9

LAND DISPOSAL

The basis of a good solid waste management system is the municipal solid waste (MSW) landfill. MSW landfills provide for the environmentally sound disposal of waste that cannot be reduced, recycled, composted, combusted, or processed in some other manner. A landfill is needed for disposing of residues from recycling, composting, combustion, or other processing facilities and can be used if the alternative facilities break down. The federal government sets minimum national standards applicable to municipal solid waste landfills and these federal regulations are implemented by the states. A properly designed MSW landfill includes provisions for leachate management and the possible collection of landfill gas and its potential use as an energy source. Innovative planning will also facilitate productive use of the landfill property after closure. Good design and operation will also limit the effort and cost necessary for maintaining the landfill after final site closure.

This chapter provides an information base from which to work when designing new landfills and operating existing facilities. It also provides information necessary for closing an entire landfill, closing completed phases of an operating facility, and for providing long-term care at a closed landfill.

From: Decision Maker's Guide to Solid Waste Management, Volume II, (EPA 530-R-95-023), 1995. Project Co-Directors: Philip R. O'Leary and Patrick W. Walsh, Solid and Hazardous Waste Education Center, University of Wisconsin-Madison/Extension. This document was supported in part by the Office of Solid Waste (5306), Municipal and Industrial Solid Waste Division, U.S. Environmental Protection Agency under grant number CX-817119-01. The material in this document has been subject to Agency technical and policy review and approved for publication as an EPA report. Mention of trade names, products, or services does not convey, and should not be interpreted as conveying, official EPA approval, endorsement, or recommendation.

9 ❖ HIGHLIGHTS

Modern MSW landfills:
- provide for disposal
- produce usable gas
- can provide useful land after closure.

(p. 9-9)

MSW landfills provide for the environmentally sound disposal of waste that cannot be reduced, recycled, composted, incinerated, or processed in some other manner. A landfill is needed for disposing of residues from recycling, composting, incineration, or other processing facilities and can be used if the alternative facilities break down. A properly designed MSW landfill includes provisions for collecting landfill gas and for its potential use as an energy source. Innovative planning may also facilitate productive use of the landfill property after the landfill is closed.

Building a landfill requires large sums of money and long periods of time.

(p. 9-11)

Careful planning by the developers of new or expanding landfills is important. A large amount of money and a long period of time are required to build a landfill. Some of the cost elements and time periods are listed below:

- siting, design, and construction: 3-10 years
- operation, monitoring, and administration: 15-30 years
- closure: 1-2 years
- monitoring and post-closure maintenance: 30 or more years
- remedial actions: unknown.

Landfill development can be organized into four phases. A 16-step process is provided in the text.

(p. 9-11)

Landfill development involves numerous technical details, significant public involvement, and extensive regulations. A 16-step process is outlined on page 9-11. The steps are organized into four phases:

- Phase 1 (steps 1-6) involves developing an information base and making some preliminary site decisions.
- Phase 2 (steps 7-12) includes making a detailed design for the landfill and for managing related issues such as groundwater monitoring and leachate and gas management.
- Phase 3 (steps 13-14) involves establishing financial assurance and beginning actual operation.
- Phase 4 (steps 15-16) includes closure and post-closure care.

Determining landfill volume is the first task in the design process.

(p. 9-12 — 9-14)

Estimating landfill volume is the first task in the design process because volume estimates are necessary for determining the landfill's dimensions. The following factors are crucial:

- Determine accurate tonnage estimates of waste to be received at the site. (Chapter 3 provides waste inventory projection procedures.)
- Estimate anticipated increases or decreases in the diversion of material to waste-to-energy facilities, composting, recycling, reuse efforts, or waste minimization efforts.
- Determine density figures for the waste. See Table 9-1 and Table 9-2.
- Estimate the amount of waste settlement.

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Site selection should include consideration of these characteristics.

(p. 9-15 — 9-16)

Potential sites must be in areas that are suitable for landfill development. The following considerations should be key factors in locating and operating a landfill.

- A landfill must be consistent with the overall land-use planning in the area.
- The site must be accessible from major roadways or thoroughfares.
- The site should have adequate quantity of earth cover material that is easily handled and compacted.
- The site must be chosen with regard for the sensitivities of the community's residents.
- The site must be located in an area where the landfill's operation will not detrimentally affect environmentally sensitive resources.
- The site should be large enough to accommodate the community's wastes for a reasonable time (10 to 30 years).
- The site chosen should facilitate developing a landfill that will satisfy budgetary constraints, including site development, operation for many years, closure, post-closure care, and possible remediation costs.
- Operating plans must include provisions for coordinating with recycling and resource recovery projects.

Federal restrictions affecting landfill siting must be considered.

(p. 9-16)

In addition to determining the suitability of a site, location restrictions must be considered. Resource Conservation and Recovery Act (RCRA) Subtitle D requirements place restrictions on locating landfills in the vicinity of airports, in floodplains, wetlands, fault areas, seismic impact zones, and unstable areas. Other federal agencies have standards that also affect landfill siting.

Determine applicable federal, state and local requirements.

(p. 9-18)

The Subtitle D regulations establish national minimum standards for landfills that receive household waste. The states are to incorporate these national minimum standards into their permitting standards, and the state is responsible for permitting, enforcement, etc. Under the authority of RCRA, the USEPA regulates MSW landfilling with regard to the following:

- ground water quality protection
- landfill gas control
- air pollution control
- basic operating procedures
- safety issues
- flood plains
- seismic and slope stability
- disturbance of endangered species
- surface-water discharges
- site closure and long-term care
- closure and long-term care financial assurance.

9 ❖ HIGHLIGHTS (continued)

State and local requirements will also apply.
(p. 9-18 — 9-19)

State regulations vary widely, but usually landfill engineering plans are submitted to the appropriate state-level regulatory body for review and approval. State standards usually contain more detail than Subtitle D standards and address concerns specific to a particular geographic region. State or local governments may require:

- a solid waste landfill plan approval
- a conditional-use zoning permit
- a highway department permit (for entrances on public roads and increased traffic)
- a construction permit (for landfill site preparation)
- a solid waste facilities permit
- a water discharge/water quality control permit
- an operation permit (for on-going landfill operations)
- a mining permit for excavations
- building permits (to construct buildings on the landfill site)
- a fugitive dust permit
- an air emission permit
- a closure permit.

Options for energy recovery must be considered.
(p. 9-19 — 9-20)

Energy recovery from the landfil in the form of landfill gas should be considered. The three uses for landfill gas include (1) as a boiler fuel, (2) as fuel for engine-generators for producing electricity, and (3) as a natural gas supplement.

The final site use must be considered early in the design phase.
(p. 9-20 — 9-21)

The final use of the landfill site should be considered during the initial site decision phase to provide for its best use. Good planning early will minimize costs and maximize the site's usefulness. Planning is particularly important if future construction or building on or near the landfill site is anticipated. Below are potential uses for closed MSW landfills:

- nature or recreation park
- wilderness area or animal refuge
- golf course
- ski or toboggan hill
- parking lot.

Detailed site characterizations are made for the most desirable sites.
(p. 9-21 — 9-25)

A detailed investigation of potential sites must be made by conducting site characterization studies. Thorough site characterizations are conducted in two phases: (1) involves collecting and reviewing as much information as possible about the site, (2) involves field investigations. Most new data collected will concern the geology and hydrogeology of potential sites and will help determine aquifer depths, geologic formations, drainage patterns, depth to groundwater, groundwater flow direction, groundwater quality, and construction characteristics of on-site soils. In addition, data about existing land use, surrounding land development, available utilities, highway access, political jurisdiction, and land cost are tabulated.

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The landfill design process should follow a logical sequence.
(p. 9-26 — 9-27)

Each landfill design project presents a unique combination of timing, site restrictions, waste characteristics, and regulatory and political factors. Some points must be covered and it is helpful to have an initial outline of a logical sequence of activities to follow. Such an outline is summarized in Table 9-3.

Both engineering design standards and performance standards must be met.
(p. 9-26 — 9-28)

Two types of federal, state, and local government standards must be met: (1) Engineering design standards are building codes describing how the facility must be built. Regulating bodies monitor compliance with these standards by reviewing the building plans and inspecting the landfill during construction. (2) Performance standards apply for the facility's life and specify that a certain level of environmental control be achieved and maintained. If the landfill as initially designed does not achieve compliance, operators must install additional protective systems.

Public involvement is crucial to the design process.
(p. 9-28)

Many of the permits needed before landfill design and operating plans are approved require a public hearing for soliciting input from interested parties. The landfill designers should also solicit input from individuals and groups who will be directly affected by the future landfill. Public participation should begin far in advance of public hearings.

State approvals are also required.
(p. 9-29)

Most states employ a multistage approval process similar to the following:

- Required landfill siting regulatory review procedures are initiated.
- A feasibility (engineering) report is submitted to the state for approval.
- Detailed engineering plans are submitted to the state.
- A final application for state landfill operating permits is submitted.

Landfill layout and design is strongly affected by site geology.
(p. 9-29 — 9-31)

Landfill layout is strongly influenced by the site's geology. The potential for gas and leachate migration and the suitability of the soil for landfill base and cover material are crucial. Site layout begins with geotechnical information, including data on the geology, hydrology, and soils at and around the site. These data are usually collected during the site-selection process, then supplemented during site investigations.

Operating plans must include working face configurations and phase dimensions.
(p. 9-31 — 9-32)

The operating plan should describe, in detail, the configuration of the working face of the landfill. Figure 9-7 illustrates a typical cross section of a portion of a municipal landfill, including the "working face," and helps to define terms. The plan should also illustrate the chronological order in which the features are to be developed. In a well-planned phased development, the landfill's end use can begin on completed sections while other areas in the landfill are still being used for disposal.

Leachate variability and concentrations must be considered.
(p. 9-33 — 9-34)

Leachate is a liquid that has passed through or emerged from landfill waste. It contains soluble, suspended, or miscible materials removed from the waste. Table 9-4 shows changes in leachate composition as a landfill proceeds through various decomposition phases. It is imperative when designing leachate collection and treatment facilities to consider the concentrations and variability of leachate with regard to its many constituents. Leachate generation rates depend on the amount of liquid originally in the waste (primary leachate) and the quantity of precipitation that enters the landfill through the cover or falls directly on the waste (secondary leachate).

9 ❖ HIGHLIGHTS (continued)

Predicting leachate amounts is crucial. (p. 9-34 — 9-35)	Several factors influence leachate generation at landfills: climate, topography, landfill cover, vegetation, type of wastes. The amount of leachate generated affects (1) operating costs if leachate collection and treatment are provided, (2) the potential for liner leakage and the potential for groundwater contamination, and (3) the cost of post-closure care. Predicting leachate formation requires water-balance calculations, which can be derived from the water-balance equation provided in Figure 9-10. The equation estimates the amount of precipitation likely to percolate through the landfill cover.
Federal regulatory controls for leachate management must be met. (p. 9-36 — 9-38)	RCRA Subtitle D regulations require that new MSW landfills be designed to control contaminant migration. The groundwater protection performance standard for landfills specifies that contaminant concentrations in groundwater cannot exceed the amounts shown in Table 9-7. Approved states may establish state-specific protocols for meeting these standards.
Composite liners are required at new landfills and expansions of existing landfills, unless an approved state issues alternative standards. (p. 9-38 — 9-41)	A liner is a hydraulic barrier that prevents or greatly restricts migration of liquids, thus allowing leachate to be removed from the unit by a leachate control system. The RCRA Subtitle D MSW landfill regulations require that new MSW landfills and expansions of existing MSW landfill facilities be constructed with a composite liner and a leachate collection system or meet a groundwater protection performance standard. The required liner consists of a flexible membrane placed over a clay layer, forming one composite liner. Figure 9-11 illustrates liner configurations.
Groundwater monitoring systems are required for new and existing units and for expansions. (p. 9-41 — 9-43)	In most cases, groundwater monitoring systems are required for new, existing, and lateral expansions of existing landfills to determine groundwater quality and detect releases of contaminants. New landfills must have such systems installed before wastes are placed in the landfill. The schedule for installing a groundwater monitoring system at existing facilities depends on the location of the landfill with respect to a drinking water source or other state priorities.
Groundwater monitoring begins with detection monitoring. (p. 9-41 — 9-44)	The RCRA Subtitle D groundwater monitoring and corrective action requirements have three steps: detection monitoring, assessment monitoring, and corrective action. Figure 9-14 shows a leaking landfill and one possible type of corrective action. Facilities move through the three steps if a "statistically significant" increase in contaminants is found.
Landfill gas migration must be controlled. (p. 9-43 — 9-45)	Uncontrolled landfill gas migration can be a problem at MSW landfills and must be controlled to avoid explosions in structures in the vicinity of the landfill. Allowable landfill gas concentrations in structures and at the property line are established. Table 9-9 provides typical landfill gas composition.
Controlling gas movement is essential. (p. 9-45 — 9-48)	Controlling gas movement begins with studying the local soils, geology, and nearby area. Gas probes (see Figure 9-16) are used to detect the location and movement of methane gas in and around a landfill. Federal rules require quarterly monitoring.

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Gas can sometimes be recovered for energy.
(p. 9-48 — 9-49)

At some landfills, it is cost-effective to install gas recovery wells or trenches throughout the landfill and recover the gas for its energy value. Before constructing an energy recovery system, it is important to conduct tests to predict the quantity and quality of gas available.

Final covers for closed landfills must meet federal or corresponding state requirements.
(p. 9-49 — 9-51)

To close an MSW Landfill, RCRA Subtitle D requires that the final cover system be composed of an infiltration layer a minimum of 18 inches thick, overlain by an erosion layer a minimum of 6 inches thick (see Figure 9-20, drawing A). Landfills with liners must have covers that are at least as impermeable as the liner. Design criteria for a final cover system should be selected to do the following:

- minimize infiltration of precipitation into the waste
- promote good surface drainage
- resist erosion
- prevent slope failure
- restrict landfill gas migration or enhance recovery
- separate waste from vectors (animals and insects)
- improve aesthetics
- minimize long-term maintenance
- otherwise protect human health and the environment.

