of the landfill gas. Also note that the weight of solid waste that is consumed in the reaction is included in the weight of the gas determined in Step 4*a* above.

$$\text{Weight of water consumed} = 4638.9 \text{ ft}^3 \times 0.01 \text{ lb/ft}^3 = 46.4 \text{ lb}$$

(*c*) Determine the weight of water vapor in the gas.

$$\text{Weight of water vapor} = 4638.9 \text{ ft}^3 \times 0.001 \text{ lb/ft}^3 = 4.6 \text{ lb}$$

(*d*) Determine the weight of water in the solid waste in lift 1 at the end of year 3.

$$\text{Weight of water} = 713.8 \text{ lb} - 46.4 \text{ lb} - 4.6 \text{ lb} = 662.8 \text{ lb}$$

(*e*) Determine the dry weight of solid waste remaining in lift 1 at the end of year 3.

$$\text{Dry weight of solid waste} = 2028.3 \text{ lb} - (387.8 \text{ lb} - 46.4 \text{ lb})$$
$$= 1686.9 \text{ lb}$$

(*f*) Determine average weight on the waste placed in lift 1.

$$\begin{aligned}\text{Average weight} &= 4631.7 \text{ lb (lift 3)} + 4408.8 \text{ lb (lift 2)} \\ &\quad + 0.5 \times (1686.9 \text{ lb} + 662.8 \text{ lb}) + 1666.7 \text{ lb} \\ &= 11{,}882.0 \text{ lb}\end{aligned}$$

(*g*) Determine the field capacity factor.

$$\text{FC} = 0.6 - 0.55 \frac{11{,}882}{10{,}000 + 11{,}882} = 0.301$$

(*h*) Determine the amount of water that can be held in the solid waste.

$$\text{Water held in solid waste in lift 1} = 0.301 \times 1686.9 \text{ lb} = 508.3 \text{ lb}$$

(*i*) Determine the amount of leachate formed.

$$\text{Leachate formed} = 662.8 - 508.3 \text{ lb} = 154.5 \text{ lb}$$

Because the field capacity of the waste is less than the actual amount of water present in the waste, leachate will be formed.

(*j*) Determine the amount of water remaining in lift 1 at the end of year 3.

$$\text{Water remaining} = (662.8 - 154.5) \text{ lb} = 508.3 \text{ lb}$$

(*k*) Determine the total weight of lift 1 at the end of year 3.

$$\begin{aligned}\text{Total weight of lift} &= \text{dry waste} + \text{water remaining} + \text{cover} \\ &= 1686.9 \text{ lb} + 508.3 \text{ lb} + 1666.7 \text{ lb} = 3861.9 \text{ lb}\end{aligned}$$

5. Prepare a water balance for lifts 1, 2, 3, and 4 at the end of year 4 and determine the quantity of leachate to be expected from the lift 1. The pertinent definition sketch for lift 4 is shown above (see Step 1). Note that lift 4 = lift 3, lift 3 = lift 2, and lift 2 = lift 1 in year 3. Also note the amount of water discharged from lift 3 to lift 4 = 154.5 lb.

(*a*) Determine the amount and weight of gas produced from lift 1 at the end of year 4.

$$\begin{aligned}\text{Gas produced} &= 2777.8 \text{ lb} \times 1.215 \text{ ft}^3/\text{lb of waste deposited in lift 1} \\ &= 3374.8 \text{ ft}^3\end{aligned}$$

$$\text{Weight of gas produced} = 3374.8 \text{ ft}^3 \times 0.0836 \text{ lb/ft}^3 = 282.1 \text{ lb}$$

(*b*) Determine the weight of water consumed in the production of the landfill gas. Also note that the weight of solid waste that is consumed in the reaction is included in the weight of the gas determined in Step 5*a* above.

$$\text{Weight of water consumed} = 3374.8 \text{ ft}^3 \times 0.01 \text{ lb/ft}^3 = 33.7 \text{ lb}$$

(*c*) Determine the weight of water vapor in the gas.

$$\text{Weight of water vapor} = 3374.8 \text{ ft}^3 \times 0.001 \text{ lb/ft}^3 = 3.3 \text{ lb}$$

(*d*) Determine the weight of water in the solid waste in lift 1 at the end of year 4. It should be noted that the initial amount of water remaining in lift 1 is equal to the field capacity determine in Step 4*h* above.

$$\text{Weight of water} = (508.3 \text{ lb} - 33.7 \text{ lb} - 3.3 \text{ lb}) + 154.5 \text{ lb (leachate from lift 3)}$$
$$= 625.7 \text{ lb}$$

(*e*) Determine the dry weight of solid waste remaining in lift 1 at the end of year 4.

$$\text{Dry weight of solid waste} = 1686.9 \text{ lb} - (282.1 \text{ lb} - 33.7 \text{ lb})$$
$$= 1438.5 \text{ lb}$$

(*f*) Determine the average weight on the waste placed in lift 1.

$$\text{Average weight} = 4631.7 \text{ lb (lift 4)} + 4408.8 \text{ lb (lift 3)} + 3861.9 \text{ lb (lift 2)}$$
$$+ [0.5 \times (1438.5 \text{ lb} + 625.7 \text{ lb}) + 1666.7 \text{ lb}] = 15{,}601.2 \text{ lb}$$

(*g*) Determine the field capacity factor.

$$\text{FC} = 0.6 - 0.55\frac{15{,}601}{10{,}000 + 15{,}601} = 0.265$$

(*h*) Determine the amount of water that can be held in the solid waste.

$$\text{Water held in solid waste in lift 1} = 0.265 \times 1438.5 \text{ lb} = 381.0 \text{ lb}$$

(*i*) Determine amount of leachate formed.

$$\text{Leachate formed} = (625.7 - 381.0) \text{ lb} = 244.7 \text{ lb}$$

Because the field capacity of the waste is less than the actual amount of water present in the waste, leachate will be formed.

(*j*) Determine the amount of water remaining in lift 1 at the end of year 4.

$$\text{Water remaining} = (625.7 - 244.7) \text{ lb} = 381.0 \text{ lb}$$

(*k*) Determine the total weight of lift 1 at the end of year 4.

$$\text{Total weight of lift} = \text{dry waste} + \text{water remaining} + \text{cover}$$
$$= 1438.5 \text{ lb} + 381.0 \text{ lb} + 1666.7 \text{ lb}$$
$$= 3486.2 \text{ lb}$$

6. Prepare a water balance for lifts 1, 2, 3, 4, and 5 at the end of year 5 and determine the quantity of leachate to be expected from lift 1. The pertinent definition sketch for the lifts 1, 2, 3, 4, and 5 is shown above (see Step 1). Note that lift 5 = lift 4, lift 4 = lift 3, lift 3 = lift 2, and lift 2 = lift 1 in year 4. Also note the amount of water discharged from lift 3 to lift 2 = 244.7 lb and lift 2 to lift 1 = 154.5 lb.

(*a*) Determine the amount and weight of gas produced from lift 1 at the end of year 5.

$$\text{Gas produced} = 2777.8 \text{ lb} \times 0.760 \text{ ft}^3/\text{lb of waste deposited in lift 1}$$
$$= 2111.4 \text{ ft}^3$$

$$\text{Weight of gas produced} = 2111.4 \text{ ft}^3 \times 0.0836 \text{ lb/ft}^3 = 176.5 \text{ lb}$$

(*b*) Determine the weight of water consumed in the production of the landfill gas. Also note that the weight of solid waste that is consumed in the reaction is included in the weight of the gas determined in Step 6*a* above.

$$\text{Weight of water consumed} = 2111.4 \text{ ft}^3 \times 0.01 \text{ lb/ft}^3 = 21.1 \text{ lb}$$

(*c*) Determine the weight of water vapor in the gas.

$$\text{Weight of water vapor} = 2111.4\ \text{ft}^3 \times 0.001\ \text{lb/ft}^3 = 2.1\ \text{lb}$$

(*d*) Determine the weight of water in the solid waste in lift 1. Note that the initial amount of water remaining in lift 1 is equal to the field capacity determined in Step 5*h* above.

$$\begin{aligned}\text{Weight of water} &= (381.0 - 21.1 - 2.1)\ \text{lb} + 244.7\ \text{lb (from lift 2)}\\ &= 602.4\ \text{lb}\end{aligned}$$

(*e*) Determine the dry weight of solid waste remaining in lift 1 at the end of year 5.

$$\begin{aligned}\text{Dry weight of solid waste} &= 1438.5\ \text{lb} - (176.5 - 21.1)\ \text{lb}\\ &= 1283.1\ \text{lb}\end{aligned}$$

(*f*) Determine average weight on the waste placed in lift 1.

$$\begin{aligned}\text{Average weight} &= 4631.7\ \text{lb (lift 5)} + 4408.8\ \text{lb (lift 4)}\\ &\quad + 3861.9\ \text{lb (lift 3)} + 3486.2\ \text{lb (lift 2)}\\ &\quad + [0.5 \times (1283.1\ \text{lb} + 602.4\ \text{lb}) + 1666.7\ \text{lb}]\\ &= 18{,}998.0\ \text{lb}\end{aligned}$$

(*g*) Determine the field capacity factor.

$$FC = 0.6 - 0.55\frac{18{,}998}{10{,}000 + 18{,}998} = 0.240$$

(*h*) Determine the amount of water that can be held in the solid waste.

$$\text{Water held in solid waste in lift 1} = 0.240 \times 1283.1\ \text{lb} = 307.5\ \text{lb}$$

(*i*) Determine amount of leachate formed.

$$\text{Leachate formed} = (602.4 - 307.5)\ \text{lb} = 294.9\ \text{lb}$$

Because the field capacity of the waste is less than the actual amount of water present in the waste, leachate will be formed.

(*j*) Determine the amount of water remaining in lift 1 at the end of year 5.

$$\text{Water remaining} = (602.4 - 294.9)\ \text{lb} = 307.5\ \text{lb}$$

(*k*) Determine the total weight of lift 1 at the end of year 5.

$$\text{Total weight of lift} = \text{dry waste} + \text{water remaining} + \text{cover}$$

$$\text{Total weight of lift} = (1283.1 + 307.5 + 1666.7)\ \text{lb} = 3257.3\ \text{lb}$$

Solution—Part 2: for year 6 and following years. The weight of rainfall entering the landfill starting with year 6 is

$$\begin{aligned}\text{Rainfall weight} &= [1\ \text{in}/(12\ \text{in/ft})] \times 1.0\ \text{yd}^2 \times 9\ \text{ft}^2/\text{yd}^2 \times (62.4\ \text{lb/ft}^3)\\ &= 46.8\ \text{lb}\end{aligned}$$

To determine the leachate released from lift 1 each lift must be considered for each year. The analysis for year 6, which is the same for subsequent years, is illustrated below.

1. Determine the leachate from lift 5 in year 6.

   (*a*) Determine the amount and weight of gas produced from lift 5 at the end of year 6 (see Part 1, Step 3*a*).

$$\text{Gas produced} = 2777.8 \text{ lb} \times 0.949 \text{ ft}^3/\text{lb of waste deposited in lift 5}$$
$$= 2635.0 \text{ ft}^3$$
$$\text{Weight of gas produced} = 2635.0 \text{ ft}^3 \times 0.0836 \text{ lb/ft}^3 = 220.3 \text{ lb}$$

   (*b*) Determine the weight of water consumed in the production of the landfill gas. Note that the waste consumed is included in the weight of the gas determined in Step 3*a* above.

$$\text{Weight of water consumed} = 2635.0 \text{ ft}^3 \times 0.01 \text{ lb/ft}^3 = 26.3 \text{ lb}$$

   (*c*) Determine the weight of water vapor in the gas.

$$\text{Weight of water vapor} = 2635.0 \text{ ft}^3 \times 0.001 \text{ lb/ft}^3 = 2.6 \text{ lb}$$

   (*d*) Determine the weight of water in the solid waste in lift 5. Note that the calculations for lift 5 in year 5 correspond to the calculations for lift 1 in year 1 (See Part 1, Step 2*j*).

$$\text{Weight of water} = 742.8 \text{ lb} - 26.3 \text{ lb} - 2.6 \text{ lb} + 46.8 \text{ lb (from rainfall)}$$
$$= 760.6 \text{ lb}$$

   (*e*) Determine the dry weight of solid waste remaining in lift 5.

$$\text{Dry weight of solid waste} = 2222.2 \text{ lb} - (220.3 - 26.3) \text{ lb}$$
$$= 2028.3 \text{ lb}$$

   (*f*) Determine the average weight on the waste placed in lift 5.

$$\text{Average weight} = [0.5 \times (2028.3 \text{ lb} + 760.6 \text{ lb}) + 1666.7 \text{ lb}] = 3061.1 \text{ lb}$$

   (*g*) Determine the field capacity factor.

$$FC = 0.6 - 0.55 \frac{3061.1}{10{,}000 + 3061.1} = 0.471$$

   (*h*) Determine the amount of water that can be held in the solid waste.

$$\text{Water held in solid waste in lift 5} = 0.471 \times 2028.3 \text{ lb} = 955.5 \text{ lb}$$

   (*i*) Determine the amount of leachate formed.

$$\text{Leachate formed} = (760.6 - 955.5) \text{ lb} = -194.9 \text{ lb}$$

   Because the field capacity of the waste is greater than the actual amount of water present in the waste, no leachate will be formed.

   (*j*) Determine the amount of water remaining in lift 5 at the end of year 6.

$$\text{Water remaining} = (760.6 - 0) \text{ lb} = 760.6 \text{ lb}$$

   (*k*) Determine the total weight of lift 5 at the end of year 6.

$$\text{Total weight of lift 5} = \text{dry waste} + \text{water remaining} + \text{cover}$$
$$= 2028.3 \text{ lb} + 760 \text{ lb} + 1666{,}7 \text{ lb} = 4455.6 \text{ lb}$$

2. Determine the leachate from lift 4 in year 6.

(*a*) Determine the amount and weight of gas produced from lift 4 at the end of year 6 (see Part 1, Step 4*a*).

$$\text{Gas produced} = 2777.8 \text{ lb} \times 1.67 \text{ ft}^3/\text{lb of waste deposited in lift 4}$$
$$= 4638.3 \text{ ft}^3$$

$$\text{Weight of gas produced} = 4638.3 \text{ ft}^3 \times 0.0836 \text{ lb/ft}^3 = 387.8 \text{ lb}$$

(*b*) Determine the weight of water consumed in the production of the landfill gas.

$$\text{Weight of water consumed} = 4638.3 \text{ ft}^3 \times 0.01 \text{ lb/ft}^3 = 46.4 \text{ lb}$$

(*c*) Determine the weight of water vapor in the gas.

$$\text{Weight of water vapor} = 4638.3 \text{ ft}^3 \times 0.001 \text{ lb/ft}^3 = 4.6 \text{ lb}$$

(*d*) Determine the weight of water in the solid waste in lift 4 (see Part 1, Step 3*j*).

$$\text{Weight of water} = (713.8 - 46.4 - 4.6) \text{ lb} = 662.8 \text{ lb}$$

(*e*) Determine the dry weight of solid waste remaining in lift 4.

$$\text{Dry weight of solid waste} = 2028.3 \text{ lb} - (387.8 - 46.4) \text{ lb}$$
$$= 1686.9 \text{ lb}$$

(*f*) Determine the average weight on the waste placed in lift 4.

$$\text{Average weight} = 4455.6 \text{ lb (lift 5)} + [0.5 \times (1686.9 \text{ lb} + 662.8 \text{ lb}) + 1666.7 \text{ lb}]$$
$$= 7297.1 \text{ lb}$$

(*g*) Determine the field capacity factor.

$$FC = 0.6 - 0.55 \frac{7297.1}{10{,}000 + 7297.1} = 0.368$$

(*h*) Determine the amount of water that can be held in the solid waste.

$$\text{Water held in solid waste in lift 4} = 0.368 \times 1686.9 \text{ lb} = 620.7 \text{ lb}$$

(*i*) Determine the amount of leachate formed.

$$\text{Leachate formed} = (662.8 - 620.7) \text{ lb} = 42.1 \text{ lb}$$

Because the field capacity of the waste is less than the actual amount of water present in the waste, leachate will be formed.

(*j*) Determine the amount of water remaining in lift 4 at the end of year 6.

$$\text{Water remaining} = (662.8 - 42.1) \text{ lb} = 620.7 \text{ lb}$$

(*k*) Determine the total weight of lift 4 at the end of year 6.

$$\text{Total weight of lift 4} = \text{dry waste} + \text{water remaining} + \text{cover}$$
$$= 1686.9 \text{ lb} + 620.7 \text{ lb} + 1666.7 \text{ lb} = 3974.3 \text{ lb}$$

3. Determine the leachate from lift 3 in year 6.

   (*a*) Determine the amount and weight of gas produced from lift 3 at the end of year 6 (see Part 1, Step 5*a*).

$$\text{Gas produced} = 2777.8 \text{ lb} \times 1.215 \text{ ft}^3/\text{lb of waste deposited in lift 3}$$
$$= 3374.8 \text{ ft}^3$$
$$\text{Weight of gas produced} = 3374.8 \text{ ft}^3 \times 0.0836 \text{ lb/ft}^3 = 282.1 \text{ lb}$$

   (*b*) Determine the weight of water consumed in the production of the landfill gas.

$$\text{Weight of water consumed} = 3374.8 \text{ ft}^3 \times 0.01 \text{ lb/ft}^3 = 33.7 \text{ lb}$$

   (*c*) Determine the weight of water vapor in the gas.

$$\text{Weight of water vapor} = 3374.8 \text{ ft}^3 \times 0.001 \text{ lb/ft}^3 = 3.4 \text{ lb}$$

   (*d*) Determine the weight of water in the solid waste in lift 3 (see Part 1, Step 4*j*).

$$\text{Weight of water} = 508.3 \text{ lb} - 33.7 \text{ lb} - 3.7 \text{ lb} + \underset{\text{(leachate from above)}}{42.1 \text{ lb}}$$
$$= 513.3 \text{ lb}$$

   (*e*) Determine the dry weight of solid waste remaining in lift 4.

$$\text{Dry weight of solid waste} = 1686.9 \text{ lb} - (282.1 \text{ lb} - 33.7 \text{ lb})$$
$$= 1438.5 \text{ lb}$$

   (*f*) Determine the average weight on the waste placed in lift 3.

$$\text{Average weight} = 4455.5 \text{ lb (lift 5)} + 3974.3 \text{ lb (lift 4)}$$
$$+ [0.5 \times (1438.5 \text{ lb} + 513.3 \text{ lb}) + 1666.7 \text{ lb}]$$
$$= 11{,}072.5 \text{ lb}$$

   (*g*) Determine the field capacity factor.

$$FC = 0.6 - 0.55\frac{11{,}072.5}{10{,}000 + 11{,}072.5} = 0.311$$

   (*h*) Determine the amount of water that can be held in the solid waste.

$$\text{Water held in solid waste in lift 3} = 0.311 \times 1438.5 \text{ lb} = 447.4 \text{ lb}$$

   (*i*) Determine the amount of leachate formed.

$$\text{Leachate formed} = (513.3 - 447.4) \text{ lb} = 65.9 \text{ lb}$$

   Because the field capacity of the waste is less than the actual amount of water present in the waste, leachate will be formed.