Other design elements must be considered.
(p. 9-51 — 9-52)

In addition to the major issues of gas and leachate control and final cover, many other elements of landfill design require attention. These include roads, storm water drainage, utilities for landfill operation, and scales for weighing incoming loads of waste.

Obtaining regulatory approval is a long-term process.
(p. 9-52 — 9-53)

Achieving regulatory approval is a long-term effort beginning early in the development process. Chapter 1, on public education, and Chapter 2, on siting, should be consulted for facilitating public participation. Projects lacking public review or input until the design is completed may face substantial delays. Obtaining approval from regulatory agencies is the final task in developing the plan. Close liaison with regulatory people throughout the design process should be maintained to ensure compliance with regulatory standards.

A program for detecting and excluding hazardous and PCB wastes is required.
(p. 9-53)

The owner or operator is required to implement a program to detect and exclude regulated hazardous wastes and PCBs from disposal in the landfill. It should include:

- performing random inspections of incoming loads or other prevention methods
- maintaining inspection records
- training facility personnel
- notifying appropriate authorities if hazardous or PCB wastes are detected.

9 HIGHLIGHTS (continued)

Select landfill equipment carefully. (p. 9-56 — 9-58)	Equipment at sanitary landfills falls into three functional categories: waste movement and compaction, earth cover transport and compaction, and support functions. The amount of waste is the major variable influencing the selection of an appropriate-size machine. Table 9-12 shows equipment needs.
Safety concerns are crucial. (p. 9-60 — 9-61)	Safety concerns are crucial. To maintain an efficient landfill operation, employees must be carefully selected, trained, and supervised. Safety guidelines specific to the operation of landfill equipment are shown in Table 9-13.
Financial assurance is required. (p. 9-61 — 9-62)	Federal standards require that landfill owners and operators, including municipalities that operate landfills, have financial assurances in place to cover the costs of closure and post-closure. Financial assurance is also required when corrective action is necessary to clean up releases of hazardous constituents to groundwater.
Landfill closure must follow certain procedures. (p. 9-62 — 9-64)	The primary objectives of landfill closure are to establish low-maintenance cover systems and to design a final cover that minimizes the infiltration of precipitation into the waste. Table 9-14 shows the procedures to follow when either the entire landfill or a phase of it has been filled to capacity.

9

LAND DISPOSAL

LANDFILLING—AN OVERVIEW

MSW landfills provide for the environmentally sound disposal of waste that cannot be otherwise managed.

The basis of a good solid waste management system is the municipal solid waste (MSW) landfill. MSW landfills provide for the environmentally sound disposal of waste that cannot be reduced, recycled, composted, combusted, or processed in some other manner. A landfill is needed for disposing of residues from recycling, composting, combustion, or other processing facilities and can be used if the alternative facilities break down. A properly designed MSW landfill includes provisions for leachate management and the possible collection of landfill gas and its potential use as an energy source. Innovative planning may also facilitate productive use of the landfill property after the landfill is closed.

Modern MSW landfills differ greatly from simple land disposal. Today's MSW landfills which have evolved in design and operating procedures over the last 20 years, are very different from landfills of even 5 or 10 years ago. Design improvements have reduced environmental impacts and improved the efficient use of resources.

A schematic of a typical MSW landfill is shown in Figure 9-1. Note that in the completed landfill, the waste is enclosed by cover material at the top and by a liner system at the bottom. Appropriate systems are in place to control contaminated water and gas emissions and reduce adverse impacts on the environment. Key terms used in MSW landfill design include the following:

- **Waste management boundary:** The waste management unit boundary is the boundary around the area occupied by the waste in a landfill. It is measured in square meters or in acres.
- **Liner:** The liner is a system of clay layers and / or geosynthetic membranes used to collect leachate and reduce or prevent contaminant flow to groundwater.
- **Cover:** A typical MSW landfill has two forms of cover consisting of soil and geosynthetic materials: (1) a daily cover placed over the waste at the close of each day's operations and (2) a final cover, or cap, which is the material placed over the completed landfill to control infiltration of water, gas emission to the atmosphere, and erosion. It also protects the waste from long-term contact with the environment.
- **Leachate:** Leachate is a liquid that has passed through or emerged from solid waste and contains soluble, suspended, or miscible materials removed from such waste. Leachate typically flows downward in the landfill but may also flow laterally and escape through the side of the landfill.
- **Leachate collection system:** Pipes are placed at the low areas of the liner to collect leachate for storage and eventual treatment and discharge. Leachate flow over the liner to the pipes is facilitated by placing a drainage blanket of soil or plastic netting over the liner. An alternative

to collection pipes is a special configuration of geosynthetic materials that will hydraulically transmit leachate to collection points for removal.

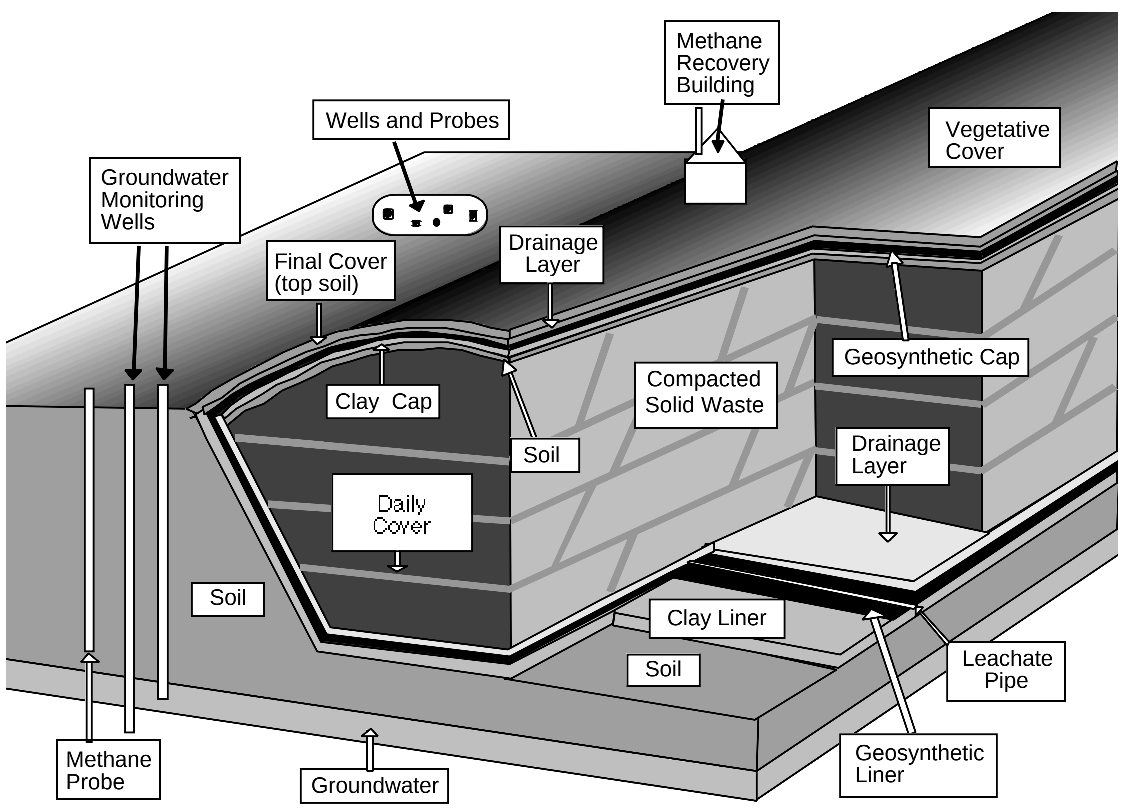
- **Landfill gas:** Generated by the anaerobic decomposition of the organic wastes, landfill gas is a mixture of methane and carbon dioxide, plus trace gas constituents.
- **Gas control and recovery system:** A series of vertical wells or horizontal trenches containing permeable materials and perforated piping is placed in the landfill to collect gas for treatment or productive use as an energy source.
- **Gas monitoring probe system:** Probes placed in the soil surrounding the landfill above the groundwater table to detect any gas migrating from the landfill.
- **Groundwater monitoring well system:** Wells placed at an appropriate location and depth for taking water samples that are representative of groundwater quality.

Owners and operators must carefully plan new facilities and optimize the performance of existing facilities.

The goal of MSW landfilling is to place residuals in the land according to a coordinated plan designed to minimize environmental impacts, maximize benefits, and keep the resource and financial cost as low as possible. To achieve these ends, the solid waste manager and the landfill owner and operator must carefully plan the development of new facilities and optimize the performance of existing facilities.

Figure 9-1

Schematic of a Typical Municipal Solid Waste Landfill



Source: P. O'Leary and P. Walsh, University of Wisconsin–Madison Solid and Hazardous Waste Education Center, reprinted from *Waste Age* 1991-1992

NEW LANDFILLS

Technical details, public involvement, and regulations make landfill development challenging.

The steps outlined here provide a helpful structure to guide the process.

Careful planning by the developers of new or expanding landfills is important. A large amount of money and a long period of time are required to build a landfill. Some of the cost elements and time periods are listed below:

- siting, design, and construction: 3-10 years
- operation, monitoring, and administration: 15-30 years
- closure: 1-2 years
- monitoring and post-closure maintenance: 30 or more years
- remedial actions: unknown.

Numerous technical details, significant public involvement, and extensive regulations all present challenges to the new landfill developer. The steps outlined below should be considered:

1. Estimating landfill volume requirements.
2. Investigating and selecting potential sites.
3. Determining applicable federal, state, and local requirements.
4. Assessing landfill options for energy and materials recovery.
5. Considering the site's final use.
6. Determining the suitability of sites.
7. Designing the fill area to satisfy plan / permit requirements.
8. Establishing a leachate management plan.
9. Instituting groundwater monitoring.
10. Setting up a gas management plan.
11. Preparing landfill final cover specifications.
12. Obtaining plan and permit approvals.

14. Establishing financial assurance for closure and post-closure care.

13. Operating the landfill.

15. Closing the landfill.
16. Providing post-closure care.

These steps may be organized into four phases. The first phase (steps 1-6) involves developing an information base and making some preliminary site decisions. The second phase (steps 7-12) includes making a detailed design for the landfill and for managing related issues such as groundwater monitoring and leachate and gas management. In the third phase (steps 13-14) financial assurance is established and actual operation begins. The fourth phase (steps 15-16) includes closure and post-closure care.

Some of the steps, particularly the design activities in phase two, may take place simultaneously, but it is useful to separate them for discussion purposes. Likewise, many are interrelated; for example, decisions about landfill type will affect plans for leachate and gas control. This chapter discusses each of these 16 steps in detail.

EXISTING OR CLOSED LANDFILLS

Owners and operators of existing landfills must also execute a number of these steps in order to comply with recently established regulations. Leachate and gas management, groundwater monitoring, financial assurance, operating procedures, and closure activities are among the activities described in this chapter which must be carried out at existing landfills. The steps summarized below are equally crucial to existing and closed landfills as they are to new landfills.

The 9 steps summarized here are equally crucial for both existing and closed landfills as well as new units.

1. Establishing a leachate management plan.
2. Instituting groundwater monitoring.
3. Setting up a gas management plan.
4. Preparing landfill final cover specifications.
5. Obtaining closure plan approval.
6. Establishing financial assurance for closure and post-closure care.
7. Operating the landfill.
8. Closing the landfill.
9. Providing post-closure care.

DEVELOPING AN INFORMATION BASE AND MAKING INITIAL SITE DECISIONS

The specific approach followed in designing an MSW landfill will vary from project to project, but certain preliminary information must be gathered and initial site decisions must be made for any project. Landfill volume is the first consideration to be made in the design process. Initial investigations should focus on locating potential sites, determining the applicability of federal, state and local requirements, and identifying the environmental impacts of the landfill. The end use of the site should also be considered during the initial site decision phase. The landfill could be closed with restricted access, or it may be feasible to design systems for productive site end use and energy and materials recovery. These initial design considerations must be addressed before a more detailed design can be developed. This section discusses each of these beginning steps in detail.

Estimate Landfill Volume Requirements

Landfill volume estimates are necessary to determine the dimensions for the landfill. An adequate prediction of landfill volume requirements can be made by projecting records of past landfill volume consumption, refuse weight, or gate volume. Such projections must be made in light of population growth estimates and anticipated changes in commercial or industrial wastes. Depending on the accuracy of previous records, especially with regard to the volume filled per year over the period of record, such a projection can be reasonably reliable and can be used to estimate the landfill volume requirements for a design period of perhaps seven to ten years of site operation.

Accurate tonnage estimates of waste to be received at the site are necessary.

Accurate tonnage estimates of waste to be received at the site will be necessary. Such estimates can range in complexity from simple projections using national or regional data to detailed weighing programs and sophisticated population projections. Chapter 3 provides waste inventory projection procedures.

Once general projections have been made for the amount of waste to be landfilled, the next step is to estimate any anticipated increase or decrease in the diversion of material to waste-to-energy facilities, composting, recycling, reuse efforts, or waste minimization efforts. Other chapters in this guidebook deal with the amount of waste that can potentially be diverted from the landfill by these different options and the amount of materials the landfill can expect to get back from them as residuals requiring disposal. Reusable items such as clothes, doors, windows, appliances, and miscellaneous household items can be separated at the gate and sold. Waste-to-energy plants typically reduce incoming volume by 90 percent and weight by 75-80 percent.

To estimate landfill capacity, one needs density figures for the waste. Density figures at the level of compaction obtained in the typical collection vehicle have been established and are listed in Table 9-1. If the composition of the waste is known, it can be used to estimate the density in the truck, and compaction figures can be used to estimate the density to be expected in the landfill.

The density of material in an MSW landfill depends on refuse composition, moisture content, and the degree of compaction.

The density of material in an MSW landfill is usually 1,000 pounds/cubic yard, but the range depends on refuse composition, moisture content, and the degree of compaction. Table 9-2 lists estimates of the density of several categories of waste as compacted in a landfill. The compacted range is from 185 to 2,800 pounds of refuse per cubic yard of landfill volume. Deeper landfills achieve higher density because the weight of the refuse compacts lower portions of the landfill. When waste is dumped from trucks at the landfill face, it loses its compaction. The load is then broken up as it is spread by the bulldozer and then recompacted by the bulldozer/compactor. Only small-volume landfills with inadequate equipment obtain the lower compaction figure cited.

The amount of soil necessary for daily and final cover must be added to the refuse volume data to obtain the final landfill space projection. The refuse-to-soil ratio usually ranges from 2:1 to 5:1 on a volumetric basis. Therefore, every two to five parts by volume of refuse will require one part by volume of cover soil for all of the various forms of cover in the typical landfill space.

In general, a ratio of 3:1 (refuse to soil) can be used to plan for the operation of most sites. The ratio can be modified upward or downward, depending on any special cover requirements, phasing requirements, or final cover requirements. These figures do not include soil requirements for special berms or unusual amounts of final cover.

A final factor to consider in developing volume estimates is the amount of settlement that will take place. Settlement will occur as the refuse decom-

Table 9-1

Typical Densities of Solid Wastes

Waste	Density Range (lb/cu yd)		
	From	To	Typical
Residential (uncompacted)			
Food Wastes (mixed)	220	810	490
Paper	70	220	150
Cardboard	70	135	85
Plastics	70	220	110
Glass	270	810	330
Tin cans	85	270	150
Aluminum	110	405	270
Leaves (loose and dry)	50	250	100
Yard trimmings	100	380	170
Green grass (loose and moist)	350	500	400
Green grass (wet and compacted)	1000	1400	1000
Municipal Waste			
In compactor truck	300	760	500
In landfill			
normally compacted	610	840	760
well compacted	995	1250	1010
Commercial Waste			
Food wastes	800	1600	910
Wooden crates	185	270	185
Construction and Demolition Waste			
Mixed demolition (noncombustible)	1685	2695	2395
Mixed demolition (combustible)	550	675	605
Mixed construction (combustible)	305	605	440
Broken concrete	2020	3035	2595

Source: Tchobanoglous et al. *Integrated Solid Waste Management: Engineering Principles and Management Issues,* 1993

Table 9-2
Summary of Density Factors for Landfilled Materials

Material	Density (lbs/cu yd)
Durable Goods*	475
Nondurable Goods	
Nondurable paper	800
Nondurable plastic	315
Disposable diapers	
Diaper materials	795
Urine and feces	1,350
Rubber	345
Textiles	435
Misc. nondurables (mostly plastics)	390
Packaging	
Glass containers	
Beer & soft drink bottles	2,800
Other containers	2,800
Steel containers	
Beer & soft drink cans	560
Food cans	560
Other packaging	560
Aluminum	
Beer & soft drink cans	250
Other packaging	550
Paper and Paperboard	
Corrugated	750
Other paperboard	820
Paper packaging	740
Plastics	
Film	670
Rigid containers	355
Other packaging	185
Wood packaging	800
Other miscellaneous packaging	1,015
Food Wastes	2,000
Yard Trimmings	1,500

* No measurements were taken for durable goods or plastic coatings.

Source: USEPA, *Characterization of Municipal Solid Waste in the United States: 1994 Update*

The surface will settle to 80 or 85 percent of the original (undecomposed) height within five years.

poses or becomes compacted by the weight of overlying materials. For average-to-good compaction (1200 pounds per cubic yard), the surface will settle to 80 or 85 percent of the original (undecomposed) height within five years. This probably will be 90 percent of the ultimate settlement. Some landfills have soil temporarily placed on the surface, the weight of which will promote settlement to final grades.

Conduct Initial Investigation and Select Potential Sites

Landfill site selection is usually an extensive process which will likely involve public input. More information regarding facility siting is provided in Chapter 3.

Starting the Project

Clearly identifying project objectives and having well-defined goals and objectives are important.

The community or private company developing a landfill should clearly identify project objectives; having well-defined goals and objectives makes it easier to communicate with citizens (those who support and those who oppose the project) and with political officials. Each party involved will have specific needs to address, but common factors will include the following:

- geographic area and population to be served by the site
- type of waste and quantity to be disposed of
- tipping fee or cost of operation
- unacceptable wastes
- maximum hauling distance
- minimum, and possibly maximum, site operating life span
- profile of potential site users.

Developers must determine if the new facility can compete economically with existing facilities.

If the addition of a new facility means that more than one landfill or waste recycling / treatment operation will be serving the area, facility developers must determine if the new facility can compete economically with existing units. For example, there are recent indications that economies-of-scale favor large landfill sites. When planning to develop such a site, however, one must compare the cost of hauling longer distances to the large landfill with the economics of existing waste management options.

Fulfilling Land Use Goals

Potential sites must be in areas that are suitable for landfill development. Operation and end use of a landfill site should also conform to long-term land use goals. Most areas have projected land-use plans of 10 to 20 years.

Special consideration must be given when evaluating potential sites in areas with endangered plant or animal habitats, virgin timber land, wildlife corridors, unique physical features, or significant historical or archaeological sites. Developers should anticipate possible competing land use interests associated with such areas and realize that certain aspects of the siting and development process may be more complicated. A careful evaluation of possible short- and long-term environmental, political, and social impacts should be made and the anticipated benefits of developing the site must be evaluated in light of the potential impacts and the availability of alternative sites.

Potential sites should be in areas where a landfill will conform with long-term land use goals.

A site selected for a landfill will have some characteristics that are less than ideal. Engineering techniques may overcome these limitations and enable the site to meet design goals, but it is important to start with the best site possible. In selecting a site, some factors to consider include health, safety, accessibility, drainage, soils, proximity to groundwater and surface water, zoning, hauling distance, and adjacent land use. The following considerations should be key factors in locating and operating a landfill.

- A landfill must be consistent with the overall land-use planning in the area.
- The site must be accessible from major roadways or thoroughfares.
- The site should have an adequate quantity of earth cover material that is easily handled and compacted.
- The site must be chosen with regard for the sensitivities of the community's residents.
- The site must be located in an area where the landfill's operation will not detrimentally affect environmentally sensitive resources.
- The site should be large enough to accommodate the community's wastes for a reasonable time (10 to 30 years).

- The site chosen should facilitate developing a landfill that will satisfy budgetary constraints, including site development, operation for many years, closure, post-closure care, and possible remediation costs.
- Operating plans must include provisions for coordinating with recycling and resource recovery projects.

Federal, state, and local regulations for landfill siting must be followed.

In addition to determining the suitability of a site, location restrictions must be considered. Resource Conservation and Recovery Act (RCRA) Subtitle D requirements place restrictions on locating landfills in the vicinity of airports, in flood plains, wetlands, fault areas, seismic impact zones, and unstable areas. RCRA Subtitle D location restrictions include the following:

- **Airports:** If a landfill is located within a specified distance of an airport, the owner or operator must demonstrate that the landfill will not present a bird hazard to aircraft.
- **Flood plains:** For landfills located on a 100-year flood plain, the owner or operator must demonstrate that the landfill will not restrict the flow of a 100-year flood, reduce the storage capacity of the flood plain, or result in the washout of solid waste.
- **Wetlands:** New landfills and lateral expansions cannot be located in wetlands except where an owner demonstrates to an approved state/tribe that there is no practical alternative. The landfill must not cause or contribute to violations of any state water quality criteria, contribute to significant degradation of wetlands, cause net loss of wetlands, or violate any other federal requirements.
- **Fault areas:** New landfills and lateral expansions must not be located within 200 feet of a fault that has experienced displacement during the Holocene Epoch (approximately the last 10,000 years) unless it can be shown to an approved state/tribe that damage to the unit can be prevented at shorter distances.
- **Seismic zones:** New landfills and lateral expansions are restricted in areas susceptible to ground motion resulting from earthquakes. If the site is in an earthquake zone, investigations that demonstrate to an approved state/tribe the suitability of locating a landfill at the designated location must be conducted.
- **Unstable areas:** Unless it can be demonstrated otherwise, landfills must not be located in areas susceptible to natural or human-induced events or forces capable of impairing the integrity of landfill components. Examples of unstable areas are those with poor foundation conditions, areas susceptible to mass movements (landslides, rock falls, etc.), and areas with karst terrains (sinkholes).

In addition to USEPA, other federal agencies have established standards that affect the identification of potential sites.

Other federal agencies have established standards that will also affect the identification of potential sites. For example, Federal Aviation Administration Order 5200.5 establishes a zone within which landfill design and operational features must be used to prevent bird hazards to aircraft. Owners or operators proposing to locate a new landfill or a lateral expansion within a five-mile radius of a public-use airport must notify the affected airport and the FAA.

Using Soil Maps in Selecting Potential Sites

Soil maps prepared by the U.S. Department of Agriculture's Soil Conservation Service (SCS) may provide useful preliminary information about potential landfill sites. These maps identify soil profile characteristics to a depth of five feet.

The land's contour and subsurface formations are important in developing a landfill. Surface features will affect the landfill's layout and drainage characteristics. In addition to soil type, other important features such as roads, railroad tracks, buildings, and surface waters are shown.

Soil is used in landfill development for three purposes:

- **As cover:** Soil is used daily to cover the solid waste. It is also used when an area of the landfill is completed. The permeability of the final cover will greatly affect the quantity of leachate generated.
- **For migration control:** Soil is used to control the movement of leachate and methane gas away from the landfill. An impermeable soil will retard such movement; a permeable soil will provide less protection and may require installing additional controls in the landfill.
- **As foundational support:** The soil below and adjacent to the landfill must be suitable for construction. It must provide a firm foundation for liners, roads, and other construction activities.

The Soil Conservation Service (SCS) can provide data on the soil types of many, but not all, areas of the U.S.

The Soil Conservation Service (SCS) can provide data on the soil types of many, but not all, areas of the United States. Land with a potential for solid waste disposal can be located by determining the SCS limitations of the particular soil for landfilling. The SCS has defined each soil type as having "slight," "moderate," or "severe," limitations for use as a landfill site.

The fact that soil maps only describe the soil to a depth of five feet is a major limitation in using them for selecting potential sites. As a result, a site first judged suitable during work with the soil maps may be deemed unsuitable once data are collected at depths greater than five feet.

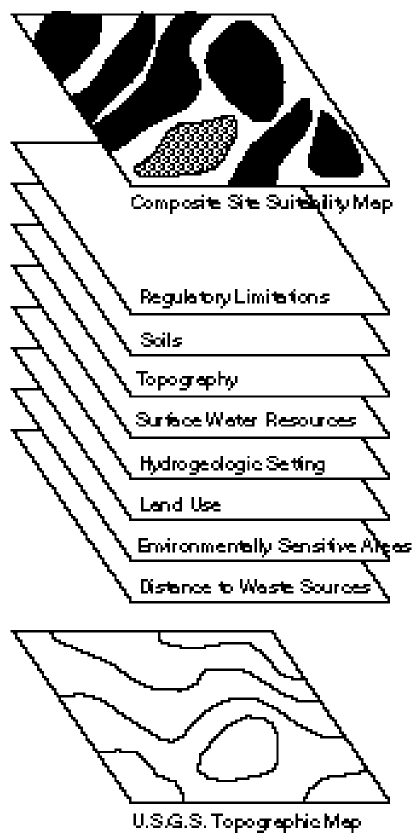
Tabulating Site Identification Data

When identifying potential sites, the best approach is to follow criteria defined by

- *the developer*
- *public officials*
- *interested citizens, and*
- *regulatory officials*

Figure 9-2

Examples of Map Overlays



Source: W. Lane and R. McDonald, "Land Suitability Analysis for Sanitary Landfill Siting," 1981

Several procedures may be used to collect and tabulate the necessary data. The most informal approach is to identify a list of potential sites based on personal knowledge of the area being studied. This approach limits the area being considered but presents a major handicap because other suitable areas may be overlooked.

One way of incorporating the various siting criteria is to prepare a series of map overlays. Each overlay identifies land areas with moderate or severe limitations in regard to a particular criterion. A USGS (U.S. Geological Service) quadrangle map is often used as the base map. The overlays, shown in Figure 9-2, are prepared on transparent plastic sheets placed over the base map.

The best approach for establishing the limitations ratings for each criterion is through a technical assessment conducted in combination with input from public officials, interested citizens, and regulatory officials. A unique criteria rating should be prepared for each proposed landfill development project to ensure that local concerns are addressed.

Once a map is prepared for each criteria the maps are assembled as overlays and the most suitable areas identified. Both graphical or computer techniques are available for assembling the data.

When using soil and site identification data, project developers should keep in mind that these sources do not provide absolute data, but only estimates or approximations of predominant soil types, depths, and other features. The estimates or approximations should be confirmed later by conducting soil borings if the potential site is otherwise found to be a good candidate for a landfill.

A well-planned siting program must include opportunities for public participation.

A well-planned siting program must include opportunities for public participation at appropriate times. Citizens may participate through public hearings, advisory committees, surveys, tours of established landfills, and public meetings in which small-group discussions between citizens and project planners are encouraged. The public may also be involved in publishing newsletters or issuing press releases to keep other residents informed about the program's progress. Chapter 1 provides additional information on public participation.

Determine Applicable Federal, State, and Local Requirements

The Resource Conservation and Recovery Act (RCRA)

State programs for landfill regulation are required by RCRA Subtitle D to incorporate the federal regulations.

The RCRA Subtitle D approach uses a combination of design and performance standards for regulating MSW landfills. USEPA's Subtitle D rule, published October 9, 1991, also establishes facility design and operating standards, groundwater monitoring, corrective action measures, and conditions (including financial requirements) for closing municipal landfills and providing post-closure care for them. A phased implementation of the regulations began on October 9, 1993. A current version of 40 CFR Parts 257 and 258 should be consulted to determine the applicable deadline dates for each type and size of municpal landfill. State programs for landfill regulation are required by Subtitle D to incorporate the federal regulations into the state codes. Recommended practices described in this chapter are consistent with Subtitle D rule requirements. State regulations under Subtitle D may be flexible to accommodate local conditions.