   (*j*) Determine the amount of water remaining in lift 3 at the end of year 6.

$$\text{Water remaining} = (513.3 - 65.9) \text{ lb} = 447.4 \text{ lb}$$

   (*k*) Determine the total weight of lift 3 at the end of year 6.

$$\text{Total weight of lift 3} = \text{dry waste} + \text{water remaining} + \text{cover}$$
$$= 1438.5 \text{ lb} + 447.4 \text{ lb} + 1666.7 \text{ lb} = 3552.6 \text{ lb}$$

4. Determine the leachate from lift 2 in year 6.

(*a*) Determine the amount and weight of gas produced from lift 2 at the end of year 6 (see Part 1, Step 6*a*).

$$\text{Gas produced} = 2777.8 \text{ lb} \times 0.760 \text{ ft}^3/\text{lb of waste deposited in lift 2}$$
$$= 2111.4 \text{ ft}^3$$

$$\text{Weight of gas produced} = 2111.4 \text{ ft}^3 \times 0.0836 \text{ lb/ft}^3 = 176.5 \text{ lb}$$

(*b*) Determine the weight of water consumed in the production of the landfill gas.

$$\text{Weight of water consumed} = 2111.4 \text{ ft}^3 \times 0.01 \text{ lb/ft}^3 = 21.1 \text{ lb}$$

(*c*) Determine the weight of water vapor in the gas.

$$\text{Weight of water vapor} = 2111.4 \text{ ft}^3 \times 0.001 \text{ lb/ft}^3 = 2.1 \text{ lb}$$

(*d*) Determine the weight of water in the solid waste in lift 2 (see Part 1, Step 5*j*).

$$\text{Weight of water} = 381.0 \text{ lb} - 21.1 \text{ lb} - 2.1 \text{ lb} + 65.9 \text{ lb}$$

(leachate from above)

$$= 423.6 \text{ lb}$$

(*e*) Determine the dry weight of solid waste remaining in lift 4.

$$\text{Dry weight of solid waste} = 1438.5 \text{ lb} - (176.5 - 21.1) \text{ lb} = 1283.1 \text{ lb}$$

(*f*) Determine the average weight on the waste placed in lift 2.

$$\text{Average weight} = 4455.5 \text{ lb (lift 5)} + 3974.3 \text{ lb (lift 4)} + 3552.6 \text{ lb (lift 3)}$$
$$+ [0.5 \times (1283.1 \text{ lb} + 423.6 \text{ lb}) + 1666.7 \text{ lb}] = 14{,}502.5 \text{ lb}$$

(*g*) Determine the field capacity factor.

$$FC = 0.6 - 0.55\frac{14{,}502.5}{10{,}000 + 14{,}502.5} = 0.274$$

(*h*) Determine the amount of water that can be held in the solid waste.

$$\text{Water held in solid waste in lift 2} = 0.274 \times 1283.1 \text{ lb} = 352.2 \text{ lb}$$

(*i*) Determine the amount of leachate formed.

$$\text{Leachate formed} = (423.6 - 352.2) \text{ lb} = 71.5 \text{ lb}$$

Because the field capacity of the waste is less than the actual amount of water present in the waste, leachate will be formed.

(*j*) Determine the amount of water remaining in lift 2 at the end of year 6.

$$\text{Water remaining} = (423.6 - 71.5) \text{ lb} = 352.2 \text{ lb}$$

(*k*) Determine the total weight of lift 2 at the end of year 6.

$$\text{Total weight of lift 2} = \text{dry waste} + \text{water remaining} + \text{cover}$$
$$= 1283.1 \text{ lb} + 423.6 \text{ lb} + 1666.7 \text{ lb} = 3302.0 \text{ lb}$$

5. Determine the leachate from lift 1 in year 6.

(*a*) Determine the amount and weight of gas produced from lift 1 at the end of year 6.

$$\text{Gas produced} = 2777.8 \text{ lb} \times 0.305 \text{ ft}^3\text{/lb of waste deposited in lift 1}$$
$$= 848.0 \text{ ft}^3$$

$$\text{Weight of gas produced} = 848.0 \text{ ft}^3 \times 0.0836 \text{ lb/ft}^3 = 70.9 \text{ lb}$$

(*b*) Determine the weight of water consumed in the production of the landfill gas.

$$\text{Weight of water consumed} = 848.0 \text{ ft}^3 \times 0.01 \text{ lb/ft}^3 = 8.5 \text{ lb}$$

(*c*) Determine the weight of water vapor in the gas.

$$\text{Weight of water vapor} = 848.0 \text{ ft}^3 \times 0.001 \text{ lb/ft}^3 = 0.8 \text{ lb}$$

(*d*) Determine the weight of water in the solid waste in lift 3 (see Part 1, Step 6*j*).

$$\text{Weight of water} = 307.5 \text{ lb} - 8.5 \text{ lb} - 0.8 \text{ lb} + 71.5 \text{ lb (leachate from above)}$$
$$= 369.7 \text{ lb}$$

(*e*) Determine the dry weight of solid waste remaining in lift 1.

$$\text{Dry weight of solid waste} = 1283.1 \text{ lb} - (70.9 - 8.5) \text{ lb}$$
$$= 1220.7 \text{ lb}$$

(*f*) Determine average weight on the waste placed in lift 1.

$$\text{Average weight} = 4455.5 \text{ lb (lift 5)} + 3974.3 \text{ lb (lift 4)} + 3552.6 \text{ lb (lift 3)}$$
$$+ 3302.0 \text{ lb (lift 2)} + [0.5 \times (1220.7 \text{ lb} + 369.7 \text{ lb})$$
$$+ 1666.7 \text{ lb}] = 17{,}746.3 \text{ lb}$$

(*g*) Determine the field capacity factor.

$$FC = 0.6 - 0.55 \frac{17{,}746.3}{10{,}000 + 17{,}746.3} = 0.248$$

(*h*) Determine the amount of water that can be held in the solid waste.

$$\text{Water held in solid waste in lift 1} = 0.248 \times 1220.7 \text{ lb} = 303.0 \text{ lb}$$

(*i*) Determine the amount of leachate formed.

$$\text{Leachate formed} = (369.7 - 303.0) \text{ lb} = 66.7 \text{ lb}$$

Because the field capacity of the waste is less than the actual amount of water present in the waste, leachate will be formed.

(*j*) Determine the amount of water remaining in lift 1 at the end of year 6.

$$\text{Water remaining} = (368.7 - 66.7) \text{ lb} = 303.0 \text{ lb}$$

(*k*) Determine the total weight of lift 1 at the end of year 6.

$$\text{Total weight of lift 1} = \text{dry waste} + \text{water remaining} + \text{cover}$$
$$= 1220.7 \text{ lb} + 303.0 \text{ lb} + 1666.7 \text{ lb} = 3190.4 \text{ lb}$$

Solution—Part 3: estimate total leachate quantities

1. Determine the total number of square yards occupied by the landfill.
   (*a*) The total weight of solid waste placed in a landfill lift that is one yard square and 10 ft high = 2777.8 lb.
   (*b*) The total area occupied by each lift expressed in square yards is

$$\text{Total area} = (6 \times 10^8 \text{ lb/yr})/(2777.8 \text{ lb/yd}^2 \cdot \text{yr})$$
$$= 216{,}000 \text{ yd}^2$$

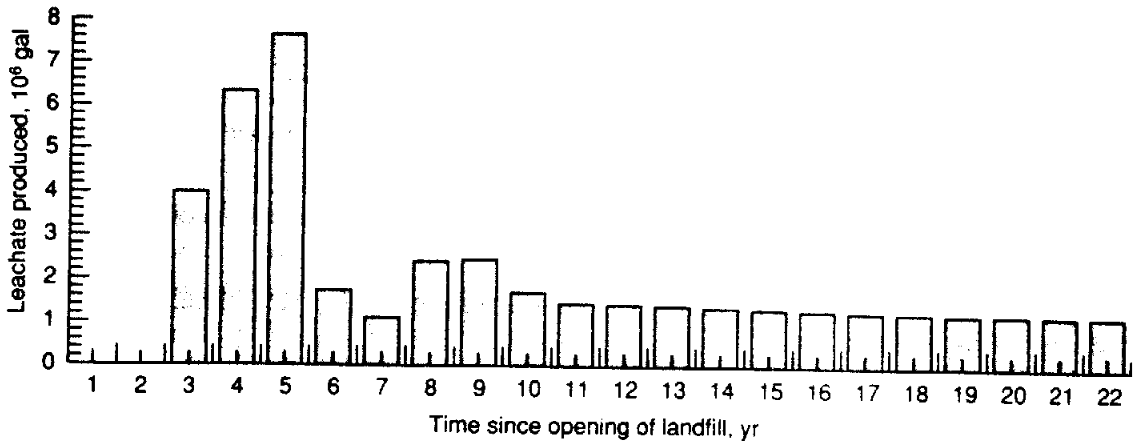
2. Determine the conversion factor to convert the lb of leachate obtained per square yard to gals/yr for the entire landfill.

$$\text{Conversion factor} = (\text{lb/yd}^2 \cdot \text{yr} \times 216{,}000 \text{ yd}^2)/(8.34 \text{ lb/gal})$$
$$= \text{lb/yd}^2 \cdot \text{yr} \times 25{,}900$$
$$= \text{gal/yr}$$

3. Prepare a summary table of the total leachate quantities to be expected with time and plot the results. The required data are summarized in the following table and illustrated in the figure presented below.