RCRA creates a framework for federal, state, and local government cooperation in controlling the disposal of municipal solid waste. While the federal landfill rule establishes national minimum standards for protecting human health and the environment, implementation of solid waste programs remains largely the responsibility of local, state, or tribal governments. Under the authority of RCRA, the USEPA regulates the following:

- **Location Restrictions:** airport safety, flood plains, wetlands, fault areas, seismic impact zones, unstable areas
- **Design Criteria:** liners and groundwater protection
- **Groundwater Monitoring and Corrective Action:** groundwater monitoring systems, groundwater sampling and analysis, detection monitoring, assessment monitoring, assessment of corrective measures, selection of remedy, implementation of corrective action program
- **Closure and Post-Closure Care:** closure criteria, post-closure care requirements
- **Financial Assurance Criteria:** financial assurance for closure, financial assurance for post-closure care, financial assurance for corrective action
- **Operating Criteria:** procedures for excluding hazardous waste, cover materials, disease vector controls, explosive gasses control, air criteria, access requirements, run-on / run-off control, surface water requirements, liquids restrictions, record keeping.

State and Local Requirements

State regulations vary widely, but usually landfill engineering plans are submitted to the appropriate state-level regulatory body for review and approval. State standards are ordinarily more extensive than RCRA standards and address concerns specific to a particular geographic region.

Five-to-seven-year planning and permitting periods are becoming more common.

Procuring the various permits required to open and operate a landfill may take several months to several years, especially if there is public controversy regarding the site. Five-to-seven-year planning and permitting periods are becoming more common. State or local governments may require:

- a solid waste landfill plan approval
- a conditional-use zoning permit
- a highway department permit (for entrances on public roads and increased traffic volume)
- a construction permit (for landfill site preparation)
- a solid waste facilities permit
- a water discharge / water quality control permit
- an operation permit (for on-going landfill operations)
- a mining permit for excavations
- building permits (to construct buildings on the landfill site)
- a fugitive dust permit
- an air emission permit
- a closure permit.

Additional Concerns

Waste disposal facility owners are being held responsible for environmental damage and cleanup, even after closure.

The regulatory standards should be viewed as minimum requirements that specify a baseline standard of design and performance. Waste disposal facility owners are being held responsible for environmental damage and cleanup many years after the disposal site began operation, and even following closure, under CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act), better known as Superfund. In addition, claiming compliance with regulatory standards has not been an effective defense against pollution damage claims.

Local governments may also have regulations affecting site identification. Many municipalities restrict certain activities in designated areas. Familiarity with the laws and regulations is not enough. The planner should establish a working relationship with the people who administer the regulations. These people can help interpret and apply the rules. Although zoning for a particular site can be changed by a governing board, disagreements between different jurisdictions and citizen opposition may prevent the development of a landfill in a certain area.

Assess Landfill Options for Energy and Materials Recovery

Landfill gas can be a useful source of energy.

Gas generated from landfills can have at least three uses: (1) as a boiler fuel, (2) as fuel for an engine-generator set to produce electricity, and (3) as a natural gas supplement, when first upgraded to pipeline quality. In industrial boilers, landfill gas is best used as a supplementary fuel. This allows the boiler to be fired continuously using other fuels if landfill gas becomes unavailable for some reason. Specifications for boiler gas focus on the absence of air or oxygen, compression, and transporting the gas to the boiler. Dewatering may also be necessary to accommodate climate and pipeline distance and configuration. Depending on the situation, gas as low as 20 to 30 percent methane can be used in boilers.

Landfill gas is also used to generate electricity. Many plants in the U.S. use compressed and dewatered landfill gas to fuel either gas turbines or reciprocating engines that drive electrical generators. In general, smaller plants tend to use reciprocating engines and larger plants tend to use gas turbines. To drive a generator, the gas must be at least 30 percent methane or have a minimum heating value of at least 300 Btu's per cubic foot.

The third use for landfill gas is as a supplement for natural gas. This requires removing carbon dioxide and trace gases to upgrade the landfill gas to 100 percent methane. The gas is then directed into a natural gas transmission system. The market for this gas is virtually inexhaustible and is easily accessible with natural gas transmission lines, which are often located in the vicinity of the landfills. Difficulties in reaching markets for this use of landfill gas are usually associated with the amount and cost of processing required to upgrade the gas to pipeline quality and gaining approval of the pipeline company.

Consider Final Site Use

The final use of the landfill site should be considered during the initial site decision phase in order to provide for the best use of the property. Good planning at the earliest possible stage will minimize costs and maximize the site's usefulness after closure.

Monitoring requirements, groundwater protection, gas migration control, and uneven settlement should be carefully considered if the land can be used productively after closure.

Many case studies have shown that land formerly used for solid waste disposal can be upgraded through proper design and implementation of innovative landfill concepts. An example is land that has been converted into an open-space park in a municipality where open space may be in short supply. Many landfills have been turned over to parks departments or conservation agencies for general public use after landfilling has been completed. Careful attention must be given to monitoring requirements, groundwater protection, gas migration control, and uneven settlement. If the landfill design provides for such constraints, however, the land can be turned into productive use when the landfill is completed. Improvements also need to be properly designed to avoid disturbance of design features in the closed landfill, such as leachate collection systems.

The best strategy is to plan for the eventual use of the site before the landfill is constructed and operated. An additional benefit of planning ahead is that stating a planned use during site selection may reduce possible opposition to a new landfill. Potential uses for closed MSW landfills are provided below:

- nature park
- recreation park
- wilderness area
- animal refuge
- golf course
- ski or toboggan hill
- parking lot

Planning is particularly important if future construction or building on or near the landfill site is anticipated. Design features such as location of structures requiring special support, recreational facilities requiring specific topography, and gas control systems to protect future buildings can be anticipated during landfill operation.

Final uses under consideration must be compatible with the post-closure care plan, with other nearby land uses, and with the limited ability of the landfill to support structures.

Depending on planned site use, factors that can be modified are cover thickness, slope, cover / waste ratio, degree of compaction, use of additives and cements, selective disposal, and setting aside undisturbed areas as structural pads. The consequences of changing plans for the landfill usually include costly modifications, such as the removal of settlement-prone cover and waste layers.

When identifying potential options for final landfill use, it is important that uses under consideration be compatible with the post-closure care plan, with other nearby land uses, and with the limited ability of the landfill to support structures. Most completed landfills are used for recreational purposes, such as golf courses, nature preserves, or ski hills. Consideration must also be given to compatibility with existing land forms, settlement allowances, landfill gas protection, drainage patterns, and open-space planning.

Determine Suitability of Sites

Site characterization will concern the geology and hydrogeology of a potential site or sites.

The next step in the site selection process is to conduct a more detailed investigation of those sites designated in the site identification process as being most suitable. Site characterization studies should be conducted at sites with the most desirable characteristics. Thorough site characterizations are conducted in two phases. The first phase involves collecting and reviewing as much information as can be found about the site. The second phase involves field investigation activities. Most of the new data collected will concern the geology and hydrogeology of potential sites. Such information helps planners determine aquifer depths, geologic formations, drainage patterns, depth to groundwater, groundwater quality and flow direction, and construction characteristics of on-site soils. Data about existing land use, surrounding land development, available utilities, highway access, political jurisdiction, and land cost are also tabulated.

Conducting Site Characterizations—Information Collection and Review

Before beginning a field investigation, developers should review all available information about the site. A thorough review will include the following:

- **A literature review:** including (1) research reports that provide findings of studies conducted on the site itself or on surrounding areas, (2) journal articles dealing with the site or surrounding areas, (3) studies and reports from local, regional, and state offices (geological surveys, water boards, environmental agencies, etc.), and (4) studies from federal offices such as the U.S. Geological Service or USEPA.
- **Gathering information from file searches:** Including (1) reports of previous site characterizations for the site, (2) geological and environmental assessment data from state and federal project reports, (3) previous site uses for disposal which may have resulted in contamination.

The documentation listed above is by no means a complete listing of data necessary to conduct a preliminary investigation. There are many other sources of documentation that may be available for review during the preliminary investigation. After completing the preliminary investigation, the hydrogeology of the site must be characterized.

Conducting Site Characterizations—Field Investigations

The conceptual model should be a reliable estimation of geologic and hydrogeologic conditions at the site.

The proposed site must be characterized to determine subsurface conditions. Site characterization studies consist of geophysical investigations, soil borings and test pits below and adjacent to the proposed site. The number, location, and depth of the soil borings are dictated by the hydrogeology of the site. The number of borings needed to accurately define conditions increases with the size and geologic complexity of the site. The result of the investigations will lead to the formation of a conceptual model. This model should be a reliable estimation of geologic and hydrogeologic conditions at the site.

The borehole program usually requires more than one round of drilling. The objective of the initial boreholes is to further define the conceptual model derived from research data. The borehole program should be designed as follows:

- Determine the initial number of borings and their spacing based on the information obtained during the preliminary investigation.
- As needed, install additional borings to provide more information about the site.
- Collect samples when changes in lithology occur. For boreholes that will be completed as monitoring wells, at least one sample must be collected from the interval that will be screened. As a boring is being advanced, a soils scientist or geologist will collect samples for testing. Normally, soil samples are tested for grain size distribution and moisture content and are classified by soil type.

Soils that may later be used for liners and landfill covers will also be tested for permeability, moisture content, moisture density relationship, and moisture strength factors. This data is used to prepare a boring log, as shown in Figure 9-3.

Some states' regulations specify the minimum number of borings for each site and a minimum number per acre.

Borings should extend below the expected base elevation of the landfill, and at least a portion of the boreholes should terminate below the water table. Selected borings should extend to bedrock unless the distances involved make it unreasonable. Monitoring wells can be constructed in the boreholes as part of the hydrogeologic study. Some states' regulations specify the minimum number of borings for each site and a minimum number per acre to reduce the chances of overlooking significant hydrogeologic features such as sand lenses or perched water.

Measuring static water elevations in wells helps to determine the horizontal and vertical groundwater gradients for estimating flow rates and flow directions. The water levels can be plotted and contoured on a map that also shows adjacent land uses. Superimposing flow lines on the contours shows where leakage from a potential landfill may migrate. An example is shown in Figure 9-4.

Geophysical techniques, either surface or down-hole, can be used to plan and supplement the subsurface borehole program. Down-hole techniques include electric logging, sonic logging, and nuclear logging. Surface geophysical techniques include seismic profiling, electromagnetic profiling, and resistivity profiling.

The final output of the site characterization phase of the hydrogeological investigation is a conceptual model, which consists of an integrated picture of the hydrogeologic system and the waste management setting. The final conceptual model must be a site-specific description of the vadose zone, the uppermost aquifer, and its confining units. The model should contain all of the information necessary to design a groundwater monitoring system.

Hydrogeologic studies are expensive and should be limited to sites with the most promising characteristics.

Other conditions may exist at proposed landfill sites. The presence of bedrock can impede excavation and greatly complicate groundwater protection. Sites with multiple soil layers and formations will require careful characterization as the landfill is being designed. When soil and groundwater limitations must be overcome, specialized site layout must be carefully implemented.

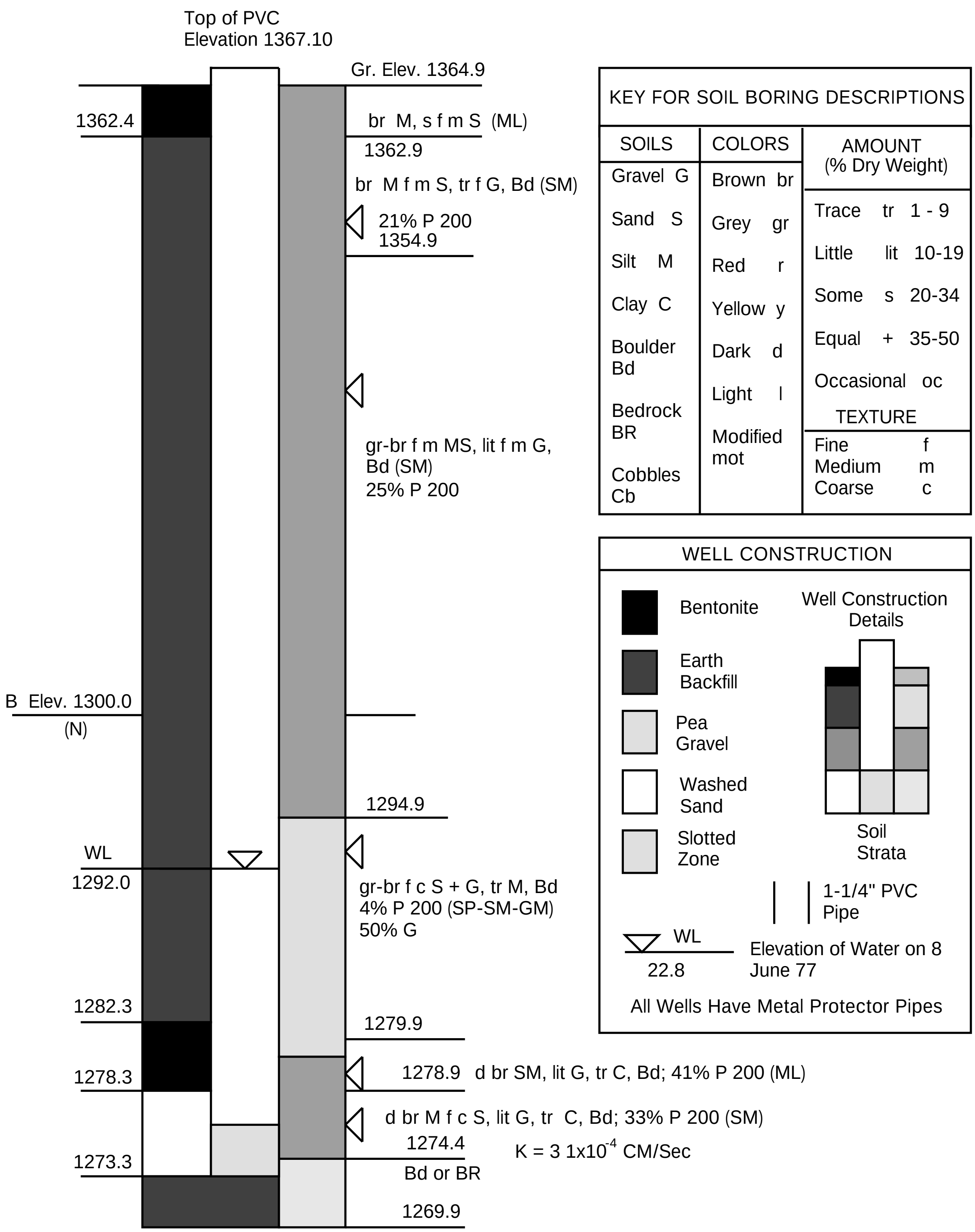
Hydrogeologic studies are relatively expensive to conduct and should, therefore, be limited to those sites with the most promising characteristics. A further cost concern is obtaining permission to do the testing without buying the property beforehand. One alternative is to purchase an option to buy, which gives the purchaser the right to buy the land within a specified period of time for a specified price. This allows time for testing and evaluating the results without commitment to purchasing the property.

The preliminary feasibility report should contain all of the pertinent information needed for determining which site to select. The report may suggest a preferred site or may leave this decision to the governing board of the unit of government or other organization that will be operating the landfill.

Once a site has been selected, a final feasibility report can be prepared and submitted to the appropriate agencies for approval. This is discussed in the following sections.

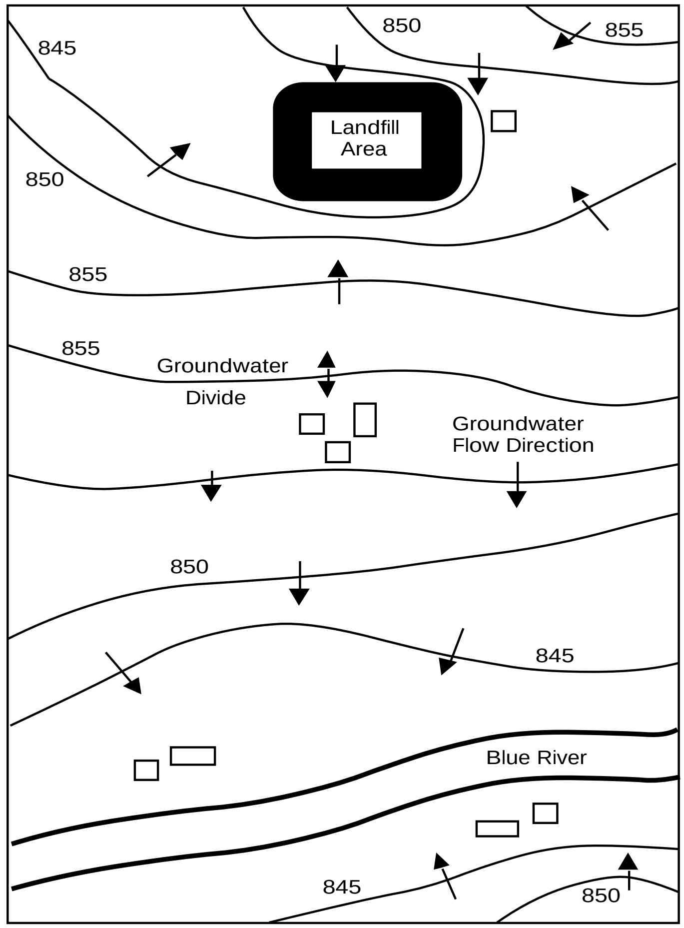
Figure 9-3

Example of Soil Boring Logs



Source: Department of Adult and Community College Education, North Carolina Sate University, reprinted from *Waste Age*, Correspondence Course articles 1991-1992

Figure 9-4
Example of Groundwater Contour Map



Source: P. O'Leary and P. Walsh, University of Wisconsin–Madison Solid and Hazardous Waste Education Center, reprinted from *Waste Age* Correspondence Course 1991-1992

The feasibility report should provide complete information to decision makers and regulatory authorities.

DEVELOPING THE FACILITY DESIGN

Preliminary Considerations

Selecting the Type of MSW Landfill

The major types of MSW landfill are the area and the canyon landfills. The area landfill is generally used in a rolling terrain where cover soil can be obtained from an area adjacent to the landfill itself. Through proper coordination, the cover soil is brought in as necessary to provide the various forms of cover and to prepare the berms. A typical area fill is shown in cross section in Figure 9-5.

A canyon fill is used in mountainous areas and may be considered a variation of the area landfill because cover is usually obtained from adjacent areas, rather than from the waste footprint. A canyon landfill tends to be deep. Total refuse depths in excess of 200 feet are common. Much of the difficulty in designing canyon landfills is routing traffic so it can reach the different elevations of the landfill as the working phase moves both over the area and also up the height of the landfill. Access involves a series of roads constructed adjacent to or on the landfill to elevate traffic to the working face. Other problems in designing canyon landfills are maintaining slope stability and preventing erosion.

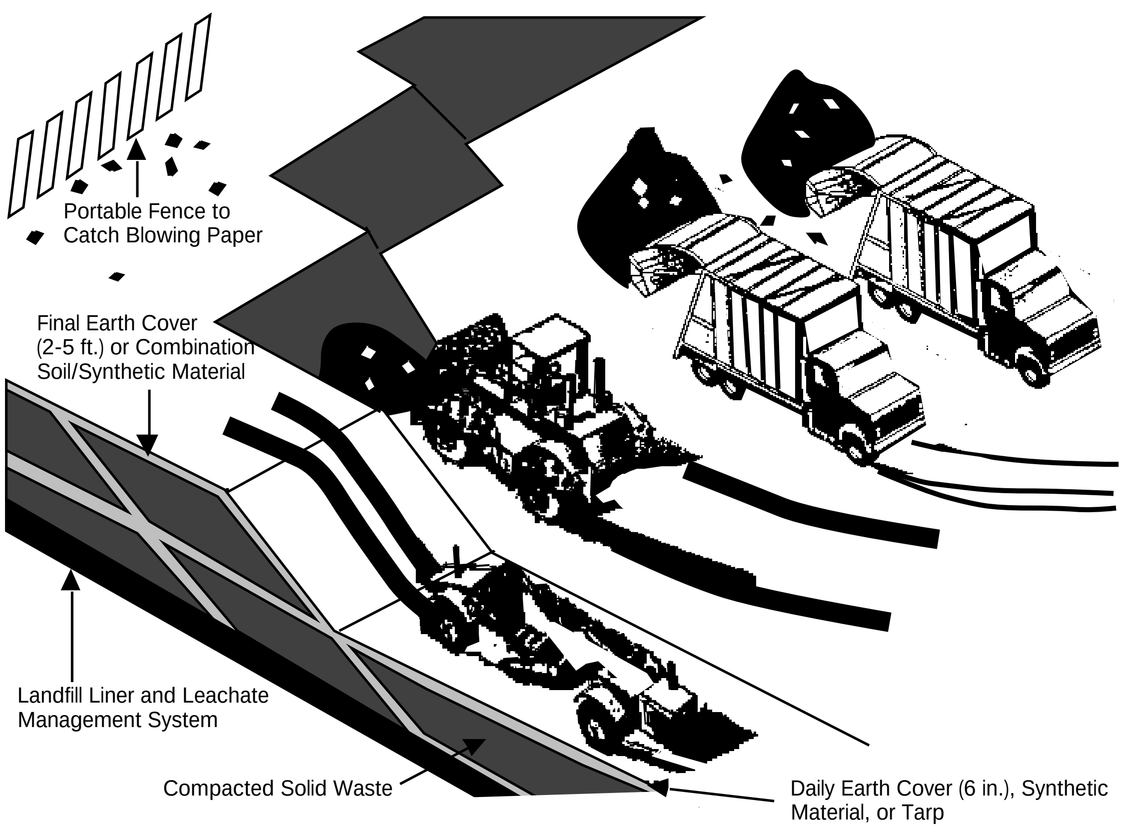
Landfills can also be defined by the types of waste disposed of and the type of preprocessing done. Waste can range from food and yard trimmings or other decomposable materials to industrial wastes that are relatively inert, such as demolition debris. The design of the landfill must reflect the potential for groundwater contamination and gaseous emissions particular to the waste accepted for disposal. Preprocessing waste may consist of shredding, baling, or a combination of residuals from other processes. Preprocessing will change the characteristics of the waste and on-site handling. These considerations must be included in the design.

A unique combination of timing, site restrictions, waste characteristics, and regulatory and political factors force design teams to adapt as projects unfold.

The Design Process

It is not possible to outline a typical landfill design process and expect a given project to follow the specified sequence. Each project presents a unique combination of timing, site restrictions, and waste characteristics, along with regulatory and political factors that force the design team to adapt as the project unfolds. Nevertheless, certain points must be covered in the landfill design

Figure 9-5
The Area Method of Sanitary Landfilling



Source: P. O'Leary and P. Walsh, University of Wisconsin–Madison Solid and Hazardous Waste Education Center, reprinted from *Waste Age* Correspondence Course 1991-1992

process, and it is helpful to have an initial outline of a logical sequence of activities to follow. Such an outline is summarized in Table 9-3. Data collected during site selection will be incorporated into the site design, but changing conditions and the need for more detail may require re-evaluation and adding to previously collected data.

Public Participation in the Site Selection Process

See Chapters 1 and 2 for suggested approaches to facilitate public participation.

Concurrent with the design and permitting processes, public education and participation programs must be undertaken. The final stage of site selection is gaining public approval. Chapter 1, on public education, and Chapter 2, on siting, should be consulted for suggested approaches to facilitate public participation. Projects lacking public review or input until the design is completed may face substantial delays in the approval process.

Meeting Regulatory Standards

There are generally two types of federal, state, and local government standards: engineering design standards and performance standards. Engineering design standards are essentially building codes that describe how the facility must be built. An example might be requiring that new landfills have a six-foot-high fence surrounding them. The regulating bodies monitor compliance with these standards by reviewing the building plans and inspecting the landfill during construction. Performance standards are applicable over a facility's life and specify that a certain level of environmental control be achieved and maintained. For example, the state agency regulating groundwater quality may specify the maximum allowable concentration of a contaminant that may be present in the groundwater below or adjacent to the site. The site operator must incorporate the necessary control systems to achieve compliance with the groundwater standard. If the landfill as initially designed does not achieve compliance, then the operator must install additional protective systems.

The final use of the landfill must be considered during the design phase in order to provide for the best use of the property. Good planning at the earliest possible stage will minimize costs and maximize the site's usefulness after closure. The long-term alternative end uses will be limited and must be consistent with the approved closure plan.

General Design Considerations

The design package should include plans, specifications, a design report, and an operator's manual, all of which will be submitted to regulatory agencies.

The design package should include plans, specifications, a design report, and an operator's manual, all of which will be submitted to regulatory agencies. A cost estimate for in-house uses should also be submitted.

Plans and Specifications

Plans and specifications typically include the following elements:

- a base map showing existing site conditions with contour intervals of one foot to five feet and a scale of one inch equal to 50 feet to one inch equal to 200 feet
- a site preparation plan designating fill and stockpile areas and site facilities
- a development plan showing initial excavated and final completed contours in filling areas
- cross sections illustrating phased development of the landfill at several interim points
- construction details illustrating detailed construction of site facilities
- a completed site plan including final site landscaping and other improvements.

Table 9-3
Sanitary Landfill Design Steps

1. Determine solid waste quantities and characteristics
   a. Existing
   b. Projected
2. Compile information for potential sites
   a. Perform boundary and topographic surveys
   b. Prepare base maps of existing conditions on and near sites
      - Property boundaries
      - Topography and slopes
      - Surface water
      - Wetlands
      - Utilities
      - Roads
      - Structures
      - Residences
      - Land use
   c. Compile hydrogeological information and prepare location map
      - Soils (depth, texture, structure, bulk density, porosity, permeability, moisture, ease of excavation, stability, pH, CATION exchange capacity)
      - Bedrock (depth, type, presence of fractures, location of surface outcrops)
      - Groundwater (average depth, seasonal fluctuations, hydraulic gradient and direction of flow, rate of flow, quality, uses)
   d. Compile climatological data
      - Precipitation
      - Evaporation
      - Temperature
      - Number of freezing days
      - Wind direction
   e. Identify regulations (federal, state, local) and design standards
      - Loading rates
      - Frequency of cover
      - Distances to residences, roads, surface water and airports
      - Monitoring
      - Groundwater quality standards
      - Seismic and fault zones
      - Roads
      - Building coas
      - Contents of application for permit
3. Design filling area
   a. Select landfilling method based on:
      - Site topography
      - Site soils
      - Site bedrock
      - Site groundwater
   b. Specify design dimensions
      - Cell width, depth, length
      - Cell configuration
      - Fill depth
      - Liner thickness
      - Interim cover soil thickness
      - Final cover specifications
   c. Specify operational features
      - Use of cover soil
      - Method of cover application
      - Need for imported soil
      - Equipment requirements
      - Personnel requirements
4. Design features
   a. Leachate controls
   b. Gas controls
   c. Surface water controls
   d. Access roads
   e. Special working areas
   f. Special waste handling
   g. Structures
   h. Utilities
   i. Recycling drop off
   j. Fencing
   k. Lighting
   l. Washracks
   m. Monitoring wells
   n. Landscaping
5. Prepare design package
   a. Develop preliminary site plan of fill areas
   b. Develop landfill contour plans
      - Excavation plans (including benches)
      - Sequential fill plans
      - Completed fill plans
      - Fire, litter, vector, odor and noise controls
   c. Compute solid waste storage volume, soil requirement volumes, and site life
   d. Develop final site plan showing:
      - Normal fill areas
      - Special working areas
      - Leachate controls
      - Gas controls
      - Surface water controls
      - Access roads
      - Structures
      - Utilities
      - Fencing
      - Lighting
      - Washracks
      - Monitoring wells
      - Landscaping
   e. Prepare elevation plans with cross-sections of:
      - Excavated fill
      - Completed fill
      - Phase development of fill at interim points
   f. Prepare construction details
      - Leachate controls
      - Gas controls
      - Surface water controls
      - Access roads
      - Structures
      - Monitoring wells
   g. Prepare ultimate land use plan
   h. Prepare cost estimate
   i. Prepare design report
   j. Prepare environmental impact assessment
   k. Submit application and obtaining required permits
   l. Prepare operator's manual

Source: Adapted from Conrad et al., *Solid Waste Landfill Design and Operation Practices*, EPA Draft Report Contract, 1981

Design Report

A design report typically includes the following four major sections:

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

Public Involvement

The mechanisms chosen to facilitate public participation must be suited to the particular group from whom input is being sought.