Leachate production

Year	Total lb/yd²	Total 10⁶ gal
1	0.0	0.0
2	0.0	0.0
3	154.5	4.00
4	244.7	6.34
5	294.9	7.64
6	66.7	1.73
7	43.0	1.11
8	93.0	2.41
9	94.9	2.46
10	65.5	1.70
11	55.7	1.44
12	55.1	1.43
13	53.9	1.40
14	52.7	1.37
15	51.5	1.33
16	50.3	1.30
17	49.1	1.27
18	48.2	1.25
19	47.4	1.23
20	46.9	1.22
21	46.8	1.21
22	46.8	1.21



Comment. The spreadsheet solution developed above allows computation of the quantities of leachate for any expected quantity of surface infiltration and for varying rates of gas production.

Example 11-12 Estimation of water percolation rates through a landfill cover. Determine the amount of water that will enter a landfill if a three-foot thick layer of clay loam is used for the final cover. Make the following assumptions: (1) The following rainfall and evapotranspiration data are applicable to the landfill site. (2) The average monthly runoff coefficient is equal to 20 percent. (3) The cover material is a clay loam with the physical characteristics given in Table 11-20. (4) The moisture content of the cover material is 50 percent of field capacity.

Month	Precipitation, in	Evapotranspiration, in
January	4.5	0.7
February	3.5	1.5
March	3.0	3.1
April	2.4	3.9
May	1.6	5.2
June	0.5	6.5
July	0.1	7.0
August	Trace	6.5
September	0.2	4.4
October	0.6	3.9
November	2.6	1.5
December	3.9	0.8
Total annual	22.9	45.0

Solution

1. Determine the water storage capacity in the cover material using the data given in Table 11-20.

   (*a*) The field capacity of the cover material in inches is

$$FC = 0.27 \times 12 \text{ in/ft} = 3.24 \text{ in/ft}$$

(*b*) The permanent wilt percent is

$$PWP = 0.12 \times 12 \text{ in/ft} = 1.44 \text{ in/ft}$$

(*c*) The moisture storage capacity available in the 3.0 ft landfill cover material is

$$SM = (3.24 \text{ in/ft} - 1.44 \text{ in/ft}) \times 3.0 \text{ ft} = 5.4 \text{ in}$$

(*d*) The initial cover material moisture deficit is

$$SM_d = (3.24 \text{ in/ft} \times 0.50 - 1.44 \text{ in/ft}) \times 3.0 \text{ ft} = 0.54 \text{ in}$$

2. Set up a computation table (presented below) to determine the amount of water that will enter a landfill through the three-foot thick cover layer of clay loam. Monthly precipitation, evapotranspiration, and runoff data are presented in columns (2), (3), and (4), respectively. The potential gain or loss of soil moisture from a unit volume of cover material is given in column (5). The cover material moisture deficit is given in column (6). The amount of water that potentially can percolate through the landfill cover is given in column (7).

	Value, in					
Month (1)	Precipitation (2)	Evapo-transpiration (3)	Runoff (4)	Moisture gain (+) or loss (−), (5)[a]	Cover material deficit (6)	Potential percolate through cover (7)
January	4.50	0.70	0.90	2.90	0.00	2.36[b]
February	3.50	1.50	0.70	1.30	0.00	1.30
March	3.00	3.10	0.60	−0.70	−0.70	0.00
April	2.40	3.90	0.48	−1.98	−2.68	0.00
May	1.60	5.20	0.36	−3.96	−5.40[c]	0.00
June	0.50	6.50	0.10	−6.10	−5.40	0.00
July	0.10	7.00	—	−6.90	−5.40	0.00
August	Trace	6.50	—	−6.50	−5.40	0.00
September	0.20	4.40	—	−4.20	−5.40	0.00
October	0.60	3.90	0.12	−3.42	−5.40	0.00
November	2.60	1.50	0.52	0.58	−4.82	0.00
December	3.90	0.80	0.78	2.32	−2.50	0.00
January	4.50	0.70	0.90	2.90	0.00	0.40
February	3.50	1.50	0.70	1.30	0.00	1.30
March	3.00	3.10	0.60	−0.70	−0.70	0.00
April	2.40	3.90	0.48	−1.98	−2.68	0.00
May	1.60	5.20	0.36	−3.96	−5.40	0.00

[a] (5) = (2) − (3) − (4)

[b] 2.36 = 2.90 − 0.54 (initial cover material deficit)

[c] 5.40 = maximum moisture storage capacity available in the cover material

Comment. The slope and depth of the landfill cover could be increased to limit the amount of rainfall that percolates through the landfill cover. Also, the runoff coefficient in this example was assumed to be constant. In practice the runoff coefficient will vary with antecedent conditions.

Example 11-13 Landfill compaction during operation and long-term compaction/consolidation. Given the following information, compute the additional capacity available in the landfill of Example 11-11 after five years as a result of compaction and gas production. Also estimate the actual height of the landfill at the end of year 5 and the long-term settlement of the landfill after closure. The calculations should continue until the landfill reaches equilibrium.

Use the same data as given in Example 11-11. Assume the initial compacted specific weight of the waste is 1000 lb/yd³ and that the following relationship can be used to estimate the specific weight of the compacted waste as a function of the overburden pressure. Assume no compaction of the cover material.

$$SW_p = 1000\ \text{lb/yd}^3 + \frac{p,\ \text{lb/in}^2}{0.0133\ (\text{yd}^3/\text{lb})(\text{lb/in}^2) + (0.001\ \text{yd}^3/\text{lb})(p,\ \text{lb/in}^2)}$$

where SW_p = compacted specific weight of the waste at pressure p, lb/yd³

Solution—Part 1: estimate the additional landfill capacity after five years

1. Calculate the height of each lift and of the cover material between the lifts. Use the specific weight and pressure at the middle of each lift to approximate the density and pressure for the whole lift.

   (*a*) Determine the height of the fifth lift.

   i. The total amount of waste in lift five at the end of year five is 4631.7 lb/yd² (waste = 2965.0 and cover material = 1666.7, see Example 11-11, Part 1, Step 1). The pressure at the midpoint of the lift can be calculated.

   $$p = \left(1666.7\ \text{lb} + \frac{2965.0\ \text{lb}}{2}\right)\left(\frac{1}{\text{yd}^2}\right)\left(\frac{1\ \text{yd}}{3\ \text{ft}}\right)^2\left(\frac{1\ \text{ft}}{12\ \text{in}}\right)^2 = 2.43\ \text{lb/in}^2$$

   ii. The specific weight is related to the pressure by the equation given in the problem statement.

   $$SW_p = 1000\ \text{lb/yd}^3 + \frac{p}{0.0133 + 0.001\ p}$$

   $$SW_p = 1000\ \text{lb/yd}^3 + \frac{2.43\ \text{lb/in}^2}{0.0133\ (\text{yd}^3/\text{ft}^2)(\text{lb/in}^2) + 0.001\ \text{yd}^3/\text{lb}\ (2.43\ \text{lb/in}^2)}$$

   $$= 1154.5\ \text{lb/yd}^3$$

   iii. Estimate the height h of the waste material in lift 5 at the end of year 5. The height is related to the amount of the initial material remaining in the lift at the end of the year including water additions or losses and the average specific weight in the lift.

   $$\text{Material remaining in lift, lb} = SW_p\left(\frac{\text{lb}}{\text{yd}^3}\right)\left(1\ \text{yd}^2 \times h\ \text{ft} \times \frac{\text{yd}}{3\ \text{ft}}\right)$$

   $$2965.0\ \text{lb} = 1154.4\left(\frac{\text{lb}}{\text{yd}^3}\right)h\ (\text{ft})\ \frac{\text{yd}^3}{3\ \text{ft}}$$

   $$h = 7.70\ \text{ft}$$

iv. Estimate the total height of lift 5 at the end of year 5. Note that, because it is assumed that there is no decomposition or compression of the cover material over time, this value is the same for each lift each year.

$$\text{Height of cover material} = 10 \text{ ft } (1/6) = 1.67 \text{ ft}$$

$$h_{\text{total}} = 7.70 + 1.67 \text{ ft} = 9.37 \text{ ft}$$

(*b*) Determine the height of the fourth lift.

i. The total amount of waste in lift 4 at the end of year 5 is 4408.8 lb/yd^2 (2742.1 = waste, and 1666.7 = cover material). The pressure at the midpoint of the lift can be calculated.

$$p = \left(4631.7 + 1666.7 + \frac{2742.1}{2}\right)\left(\frac{\text{lb}}{\text{yd}^2}\right)\left(\frac{1 \text{ yd}}{3 \text{ ft}}\right)^2\left(\frac{1 \text{ ft}}{12 \text{ in}}\right)^2 = 5.92 \text{ lb/in}^2$$

ii. Determine the specific weight from the pressure.

$$SW_p = 1000 \text{ lb/yd}^3 + \frac{5.92 \text{ lb/in}^2}{0.0133 \text{ (yd}^3\text{/lb)(lb/in}^2) + 0.001 \text{ yd}^3\text{/lb } (5.92 \text{ lb/in}^2)}$$

$$= 1307.9 \text{ lb/yd}^3$$

iii. Estimate the height of the waste material in lift 4 at the end of year 5.

$$2742.1 \text{ lb} = 1307.9\left(\frac{\text{lb}}{\text{yd}^3}\right)\left(h \text{ (ft)} \frac{\text{yd}^3}{3 \text{ ft}}\right)$$

$$h = 6.29 \text{ ft}$$

iv. Estimate the total height of lift 4 at the end of year 5.

$$h_{\text{total}} = (6.29 + 1.67) \text{ ft} = 7.96 \text{ ft}$$

(*c*) Determine the height of the third lift.

i. The total amount of waste in lift 3 at the end of year 5 is 3861.9 lb/yd^2 (2195.2 = waste, and 1666.7 = cover material). The pressure at the midpoint of the lift can be calculated.

$$p = \left(4631.7 + 4408.8 + 1667.7 + \frac{2195.2}{2}\right)\left(\frac{\text{lb}}{\text{yd}^2}\right)\left(\frac{1 \text{ yd}}{3 \text{ ft}}\right)^2\left(\frac{1 \text{ ft}}{12 \text{ in}}\right)$$

$$= 9.11 \text{ lb/in}^2$$

ii. Determine the specific weight from the pressure.

$$SW_p = 1000 \text{ lb/yd}^3 + \frac{9.11 \text{ lb/in}^2}{0.0133 \text{ yd}^3\text{/ft}^2 + 0.001 \text{ yd}^3\text{/lb } (9.11 \text{ lb/in}^2)}$$

$$= 1406.5 \text{ lb/yd}^3$$

iii. Estimate the height of the waste material in lift 3 at the end of year 5.

$$2195.2 \text{ lb} = 1406.5\left(\frac{\text{lb}}{\text{yd}^3}\right)\left(h \text{ (ft)} \frac{\text{yd}^3}{3 \text{ ft}}\right)$$

$$h = 4.68 \text{ ft}$$

iv. Estimate the total height of lift 3 at the end of year 5.

$$h_{total} = (4.68 + 1.67) \text{ ft} = 6.35 \text{ ft}$$

(*d*) Determine the height of the second lift.

i. The total amount of waste in lift 2 at the end of year 5 is 3486.2 lb/yd² (1819.5 = waste, and 1666.7 = cover material). The pressure at the midpoint of the lift can be calculated.

$$p = \left(4631.7 + 4408.8 + 3861.9 + 1666.7 + \frac{1819.5}{2}\right)\left(\frac{\text{lb}}{\text{yd}^2}\right)\left(\frac{1 \text{ yd}}{3 \text{ ft}}\right)^2\left(\frac{1 \text{ ft}}{12 \text{ in}}\right)^2$$
$$= 11.94 \text{ lb/in}^2$$

ii. Determine the specific weight from the pressure.

$$SW_p = 1000 \text{ lb/yd}^3 + \frac{11.9 \text{ lb/in}^2}{0.0133 \text{ (yd}^3\text{/lb)(lb/in}^2) + 0.001 \text{ yd}^3\text{/lb } (11.9 \text{ lb/in}^2)}$$
$$\doteq 1473.1 \text{ lb/yd}^3$$

iii. Estimate the height of the waste material in lift 3 at the end of year 5.

$$1819.5 \text{ lb} = 1473.1 \frac{\text{lb}}{\text{yd}^3}\left(h \text{ (ft) } \frac{\text{yd}^3}{3 \text{ ft}}\right)$$
$$h = 3.71 \text{ ft}$$

iv. Estimate the total height of lift 2 at the end of year 5.

$$h_{total} = (3.71 + 1.67) \text{ ft} = 5.38 \text{ ft}$$

(*e*) Determine the total height of the first lift.

i. The total amount of waste in lift 1 at the end of year 5 is 3257.3 lb/yd² (1590.6 = waste, and 1666.7 = cover material). The pressure at the midpoint of the lift can be calculated.

$$p = \left(4631.7 + 4408.8 + 3861.9 + 3486.2 + 1666.7 + \frac{1590.6}{2}\right)$$
$$\times \left(\frac{\text{lb}}{\text{yd}^2}\right)\left(\frac{1 \text{ yd}}{3 \text{ ft}}\right)^2\left(\frac{1 \text{ ft}}{12 \text{ in}}\right)^2 = 14.6 \text{ lb/in}^2$$

ii. Determine the specific weight from the pressure.

$$SW_p = 1000 + \frac{14.6 \text{ lb/in}^2}{0.0133 \text{ (yd}^3\text{/lb)(lb/in}^2) + 0.001 \text{ yd}^3\text{/lb } (14.6 \text{ lb/in}^2)}$$
$$= 1522.4 \text{ lb/yd}^3$$

iii. Estimate the height of the waste material in lift 1 at the end of year 5.

$$1590.6 \text{ lb} = 1522.4\left(\frac{\text{lb}}{\text{yd}^3}\right)\left(h \text{ (ft) } \frac{\text{yd}^3}{3 \text{ ft}}\right)$$
$$h = 3.13 \text{ ft}$$

iv. Estimate the total height of lift 1 at the end of year 5.

$$h_{total} = (3.13 + 1.67) \text{ ft} = 4.80 \text{ ft}$$

2. Estimate the additional capacity available in the landfill at the end of year 5.
   (*a*) Estimate the total height of the landfill at the end of year 5.

$$h_{total} = 4.80 \text{ ft} + 5.38 \text{ ft} + 6.35 \text{ ft} + 7.96 \text{ ft} + 9.37 \text{ ft} = 33.87 \text{ ft}$$

   (*b*) Estimate the additional capacity of the landfill. The landfill has 50.00 ft − 33.87 ft = 16.13 ft, or

$$\frac{16.13}{33.87} \times 100\% = 47.6\%$$

   more waste could be placed in the landfill.

   (*c*) Estimate the additional amount of waste that could be placed in the landfill. Note the amount of waste placed per lift is 2777.8 lb (Problem 11-11, Step 1).

$$0.476 \times 5(2777.8 \text{ lb/yd}^2) = 6611.2 \text{ lb/yd}^2$$

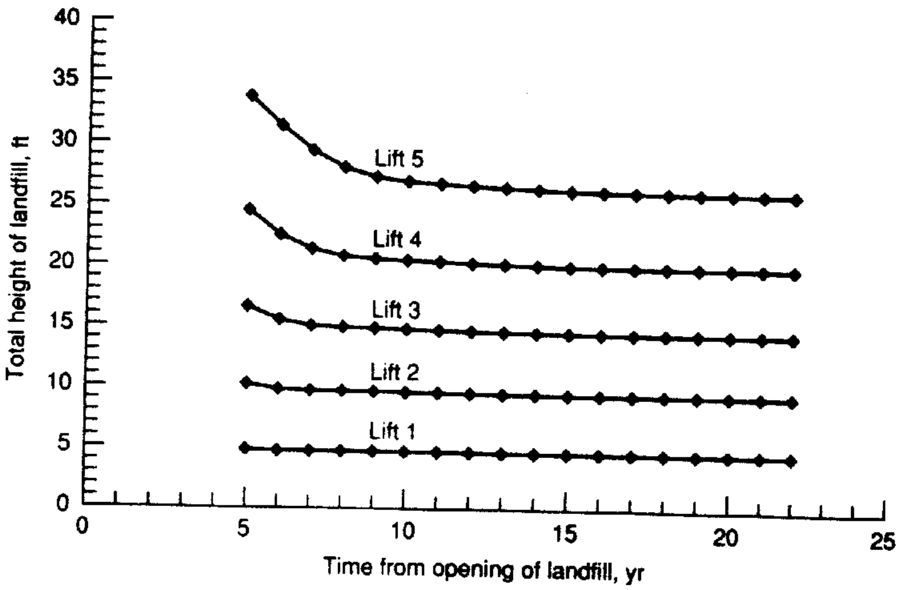
   For a landfill of 216,000 yd^2, the additional amount of waste which could be placed is

$$216{,}000 \text{ yd}^2 \times 6611.2 \text{ lb/yd}^2 = 1.43 \times 10^9 \text{ lb}$$

Solution—Part 2: long-term compaction of the landfill. To determine the long-term compaction of the landfill, each lift must be considered for each year. The analysis for year 6 and for subsequent years is the same as the analysis for year 5.

Prepare a summary table of the total height of each lift and of the total height of the landfill and plot the results. The required data are summarized in the following table and illustrated in the figure presented on page 529.