Many of the permits needed before landfill design and operating plans are approved require that a public hearing be conducted to solicit input from interested parties. The firm or agency designing the landfill should also solicit input from individuals and groups who will be directly affected by the future landfill. The mechanisms chosen to facilitate public participation must be suited to the particular group from whom input is being sought. Such techniques include advisory committees, surveys, public meetings, and tours of similar facilities. Public hearings should be conducted after the public has been provided with details about the proposed facility and any concerns voiced by representatives of the community. Some communities establish technical and citizen advisory committees that participate in establishing goals and objectives and then help prepare evaluation criteria and the final landfill design.

State-Level Approval Process

Most states employ a multistage approval process similar to the following:

1. Initiate the required landfill siting regulatory review procedures.
2. Submit a feasibility (engineering) report to the state for approval.
3. Submit detailed engineering plans to the state.
4. Submit a final application for state landfill operating permits.

Additional Requirements

Other permits may be needed from local, state, and federal agencies.

In addition, federal and state legislation may require that an environmental impact statement be prepared.

After submitting applications and plans, the agency reviewing the proposal may have additional questions to be answered by the developer. Additional permits may be needed from local agencies, state agencies other than the one dealing specifically with landfills, and federal agencies, such as the U.S. Army Corps of Engineers and the U.S. Fish and Wildlife Service.

The National Environmental Policy Act and similar legislation enacted by many states may require that a federal or state agency prepare an environmental impact statement. The purpose of the environmental impact statement is to disclose the nature of the proposed project, assess current and possible future environmental conditions, and to describe alternatives to the proposed action.

Developing the Site Layout

The landfill's layout will be strongly influenced by the site's geology. Of particular concern is the potential for gas and leachate migration and the suitability of the soil for landfill base and cover material. The site layout begins with geotechnical information, which includes data on the geology, hydrology, and soils at and around the site. These data are usually collected during the site-selection process, then supplemented during subsequent site investigation.

Many boring logs and additional cross sections are typically required to properly locate the waste disposal area within the site.

Soil-boring logs, as well as other data describing subsurface formations and groundwater conditions, are diagrammed to present an interpretation of the subsurface conditions at the planned landfill site. Figure 9-6 is a diagram of subsurface conditions along one cross section of a landfill under development. The soil-boring logs are shown, and the extent of each formation is extrapolated between the boreholes. The depths to bedrock and the groundwater table are also shown. Many more boring logs and additional cross sections at regular coordinate intervals in several (minimum of two) directions are typically required to properly locate the waste disposal area within the site under development.

Preparation of Drawings

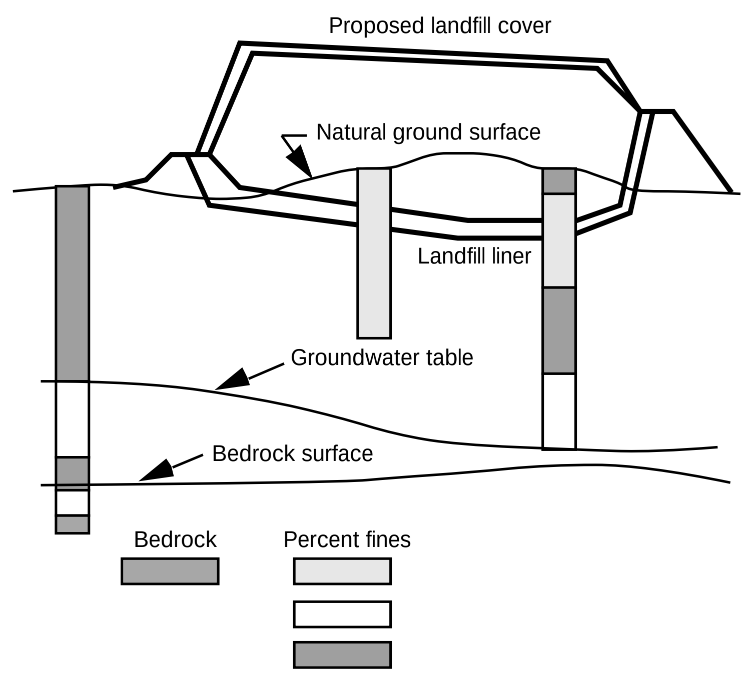
The base map usually shows the landfill location in relation to surrounding communities, roads, and other features. A site map shows the following features:

- contour lines drawn at two- or five-foot intervals
- clearly delineated property lines
- easements and rights-of-way indicated
- utility corridors, buildings, wells, roads, and other features identified
- drainage ways marked
- neighboring property ownership and land uses shown.

Contour maps show drainage patterns adjacent to and through possible disposal sites. Areas with excessive slope or direct overland flow from a potential site to surface waters must be carefully evaluated.

Figure 9-6

Subsurface Conditions Along a Cross Section of a Landfill Under Construction



Source: P. O'Leary and P. Walsh, University of Wisconsin–Madison Solid and Hazardous Waste Education Center, reprinted from *Waste Age* Correspondence Course articles, 1991-1992

Subsurface formations and ground-water conditions will influence the landfill's design features in the leachate collection system and liner requirements. A formation's geotechnical characteristics will determine its suitability as a construction material.

Subsurface formations and groundwater conditions influence the landfill's design features in the leachate collection system and liner requirements. A formation's geotechnical characteristics will determine its suitability as a construction material.

The site plans should describe landfill development in sequence, showing in chronological order which features or phases are to be developed. Development is usually planned for the landfill to be constructed and operated in phases of one to two years each. Dividing the project into phases minimizes the amount of open landfill surface and reduces the potential for precipitation to accumulate in the site. As each phase is completed, that portion of the landfill can be closed and final cover material placed over the waste. A final advantage of phasing is that it makes premature closure of the landfill more practical and economical in the event of an environmental problem. In a well-planned phase development, the landfill's end use can be implemented in the completed sections while other areas are still being used for disposal.

Concurrent with the development of plans for liners, covers, service roads, and embankments, soil cut-and-fill balances (see glossary) must be calculated. The best designs minimize the transfer of soil at the site. Substantial volumes of earth will be required for cover material and possibly for liners.

Some regulatory agencies mandate the construction of screening berms or fences around the active areas of a landfill. The extra soil needed for berm construction must be accounted for when planning excavation work. The height of the berms will depend upon the lines of sight into the landfill from adjacent areas.

When practical, the phases should be laid out so that excavated soil is used immediately. When stockpiling is necessary, the work should be organized so that stockpiled soil may be left undisturbed until needed or be used to surcharge completed areas. Stockpiled soil should be covered whenever possible to prevent erosion from wind and precipitation.

After completion of the phasing diagrams and earth work balances, a table should be prepared summarizing the waste disposal and earth volumes that will be contained within each phase of the landfill.

Operating Plans

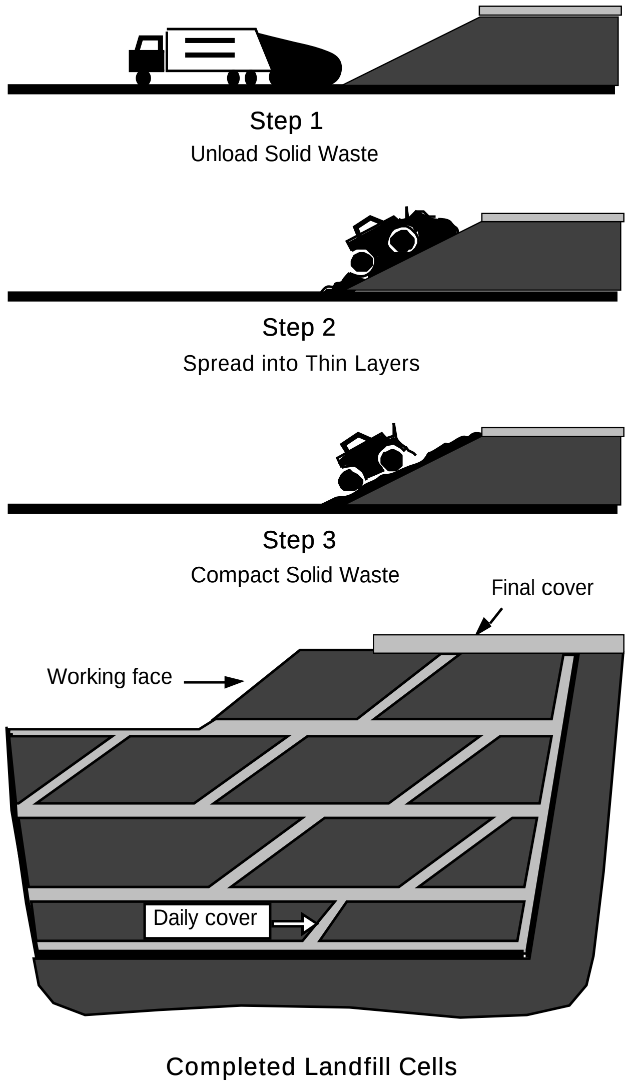
Determining Working Face and Phase Dimensions

The operating plan should describe all of the activities that will occur at the facility.

The operating plan should describe, in detail, the configuration of the working face of the landfill. Figure 9-7 illustrates a typical cross section of a portion of a municipal landfill, including the "working face," and helps to define terms. The "working face" is the area presently being worked, with new refuse being deposited and compacted into it. Once the working face has been completed and daily cover material provided, it is a completed cell or "daily cell." A "lift" is composed of the adjacent daily cells that form one layer of the landfill. Lift thicknesses are generally 8 to 20 feet. Larger landfills that accept more refuse per day have higher lift thicknesses. "Daily cover material," as shown in Figure 9-7, is applied over the working face and can extend over the horizontal surface at the top of each daily cell, depending on how long the cover will be exposed to the environment. If the landfill is not expected to receive additional wastes, closure activities must begin within 30 days of the final receipt of waste. The requirement to begin closure ensures that a proper cover is installed at the landfill.

The minimum width of the working face or daily cell should be at least wide enough to accommodate as many trucks or vehicles as are expected to be at the landfill at a given time. Typically, 10 to 15 feet per truck or vehicle is used for design purposes. Clearly, it is not a good operating practice to have extremely wide working faces to accommodate the peak flow of trucks that may occur once or twice a day. A tradeoff must be made between the width of the working face and the area needed to queue vehicles entering the site during peak hours. The

Figure 9-7
Solid Waste Placement and Compaction



Source: P. O'Leary and P. Walsh, University of Wisconsin–Madison Solid and Hazardous Waste Education Center, reprinted from *Waste Age* Correspondence Course 1991-1992

working face should be kept as small as possible because it is this area that can attract birds, provide visual problems for passersby, and be a source of blowing paper. Keeping freshly deposited refuse in a well-defined and small working face is a good indication of a well-operated landfill.

Phasing diagrams show the landfill's evolution through different stages.

Phase Diagrams

The site plan should illustrate the chronological order for developing the features. In a well-planned phased development, the landfill's end use can begin on completed sections while other areas in the landfill are still being used for disposal.

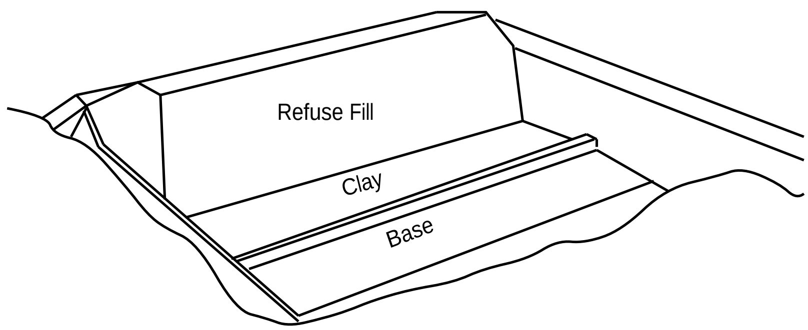
Phasing diagrams show the evolution of the landfill at different stages through the life of the site (see Figure 9-8). They should be developed for key times in sufficient detail to ensure that the operator knows what is to be done at any point. The engineers and management must be assured that the site is proceeding according to plan and contracts can be let or finances arranged for

Regulatory bodies must be assured that landfill operators are following the plan and the site will be completed as designed at the agreed-upon time.

construction activities. Regulatory bodies must also be assured that landfill operators are following the plan and the site will be completed as designed at the agreed-upon time. The dimensions of each phase are determined by several factors. Generally, each phase accommodates 2 to 3 years of refuse volume.

Figure 9-8

Landfill Construction Plan: Intermediate Phase



Source: P. O'Leary and P. Walsh, University of Wisconsin–Madison Solid and Hazardous Waste Education Center, reprinted from *Waste Age* Correspondence Course 1991-1992

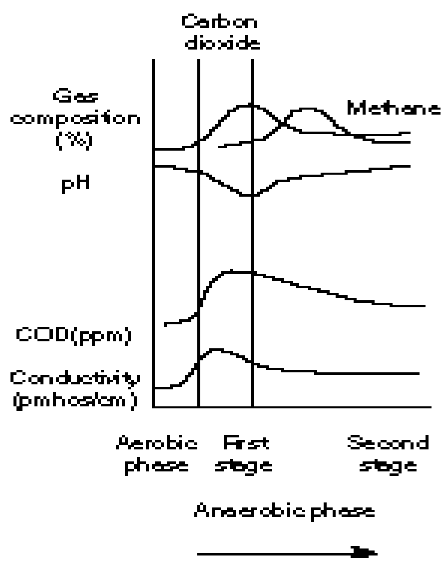
Leachate Management

Leachate is a liquid that has passed through or emerged from the waste in a landfill. It contains soluble, suspended, or miscible materials removed from the waste.