Year after opening of landfill	Height of lift, ft					
	Lift 1	Lift 2	Lift 3	Lift 4	Lift 5	h_{total}, ft
1						
2						
3						
4						
5	4.80	5.38	6.35	7.96	9.37	33.87
6	4.70	5.04	5.74	7.01	8.94	31.43
7	4.71	4.93	5.37	6.31	8.08	29.40
8	4.71	4.93	5.25	5.87	7.29	28.04
9	4.69	4.92	5.23	5.71	6.72	27.27
10	4.67	4.89	5.20	5.68	6.49	26.94
11	4.66	4.87	5.17	5.64	6.43	26.77
12	4.64	4.85	5.15	5.60	6.38	26.62
13	4.63	4.83	5.13	5.57	6.34	26.50
14	4.62	4.82	5.11	5.55	6.30	26.39
15	4.62	4.81	5.09	5.52	6.26	26.31
16	4.62	4.81	5.08	5.51	6.24	26.25
17	4.62	4.81	5.08	5.50	6.22	26.22
18	4.62	4.81	5.08	5.49	6.20	26.19
19	4.62	4.81	5.08	5.49	6.19	26.18
20	4.62	4.81	5.08	5.49	6.19	26.18
21	4.62	4.81	5.08	5.49	6.19	26.18
22	4.62	4.81	5.08	5.49	6.19	26.18



Example 11-14 Selection of a landfill leachate collection system and cover configuration. Select appropriate design criteria for a leachate collection system and landfill cover design for a municipal solid waste landfill. Assume the municipality has requested that a composite liner and cover design be used. The liner is to be composed of clay and a geomembrane with a drainage layer, and the cover is to incorporate the use of a drainage layer and a geomembrane. Also check to see if enough leachate can be transported through the drainage layer to the leachate collection channel to accommodate the leachate from the landfill in Example 11-9.

Solution—Part 1: leachate collection system

1. To meet the requirements specified by the municipality, a composite liner design of the type shown in Fig. 11-36*b* was selected.
2. Based on the information presented in Section 11-5, the appropriate design criteria for the liner configuration are reported in the table on page 530.
3. Check drainage capacity of liner cross slope.
   (*a*) Estimate drainage capacity of section of liner cross slope as shown below by considering a strip 3 ft wide by 200 ft in length with a slope of 1 percent.
   (*b*) Estimate the hydraulic capacity of the cross slope using Darcy's law. Assume the permeability of the combined drainage and filter layer is the same as coarse sand (1333 ft/d, see Table 11-15) and that the equivalent thickness of the combined drainage layer, composed of the drainage and filter layers, is 0.30 in.

   The quantity of leachate transmitted is determined using Darcy's law,

$$Q = Av = -AKi$$

where A = area, ft^2 = [0.30 in/(12 in/ft)] × 3 ft = 0.075 ft^2
K = permeability, ft/d = 1333 ft/d
$i = -dh/dl$ = slope = −0.01

$$Q = -0.075\ \text{ft}^2 \times 1333\ \text{ft/d} \times (-0.01)$$
$$= 1.0\ \text{ft}^3/\text{d} = 7.48\ \text{gal/d}$$

Landfill liner design criteria, Example 11-14, Part 1, Step 2

Item	Unit	Value
Liner configuration		See Fig. 11-36*b*
Subbase		
Material		Native soil
Treatment		Compacted
Clay layer		
Thickness	ft	2[a]
Permeability	cm/s	1×10^{-7}
Geomembrane		
Material		Polyethylene
Thickness	mil	80
Drainage layer		
Material		Polyethylene
Configuration		Cross weave
Thickness	in	0.25
Filter layer		
Material		Polyethylene
Thickness	in	0.25
Protective layer		
Material		Native soil
Thickness	ft	2
Liner design		
Length of cross slope	ft	200
Cross slope	%	1
Drainage channels	%	0.5

[a] To be applied in 6 in (150 mm) lifts.

(*c*) Compare the amount of leachate that can be transmitted with the actual quantity of leachate generated.

i. The maximum amount of leachate generated per yd^2 occurs at the end of year 5 and is equal to 282 $lb/yd^2 \cdot yr$ = 33.9 $gal/yd^2 \cdot yr$.

ii. The maximum quantity of leachate generated from the quantity of waste placed on an area of 66.7 yd^2 [(3 ft × 200 ft)/(9 ft^2/yd^2)] is equal to 33.9 $gal/yd^2 \cdot yr$ × 66.7 yd^2 = 2261 gal/yr = 6.19 gal/d.

iii. Because the quantity of leachate that can be transmitted per day (7.48 gal/d) is greater than the amount of leachate generated per day (6.19 gal/d) the capacity of the cross slope is adequate. It should also be noted that after year 6 the quantity of leachate drops to 25 percent of the value used in these computations.

Solution—Part 2: cover design

1. Assume the cover will be a composite design as shown in Fig. 11-53*a*.
2. Based on the information presented in Sections 11-4 and 11-6, the appropriate design criteria for the landfill cover are reported in the following table.

Landfill cover design criteria, Example 11-14, Part 2, Step 2

Item	Unit	Value
Cover configuration		See Fig. 11-53*a*
Soil layer		
Material		Native soil
Thickness	ft	2
Permeability	cm/s	1×10^{-7}
Geomembrane		
Material		Polyethylene
Thickness	mil	80
Drainage layer		
Material		Sand
Thickness	ft	1.0
Separation layer		
Material		Geotextile filter fabric
Thickness (approx.)	in	0.125
Final earth cover		
Material		Native soil
Thickness	ft	2
Cover design		
Top slope	%	5
Maximum distance to drainage channels	ft	200

Comment. Although more sophisticated approaches are available for computing the hydraulic capacity of the drainage layer, the reliability of the computations is no better than the approach used in this example problem.

11-13 DISCUSSION TOPICS AND PROBLEMS

11-1. Estimate the theoretical amount of gas (methane and carbon dioxide) that could be produced under anaerobic conditions from wastes with the following chemical composition: (*a*) $C_{12}H_{22}O_{11}$ (sucrose), (*b*) $C_2H_5O_2N$ (glycine), and (*c*) $C_{60}H_{96}O_{38}N$.

11-2. Estimate the emission rates, expressed as $g/m^2 \cdot d$, for carbon dioxide and methane from the surface of a landfill due to diffusion alone. Assume the following conditions apply:

(*a*) Temperature = 30°C

(*b*) Landfill cover material = clay-loam mixture

(*c*) Porosity of landfill cover material = 0.23

(*d*) Landfill cover thickness = 2 ft

(*e*) Coefficient of diffusion for methane = 0.20 cm^2/s (18.6 ft^2/d)

(*f*) Coefficient of diffusion for carbon dioxide = 0.13 cm^2/s (12.1 ft^2/d)

(*g*) Note that $(g/cm^2 \cdot s) \times 0.864 \times 10^9 = g/m^2 \cdot d$

11-3. A 50-ft deep sanitary landfill in alluvial gravel has been completed for several years. The normal groundwater level is 150 ft below the surface, or 100 ft below the bottom of the fill. A special sampling well at the edge of the landfill shows that the atmosphere in the interstices of the soil 20 ft above the water table contains 48 percent CO_2, 28 percent CH_4, 20 percent N_2, 2 percent O_2, 1 percent H_2S, and 1 percent other gases, analyzed and calculated on a dry basis at 0°C and 760 mm pressure. On the basis of a long period of contact (i.e., equilibrium) at 10°C, compute the concentration in mg/L of each of these five gases to be expected in the upper layers of the groundwater under a total pressure of 1 atm at 10°C. Assume saturation with respect to vapor pressure. (Problem courtesy of Dr. Paul H. King.)

11-4. Using Henry's law (see Appendix F), estimate the maximum concentrations of methane and carbon dioxide that would be present in the leachate if the partial pressure of each gas within the landfill was equal to one atmosphere.

11-5. If the bicarbonate concentration of a leachate is 1000 mg/L and the pH measured in the field is found to be 5.8, estimate the partial pressure of the carbon dioxide within the landfill.

11-6. If the partial pressure of the carbon dioxide in the gas in contact with leachate within a landfill is one atmosphere, estimate the pH of the leachate. Assume the carbon dioxide in the landfill gas is the only factor affecting the pH of the leachate.

11-7. Determine the breakthrough time in years for leachate to penetrate a 4-foot thick clay liner. Assume the effective porosity is 0.20, the coefficient of permeability is 10^{-7} cm/s, and the hydraulic head is 6 ft.

11-8. If the breakthrough time for leachate to penetrate a 3-foot thick clay liner is 12 years, estimate the coefficient of permeability given that the effective porosity is 0.20 and the hydraulic head is 5.5 ft.

11-9. Determine the effect of a 10°C rise in temperature on the rate of percolation of leachate through a clay liner. Assume the coefficient of permeability is equal to 1×10^{-6} cm/s.

11-10. What thickness of clay liner would be required if the breakthrough time for leachate to penetrate the liner is to be 20 years? The coefficient of permeability is 5×10^{-8} cm/s and the effective porosity is 0.17. Assume the hydraulic gradient is 1 ft greater than the thickness of the liner.

11-11. If MSW with the composition given in Table 3-4 is to be mixed with wastewater treatment plant sludge containing 5 percent solids to achieve a final moisture content of 55 percent, estimate the ultimate amount of leachate that would be produced per cubic yard of compacted solid waste if no surface infiltration were allowed to enter the completed landfill. Assume that the following data and information are applicable:

(*a*) Initial moisture content of MSW = 20 percent

(*b*) In-place specific weight of compacted mixture of solid wastes and sludge = 1200 lb/yd^3

(*c*) Chemical formula for decomposable portion of the organic fraction of the MSW = $C_{60}H_{96}O_{38}N$

(*d*) Sixty-five percent of the organic fraction of the MSW is biodegradable

(*e*) Assume the biodegradable portion of the organic wastes will be converted according to Eq. (11-2)

(*f*) Final moisture content of wastes remaining in landfill = 35 percent

(*g*) Neglect surface evaporation

11-12. Review the current literature, and prepare a brief (two-page) assessment of the need for the use of soil as an intermediate cover material. In your review you should question whether any intermediate cover material is required.

11-13. Contact your local waste management agency and obtain the designs of the landfill liner and final cover used for landfills under their jurisdiction. Based on what you have read in this chapter and other literature sources, what is your assessment of the liner and cover designs that are being used?

11-14. Determine the compacted specific weight of the wastes in the landfill in Example 11-3 if 80 percent of the yard wastes are removed for composting.

11-15. Develop a spreadsheet program for the solution of Example 11-5 in Section 11-9 for wastes that are both normally and well compacted. Check your spreadsheet program using the results provided in the example. Once your spreadsheet program is working, determine the in-place specific weight assuming normal compaction of a waste with a composition given in the following table. Waste A, B, C, D, or E will be selected by your instructor.

	Percentage distribution by weight				
Component	**A**	**B**	**C**	**D**	**E**
Organic					
Food wastes	60	50	30	15	8
Paper	4	8	20	35	34
Cardboard	2	2	4	4	6
Plastics	2	4	6	6	9
Textiles	1	1	2	2	2
Rubber	—	0.5	0.5	0.5	0.5
Leather	—	0.5	0.5	0.5	0.5
Yard wastes	2	8	10	15	19.5
Wood	—	1	1	1	1.0
Misc. organics	—	—	—	—	—
Inorganic					
Glass	1	2	4	8	8
Tin cans	1	1	4	6	6.0
Aluminum	—	—	—	0	0.5
Other metal	—	—	1	1	2.0
Dirt, ash, etc.	27	22	17	6	3.0

11-16. Assuming that the asymptotic value for the compaction data given below is 2200 lb/yd^3, derive empirical equations to describe the degree of compaction that can be achieved as a function of the applied pressure, starting with initial specific weights of 750 and 1100 lb/yd^3.

Pressure, lb/in^2	Specific weight, lb/yd^3	
	1	2
0	750	1100
50	1400	1670
100	1740	1950
150	1950	2090
250	2120	2160

11-17. Given the following values, estimate the volumetric capacity of an excavated cell or area landfill using Fig. A or of a canyon landfill using Fig. B (see page 535 for both figures), expressed in cubic yards, that can be constructed within the property line of the figure (type of landfill to be selected by your instructor) subject to the following constraints and those listed on the figures:

(*a*) Slope of all landfill faces = 3 to 1

(*b*) Lift height = 10 to 12 ft

(*c*) Cover material will be excavated from the site

11-18. How many cubic yards of waste can be placed on a regulation soccer field subject to the following constraints?

(*a*) Slope of all landfill faces = 3 to 1

(*b*) Cover material will be excavated from the site

(*c*) Neglect cover material requirements

How many soccer fields would be required per year to dispose of the wastes from your community, assuming the in-place specific weight of the waste is 1000 lb/yd^3? State your assumptions clearly.

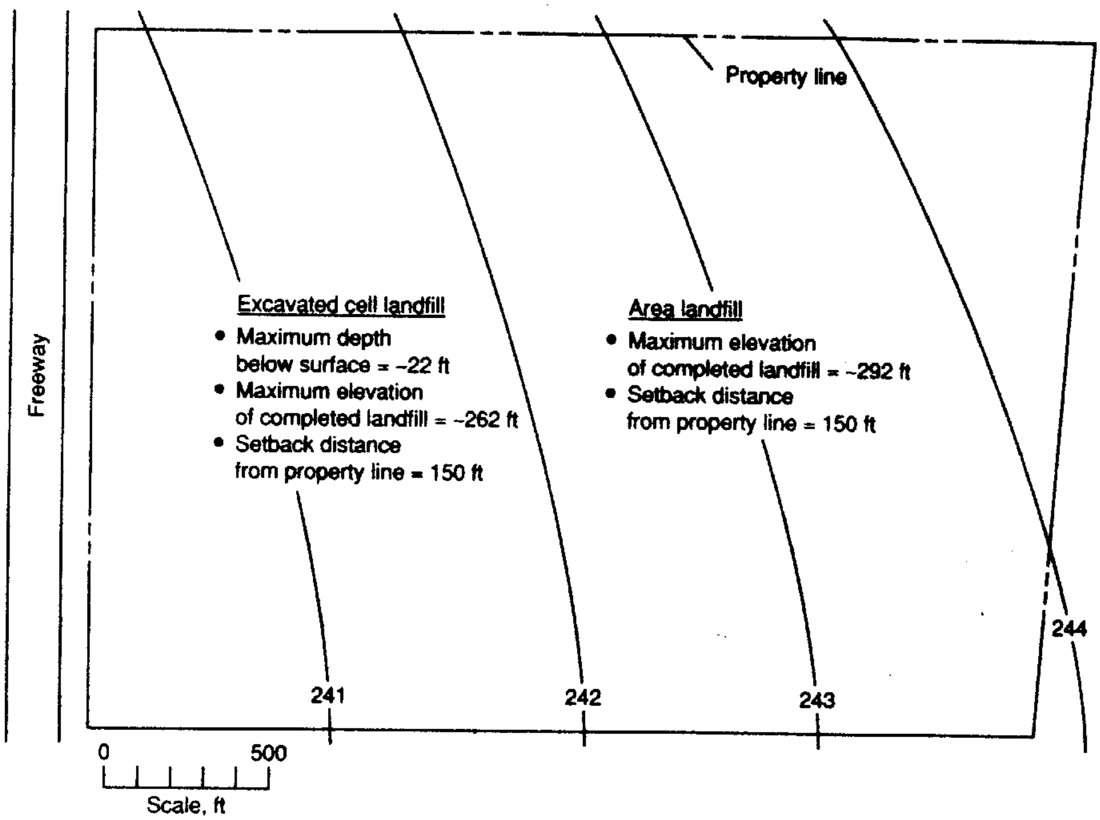
11-19. If the average final specific weight of the waste placed in the landfill of Problem 11-18 is equal to 1200 lb/yd^3, estimate the amount of as-delivered waste (expressed in cubic yards), with an average specific weight of 500 lb/yd^3, that can be placed in the landfill assuming that 30 percent of the original waste (dry basis) will be lost through the production of landfill gas.

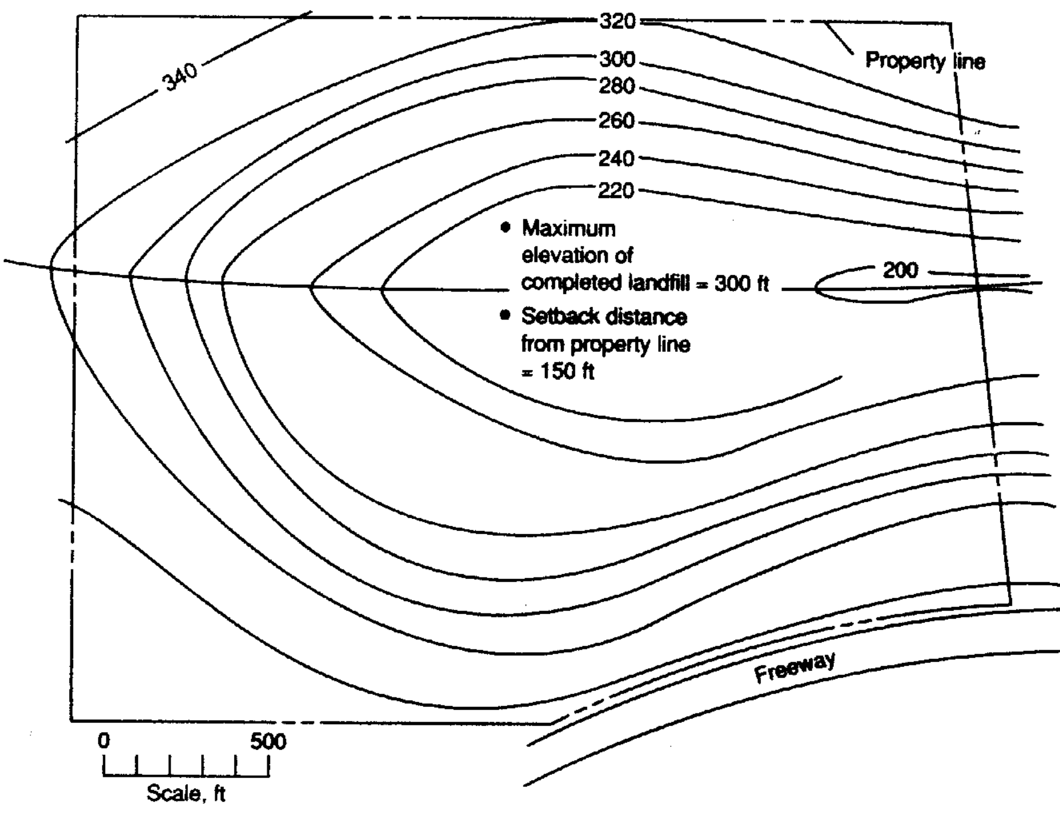
11-20. If the average final specific weight of the waste placed in the landfill of Problem 11-16 is equal to 1400 lb/yd^3, estimate (1) the amount of as-delivered waste (expressed in cubic yards), with an average specific weight of 500 lb/yd^3, that can be placed in the landfill if 30 percent of the original waste (dry basis) will be lost through the production of landfill gas, and (2) the amount of as-delivered waste (expressed in cubic yards), with an average specific weight of 500 lb/yd^3, that can be placed in the landfill if 40 percent of the waste is to be composted and used as intermediate cover. Assume that 15 percent of the weight of the waste placed directly in the landfill will be lost as a result of the production of landfill gas. Also assume that the weight of the composted materials will be reduced by 45 percent as a result of the composting process.