Refuse contains decomposable matter, as well as the nutrients and organisms that promote decomposition. The limiting factor controlling the amount of decomposition taking place in municipal solid waste is usually the availability of moisture. The decomposition of solid wastes in an MSW landfill is a complex process. It may be characterized according to the physical, chemical, and biological processes that interact simultaneously to bring about the overall decomposition. The three phases of decomposition are shown in Figure 9-9. The by-products of all these mechanisms are chemically laden leachate and landfill gas.

Figure 9-9

Phases of Solid Waste Decomposition



Sources: (a) Fa[illegible] 2; (b) Stanforth, Ham, Anderson and Stegmann 1979, *Journal of the Water Pollution Control Federation*, Vol. 51

Leachate is a liquid that has passed through or emerged from the waste in a landfill. It contains soluble, suspended, or miscible materials removed from such waste. Table 9-4 shows the changes in leachate composition that occur as a landfill proceeds through the various decomposition phases. It is imperative, therefore, when designing leachate collection and treatment facilities to consider the concentrations and variability of leachate with regard to its many constituents.

Leachate generation rates depend on the amount of liquid originally contained in the waste (primary leachate) and the quantity of precipitation that enters the landfill through the cover or falls directly on the waste (secondary leachate).

Climate, topography, landfill cover, vegetation, and waste types affect leachate generation.

Factors Affecting Leachate Generation

These factors influence leachate generation at landfills:

- **Climate:** Climate at the site significantly influences the leachate generation rate. All other factors being equal, a site located in an area of high precipitation can be expected to generate more leachate.
- **Topography:** Topography affects the site's runoff pattern and the amount of water entering and leaving the site. Landfills should be designed to limit leachate generation from areas peripheral to the site by diverting surface-water "run-on" away from the site and by constructing the landfill cover area to promote runoff and reduce infiltration. All areas of a landfill should maintain at least a two percent grade over the

Table 9-4

Changes in Leachate Compositiion in Different Stages of a Landfill

Parameters with differences between acetic and methanogenic phase

Acetic phase	Average	Range
pH	6.1	4.5-7.5
BOD_5 (mg/l)	13000	4000-40000
COD (mg/l)	22000	6000-60000
BOD_5/COD	0.58	—-
$S0_{4\ (mg/l)}$	500	70-1750
Ca (mg/l)	1200	10-2500
Mg (mg/l)	470	50-1150
Fe (mg/l)	780	20-2100
Mn (mg/l)	25	0.3-65
Zn (mg/l)	5	0.1-120

Methanogenic phase		
pH	8	7.5-9
BOD_5 (mg/l)	180	20-550
COD (mg/l)	3000	500-4500
BOD_5/COD	0.06	—-
SO_4 (mg/l)	80	10-420
Ca (mg/l)	60	20-600
Mg (mg/l)	180	40-350
Fe (mg/l)	15	3-280
Mn (mg/l)	0.7	0.03-45
Zn (mg/l)	0.6	0.03-4

Parameters for which no differences between phases could be observed

	Average	Range
Cl (mg/l)	2100	100-5000
Na (mg/l)	1350	50-4000
K (mg/l)	1100	10-2500
Alkalinity (mg $CaC0_3$/l)	6700	300-11500
NH_4 (mg N/l)	750	30-3000
OrgN (mg N/l)	600	10-4250
Total N (mg N/l)	1250	50-5000
$N0_3$ (mg N/l)	3	0.1-50
$N0_2$ (mg N/l)	0.5	0-25
Total P (mg P/l)	6	0.1-30
A0X (ug Cl/l)*	2000	320-3500
As (ug/l)	160	5-1600
Cd (ug/l)	6	0.5-140
Co (ug/l)	55	4-950
Ni (ug/l)	200	20-2050
Pb (ug/l)	90	8-1020
Cr (ug/l)	300	30-1600
Cu (ug/l)	80	4-1400
Hg (ug/l)	10	0.2-50

*adsorbable organic halogen

Source: Ehrig, H.J., "Water and Element Balances of Landfills," in *Lecture Notes in Earth Sciences: The Landfill*, 1989

Table 9-5
Impact of Soil Surface on Water Runoff

Surface and Slope	Runoff in Percent	Coefficient
Grassy/Sandy Soil		
Flat	2 %	0.05 to 0.10
Average	2-7 %	0.10 to 0.15
Steep	7 %	0.15 to 0.20
Grassy/Heavy Soil		
Flat	2 %	0.13 to 0.17
Average	2-7 %	0.18 to 0.22
Steep	7 %	0.25 to 0.35

Source: D. G. Fenn et al., *The Use of the Water Balance Method for Predicting Leachate Generation from Solid Waste Disposal Sites, 1975*

waste at all times to prevent ponding of surface water. Table 9-5 shows the difference in runoff that will occur for different soils and slopes.

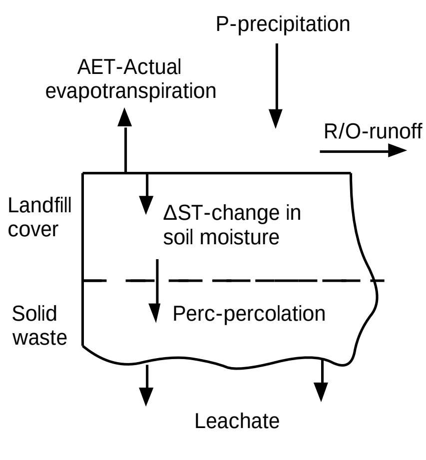
- **Landfill cover:** Landfill cover at the site affects the amount of water percolating into the landfill to form leachate. As the permeability of the soil used for final cover increases, leachate production rates increase. Consequently, to reduce the amount of leachate, modern design requires the use of low-permeability clays or geosynthetic membranes in final cover configurations.
- **Vegetation:** Vegetation plays an integral part in leachate control. It limits infiltration by intercepting precipitation directly (thereby improving evaporation from the surface) and by taking up soil moisture and transpiring it back to the atmosphere. A site with a poor vegetative cover may experience erosion that cuts gullies through the cover soil and allows precipitation to flow directly into the landfilled waste.
- **Type of waste:** The type of waste and the form that it is in (bulk, shredded, etc.) affect both the composition and quantity of leachate. Wetter wastes, for example, will generate more leachate.

The amount of leachate generated will affect operating costs for leachate collection and treatment.

Predicting Leachate Production Rates

Good landfill design requires predicting the amount of leachate that will be produced. The amount of leachate generated will affect operating costs if leachate collection and treatment are provided. The amount of leachate formed also affects the potential for liner leakage (to be calculated later) and hence to the potential for groundwater contamination. It also affects the cost of post-closure care after the landfill is closed.

Figure 9-10
Water Balance Equation



$$PERC = P - AET\ R/O - \Delta ST$$

Source: D. G. Fenn et al., *The Use of the Water Balance Method for Predicting Leachate Generation from Solid Waste Disposal Sites, 1975*

Predicting leachate formation requires water-balance calculations. The water-balance equation is given and the terms illustrated in Figure 9-10. The equation estimates the amount of water from rain or melting snow that will percolate through the landfill cover. Over time, the volume of percolating water will nearly equal the volume of leachate produced. There may be a lag between the time percolating water enters the fill material and the time leachate emanates continuously from the base of the fill. During this lag period, the solid wastes increase in moisture content until their field capacity is reached (field capacity is defined as the moisture content of the waste above which moisture will flow under the influence of gravity). Some leachate will be generated intermittently (almost immediately in wet climates), because of water channeling through the wastes. Once field capacity is achieved, however, leachate production should be more consistent.

The USEPA, in cooperation with the Army Corps of Engineers Waterways Experiment Laboratory, has prepared a computer program that calculates the water balance. The *Hydrologic Evaluation of Landfill Performance* (HELP) Model version 3.0 has weather records in data files and offers options for predicting leachate generation under many combinations of cover conditions. A portion of the output from a typical computer simulation is shown in Table 9-6.

The HELP Model is designed to model layered cover systems to find the most effective combination. This program is available for use with a personal computer. For more information or to order the software, contact the US EPA, 26 West Martin Luther King Drive, Cincinnati, OH 45260; (513) 569-7871.

Table 9-6
Output from HELP Model

Projected Average Monthly Totals in Inches Based on 20 Years of Weather Records

	Jan/Jul	Feb/Aug	Mar/Sep	Apr/Oct	May/Nov	Jun/Dec
Precipitation						
Totals	1.88	1.32	2.41	3.91	3.22	3.67
	4.98	3.87	3.05	3.01	2.09	1.95
Runoff from cover						
Totals	0.009	0.001	0.002	0.023	0.018	0.022
	0.129	0.026	0.031	0.058	0.001	0.000
Evapotranspiration from cover						
Totals	0.507	0.853	1.599	2.527	2.633	4.210
	4.954	4.198	2.256	1.371	0.709	0.527
Lateral drainage from drainage layer						
Totals	0.0000	0.0001	0.0000	0.0001	0.0000	0.0000
	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000
Percolation through landfill clay cap layer						
Totals	0.8747	1.1013	1.0550	1.3568	0.9472	0.4574
	0.3671	0.0436	0.2371	0.4947	0.8001	0.9318
Leachate collected from drainage layer above landfill liner						
Totals	0.4432	0.4259	0.5042	0.5342	0.5997	0.5818
	0.5841	0.5395	0.4795	0.4804	0.4673	0.4892
Leachate collected from drainage layer above landfill liner						
Totals	0.0970	0.0884	0.0980	0.0945	0.0989	0.0957
	0.0959	0.0959	0.0922	0.0959	0.0943	0.0990

Projected Average Annual Totals for 20 Years

	Inches	Cu.Ft./Acre	Percent
Precipitation	35.37	128384	100.00
Runoff from cover	0.321	1165	0.91
Evapotranspiration from cover	26.342	95623	74.48
Lateral drainage from cap drainage layer	0.0005	2	0.00
Percolation through landfill clay cap layer	8.6668	31461	24.51
Leachate collected from drainage layer above landfill liner	6.1290	22248	17.33

Source: P. O'Leary and P. Walsh, University of Wisconsin–Madison Solid and Hazardous Waste Education Center, reprinted from *Waste Age* Correspondence Course articles, 1991-1992

Regulatory Controls for Leachate Management

RCRA Subtitle D regulations established national standards for MSW; states with approved Subtitle D programs may allow variances to these requirements.

RCRA Subtitle D regulations establish a timetable for incorporating liners, leachate control systems, and final cover systems into the design of new municipal solid waste landfills. A current version of 40 CFR Parts 257 and 258 should be consulted to determine the applicable implementation dates. The particular type of design varies depending on the characteristics of the particular location. All liner systems incorporate leachate control systems in their design. States with approved Subtitle D programs may allow variances to these requirements.

The purpose of lining an MSW landfill is to prevent leachate from migrating from the site and entering an aquifer. A liner is a hydraulic barrier that prevents or greatly restricts migration of liquids, thus allowing leachate to be removed from the unit by the leachate control system. Liners function by two mechanisms: (1) they impede the flow of leachate into the subsoil and aquifers, and (2) they adsorb or attenuate pollutants, thus retarding contaminant migration. This adsorptive or attenuating capability depends largely on the chemical composition of the liner material and its mass. Most liner materials function by both mechanisms, but to different degrees, depending on the type of liner material and the nature of the liquid to be contained. Liners may be grouped into two major types: synthetic (flexible membrane) liners and natural (soil or clay) liners.

There are various types of liners in use, including compacted native and imported soils, compacted mixtures of native soils and bentonite, and flexible membrane liners. Flexible membrane liners are the least permeable liners, but have little capacity to attenuate dissolved pollutants. Natural liners can have a large capacity to attenuate materials of different types, but they are considerably more permeable than flexible membrane liners. A combination of both types of liner materials is referred to as a composite liner. Composite liner systems are more effective than either a single component flexible membrane liner or a soil liner. A composite liner can provide added protection to ensure that contaminant migration is controlled. The flexible membrane liner portion of the liner increases leachate collection efficiency and provides a more effective hydraulic barrier. The soil component provides support for the flexible membrane liner and the leachate collection system and acts as a back-up in the event of a flexible membrane liner failure.

The RCRA Subtitle D MSW landfill regulations require that new MSW landfills and expansions of existing MSW landfill facilities be constructed with a composite liner and a leachate collection system or meet a groundwater protection performance standard.

The RCRA Subtitle D MSW landfill regulations require that new MSW landfill facilities and expansions of existing MSW landfill facilities be constructed with a composite liner and a leachate collection system or meet a groundwater protection performance standard. The leachate collection system must be designed to maintain a leachate depth over the liner of less than 30 centimeters. The composite liner specified in the regulations is a system consisting of two components: the upper component is a flexible membrane liner installed in direct and uniform contact with a compacted soil, which forms the lower component. The flexible membrane liner must be at least 30 mils thick. If the flexible membrane liner is high-density polyethylene, the thickness must be a minimum of 60 mils. The compacted soil liner must be at least two feet thick and must have a hydraulic conductivity of no more than 1×10^{-7} centimeters per second.

The groundwater protection performance standard for landfills specifies that contaminant concentrations in groundwater flowing away from the landfill cannot exceed the amounts shown in Table 9-7. The point of measurement may be located from the waste unit boundary up to 150 meters (492 feet) from the boundary. Groundwater quality computer models are used to simulate contaminant movement, both concentration and extent, away from a planned landfill. The design of the landfill components is adjusted until compliance with the standards shown in Table 9-7 is demonstrated. The output from the models is usually a map showing changing parameter concentrations over time.

Extensive input data is needed to accurately run the models. Information required includes leachate characteristics, liner or base soil factors, geologic data, existing groundwater flow information, and interaction coefficients for leachate and materials underlying the proposed landfill. Several different modeling approaches may be necessary to characterize flow and contaminate movement away from a planned landfill towards the compliance boundary.