11-21. Prepare a lift diagram and determine the volumetric capacity of the North Valley landfill disposal site in Example 11-7. Assume the final elevation of the landfill is to be 290 ft and that the required setback distance from the property line is 200 ft.

11-22. Using the data from Example 11-7, estimate the useful life of the South Valley landfill if 40 percent of the MSW is diverted to produce compost that is to be used as intermediate cover. Assume the waste that is diverted is primarily residential and commercial MSW and that the amount of the material removed from the diverted waste (both recyclable materials and contaminants) before the waste is shredded is equal to 22 percent by weight. Assume the weight reduction achieved in the composting process is 50 percent.

11-23. Using the results from Problem 11-21, estimate the useful life of the North Valley landfill if 50 percent of the MSW is diverted to produce compost that is to be used as intermediate cover. Assume the waste that is diverted is primarily residential and commercial MSW and that the amount of the material removed from the diverted waste (both recyclable materials and contaminants) before the waste is shredded


Property line
Excavated cell landfill
• Maximum depth below surface = −22 ft
• Maximum elevation of completed landfill = −262 ft
• Setback distance from property line = 150 ft
Area landfill
• Maximum elevation of completed landfill = −292 ft
• Setback distance from property line = 150 ft
Freeway
241
242
243
244
0
500
Scale, ft


320
300
280
260
240
220
200
340
Property line
• Maximum elevation of completed landfill = 300 ft
• Setback distance from property line = 150 ft
Freeway
0
500
Scale, ft

is equal to 35 percent by weight. Assume the weight reduction achieved in the composting process is 50 percent.

11-24. Estimate the total capacity of the South Valley landfill, as given in Example 11-7, if the average final specific weight of the compacted waste is 1500 lb/yd^3 and 35 percent of the initial weight of waste placed in the landfill is lost as a result of gas production.

11-25. In Example 11-7, if the final in-place density, after all the decomposable wastes have been converted to landfill gas and the leachate has been removed, is 1600 lb/yd^3, estimate the total percentage volume reduction. State clearly all the assumptions used in solving this problem.

11-26. Develop a spreadsheet program for the solution for Example 11-8 in Section 11-12. Check your spreadsheet program using the results provided in the example. Once your spreadsheet program is working, determine the amount of gas that would be expected from the waste A, B, C, D, or E (to be selected by your instructor) given in Problem 11-15.

11-27. Assuming that the curves shown in Fig. 11-55 can be approximated by a first-order equation, estimate the surface settlement after 10 yr in a well-compacted sanitary landfill (use maximum compaction curve). What will the maximum surface settlement be after 50 yr? Is the computed result realistic? Discuss.

11-28. Develop a spreadsheet program for the solution for Example 11-11 in Section 11-12. Check your spreadsheet program using the results provided in the example. Once your spreadsheet model is working, determine the amount of leachate that would be expected from waste A, B, C, D, or E (to be selected by your instructor) given in Problem 11-15.

11-29. Develop a spreadsheet program for the solution for Example 11-12 in Section 11-12. Check your spreadsheet using the results provided in the example. Once your spreadsheet program is working, determine the amount of infiltration in a landfill using the precipitation data given in the table on page 537 (A, B, or C to be selected by your instructor). Use the evapotranspiration data given in Example 11-12 with precipitation data A and B. Use the evapotranspiration data given on page 537 with precipitation data C.

11-30. Given the site plan for a parcel of land near the Fallen Oak River (see figure on page 537), prepare a sanitary landfill operation plan for the following conditions:

- Number of collection services = 2800 (average over 20 yr)
- Amount of solid wastes generated per service = 14.0 lb/d
- Compacted specific weight of solid wastes in landfill = 800 lb/yd^3
- Maximum allowable finish grade elevation above surrounding ground = 20 ft
- Slope of all landfill faces = 3 to 1

Include the following in your plan analysis:

(*a*) Required site preparation work, if any

(*b*) Placement operation plan (i.e., the proposed method to be followed in filling the site)

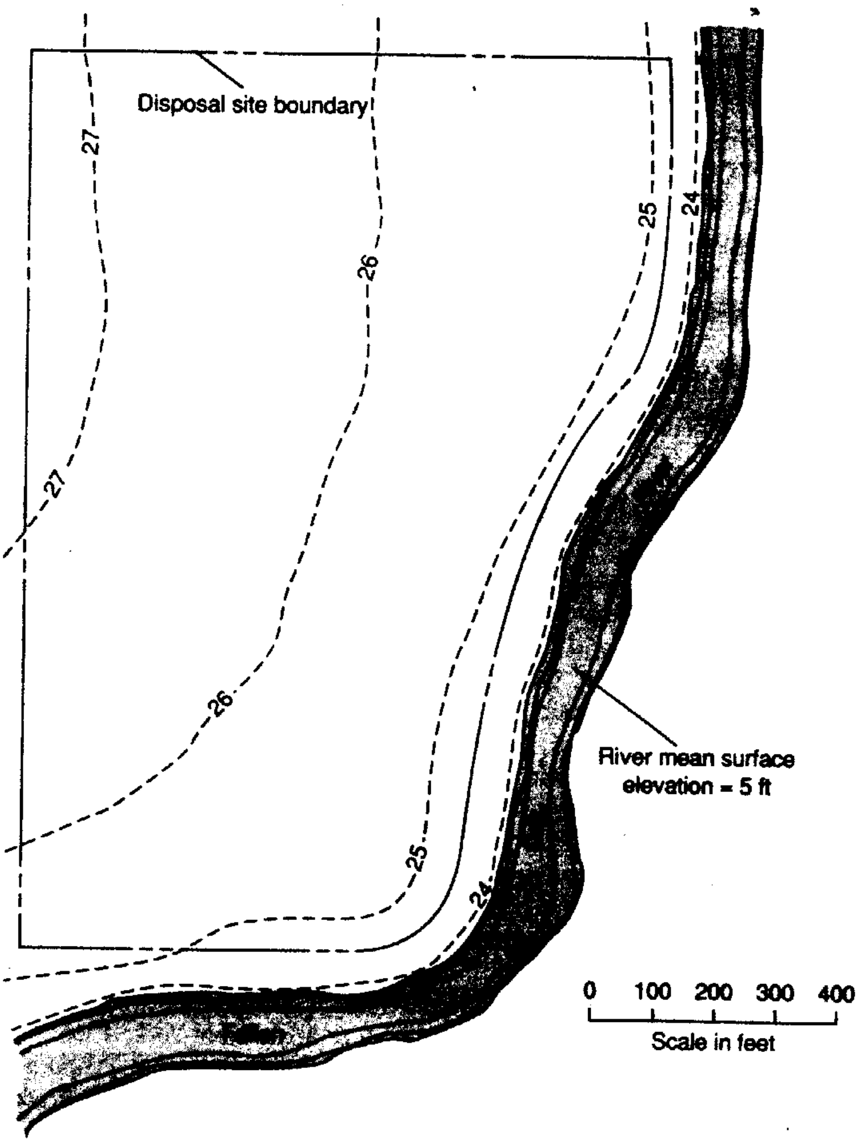
(*c*) Estimated useful life of site

(*d*) Equipment and storage facility requirements

(*e*) Work force and requirements

(*f*) Operational plan

Month	Precipitation, in/mo A	B	C	Evapotranspiration, in/mo
January	7.8	3.0	3.7	3.1
February	7.1	4.5	2.9	3.4
March	6.0	6.5	2.2	4.4
April	3.3	8.0	1.3	5.1
May	1.1	8.6	0.6	6.3
June	1.1	8.6	0.2	7.0
July	1.1	8.4	0.0	7.4
August	1.5	7.8	0.2	6.9
September	4.0	7.2	0.2	5.8
October	5.0	6.5	0.8	4.8
November	5.5	5.6	1.7	3.6
December	7.0	4.8	3.3	3.0
Total annual	50.5	79.5	17.1	60.8



11-31. Given the site plan A or B (to be selected by your instructor) shown in Problem 11-17, prepare a sanitary landfill operation plan for the following conditions:

- Number of collection services = 1500 (average over 20 yr)
- Amount of solid wastes generated per service = 12.0 lb/d
- Compacted specific weight of solid wastes in landfill = 750 lb/yd^3
- Slope of all landfill faces = 3 to 1

Include the following in your plan analysis:

(*a*) Required site preparation work, if any

(*b*) Placement operation plan (i.e., the proposed method to be followed in filling the site)

(*c*) Estimated useful life of site

(*d*) Equipment and storage facility requirements

(*e*) Work force and requirements

(*f*) Operational plan

11-32. On your first day at work for a solid waste consulting organization, your supervisor asks you to prepare a proposal (in outline form) to evaluate the feasibility of ocean dumping of baled solid wastes. The only information available is that the Press-It-Tight Baling Co. claims that it can produce bales with an average density of 78 lb/ft^3 and that if these bales of solid wastes are dumped in the ocean, they will sink to the bottom because of their greater density and remain there, causing no problems. Structure your proposal by asking yourself what kinds of information, data, and criteria would be required to protect the environment and to formulate public policy concerning ocean dumping.

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