Table 9-7
Groundwater Protection Performance Standards

Chemical	Max. Concentration Limit (mg/l)	Chemical	Max. Concentration Limit (mg/l)
Arsenic	0.05	Lindane	0.004
Barium	1.0	Lead	0.05
Benzene	0.005	Mercury	0.002
Cadmium	0.01	Methoxychlor	0.1
Carbon tetrachloride	0.005	Nitrate	10.0
Chromium (hexavalent)	0.05	Selenium	0.01
2,4-Dichlorophenoxy acetic acid	0.1	Silver	0.05
1,4-Dichlorobenzene	0.075	Toxaphene	0.005
1,2-Dichloroethane	0.005	1,1,1-Trichloromethane	0.2
1,1-Dichloroethylene	0.007	Trichloroethylene	0.005
Endrin	0.0002	2,4,5-Trichlorophenoxy acetic acid	0.01
Fluoride	4.0	Vinyl Chloride	0.002

Source: USEPA

Landfill Liner System Components

Landfill liner systems consist of several components that control leachate movement off site. Figure 9-11 illustrates several configurations.

Clay Liners

Liner materials must be carefully tested during installation.

Regulatory agencies usually require that the soil liner have a permeability of less than 10^{-7} centimeters per second. To achieve final liner permeabilities that are consistently this low, tests must be conducted to determine the optimum moisture content and degree of compaction effort needed during construction of the liner.

Additional specifications are designed to ensure that the landfill is successfully constructed. See, for example, the Wisconsin specifications in Table 9-8.

Flexible Membrane Liners

Landfill designs may call for flexible membrane liner systems for several reasons: to overcome known leakage through clay liners, to save site volume for refuse instead of clay, and to overcome costly importation of clay if suitable clay is not locally available. Many kinds of flexible membrane liners are available for containing different kinds of liquid wastes. Design considerations include ensuring compatibility with the waste, developing a structurally sound design, providing good seaming, providing a firm base free of debris or sharp objects under the liner, maintaining construction quality control, and protecting the liner after construction. Flexible membrane liners can be used as the “impermeable” layer, and geonets can be used to facilitate drainage to a collection pipe. A typical flexible membrane liner thickness is 30 to 80 mils (0.030 to 0.080 inch).

Table 9-8
Wisconsin Clay Liner Specifications

Slope	
	For base minimum 2-4%
	For side slopes maximum 3:1
Drainage blanket	
	Clean sand/gravel minimum 12" thick
Clay material specs	
	Minimum 50% P200
	LL >/= 30
	PL >/= 15
	Permeability–maximum 1x10-7 cm/sec
	Clay fraction or CEC varies
Liner compaction	
	95% standard proctor
	90% modified proctor

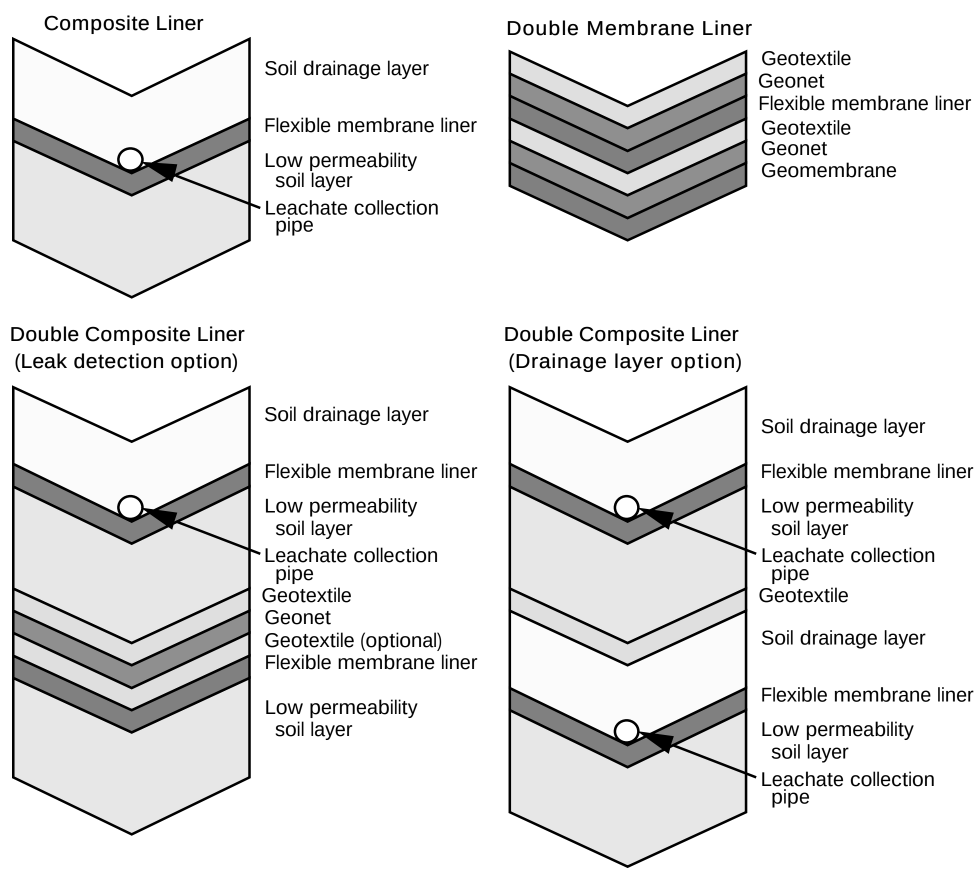
Source: G. Mitchell, 1994

A concern when relying on synthetic liners is that chemical interactions may affect the liner's integrity. Certain waste materials are known to degrade certain types of liners. Testing flexible membrane liners with MSW leachate has shown that most materials resist chemical attack under most conditions. USEPA Method 9090 was developed for hazardous waste landfills and in extreme cases could be used for MSW landfills. (See USEPA, SW-846, 1994 for further information.) This method involves an evaluation of changes in the flexible membrane liner material when immersed in leachate.

Leachate Collection Systems

The effectiveness of a leachate collection system is dependent on the design of the liner and the collection pipes. Layout of the liner and pipe network system varies, depending on the overall landfill area, phase shapes, and overall slope or topography. The slope of the liner should be at least 2 percent, and preferably 4 percent or more, to promote lateral flow of leachate to collection pipes, and pipes should be sloped at 1 percent minimum to ensure leachate flow and prevent accumulation at low spots along the pipeline.

Figure 9-11
Examples of Landfill Liner Systems



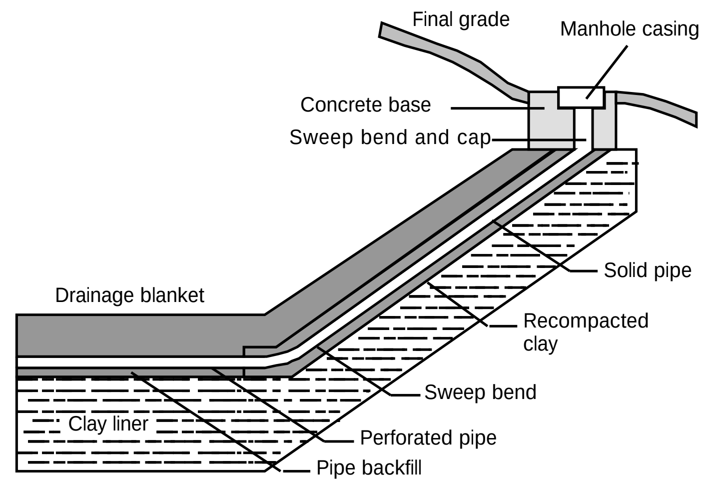
Source: P. O'Leary, University of Wisconsin–Madison Solid and Hazardous Waste Education Center, 1994

The leachate management system consists of the liner, leachate collection system, and leachate treatment process.

The pipe is placed in a trench or directly on the liner at the low points. The trench should be backfilled with gravel and the pipe must be well-supported to avoid crushing. The gravel may need to be protected by a geotextile to avoid plugging by fine-grained material in any overburden layers. Figure 9-12 shows a typical configuration providing access to pipes in the network for cleaning. Access can be direct from the surface or by manholes placed in the landfill. Because all manholes accumulate gas and are subject to shifting and settling, they can pose safety and maintenance problems.

Figure 9-12

Typical Leachate Collection System Showing Access to Pipes for Cleaning



Source: P. Kmet, 1994

Leachate Treatment Processes

Leachate treatment options include on-site treatment, discharge to a municipal sewage treatment plant, or a combination of these approaches. Limited studies have indicated that another method, leachate recirculation, has certain benefits, which include increasing the rate of waste stabilization, improving leachate quality, and increasing the quantity and quality of methane gas production. Leachate recirculation also provides a viable on-site leachate management method. Federal requirements allow leachate recirculation at landfills that are designed and equipped with composite liners and leachate collection systems constructed to maintain less than a 30 cm depth of leachate over the liner.

Leachate can be treated on or off-site but the treatment process must be carefully developed to guarantee a successful system. The most common leachate treatment option is discharge to municipal sewage treatment plants. Since leachate strengths are significantly greater than normal municipal wastewaters, care must be taken to avoid overloading the plant. Studies have shown that greater than a 2 percent hydraulic loading of a sewage treatment plant with leachate will disrupt its operations.

A scheme for leachate treatment options as a function of leachate strength is shown in Figure 9-13. Chemical precipitation for high-strength acidic leachate is commonly achieved by adding lime.

For a leachate of high BOD (biological oxygen demand), such as those typically found in a young landfill, anaerobic biological treatment is useful be-

The options for leachate treatment must be carefully evaluated.

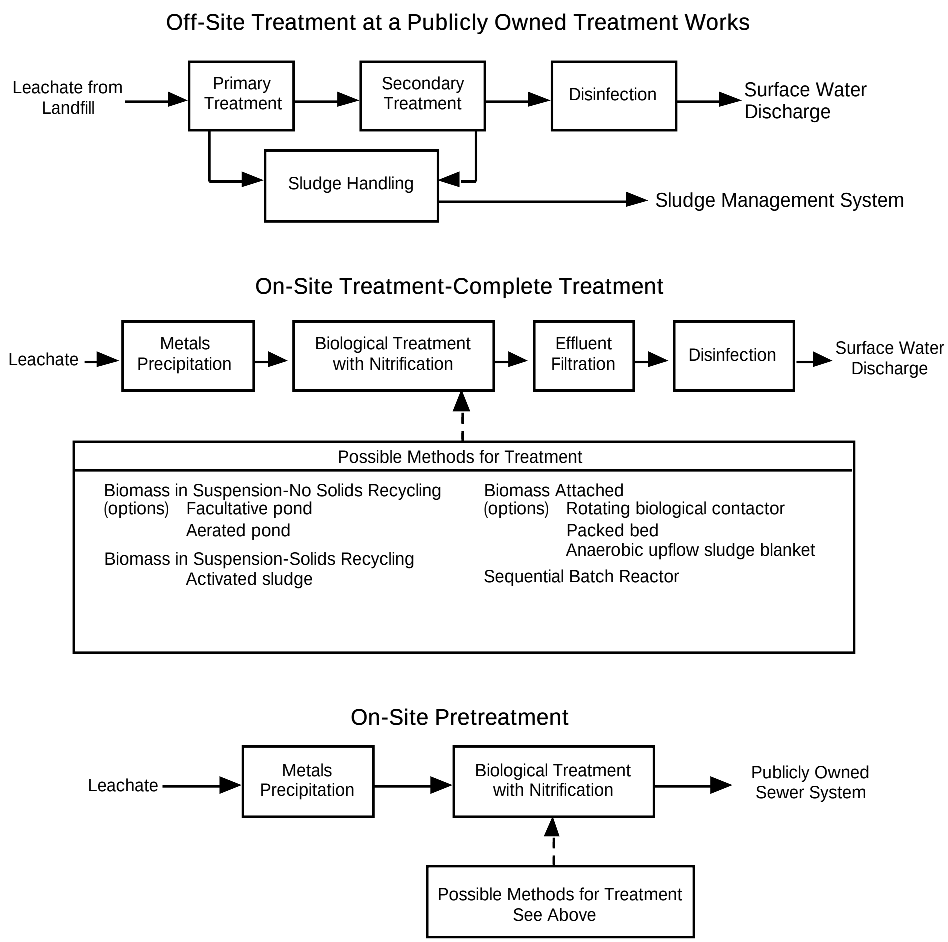
cause of its energy efficiency and low sludge generation rate. A 90 percent or more reduction in BOD can be expected using this method.

Leachate of medium BOD levels or pretreated leachate may be treated in aerobic biological systems, including activated sludge, rotating biological contractors, or sequenced batch units. Reduction of 90 percent or more of BOD, suspended solids, and precipitated metals is accomplished, but energy consumption may be high and comparatively large amounts of sludge are produced.

An aeration or facultative pond can be used to polish leachate treated by other methods, if the leachate has not yet reached a contaminant level suitable for discharge. Ponds can also be used to treat relatively low-strength leachates with BOD less than 100 mg/l. Such ponds may have surface aerators depending on the BOD, retention time, and configuration.

These systems are adequate for discharge to a Public Owned Treatment Works (POTW), if the POTW cannot, or for some reason will not, accept leachate directly from the landfill. If the leachate is to be discharged to surface water, additional treatment consisting of activated carbon adsorption, filtration, or reverse osmosis processes will be required, and air stripping or chemical precipitation may also be needed. A discharge permit will also be required.

Figure 9-13
Leachate Treatment Options



Source: G. Farquhar, 1994

The Natural Attenuation of Leachate

Many existing landfills do not have liners or have liners that can not completely contain the leachate. The chemicals in leachate that escape from the landfill base may undergo a variety of conversion and destruction reactions as they pass through the soil and into the underlying formations (a process called attenuation). For example, as leachate moves through a clay soil, most of the heavy metals (such as lead, arsenic, zinc, cadmium, and mercury) are retained by the soil. The ability of each soil to attenuate leachate is different, and not all elements or compounds are equally removed or reduced in concentration.

The unpredictable concentrations of leachate constituents, plus weather-related leachate generation surges and variations in subsurface conditions, make it extremely difficult to predict the degree of protection that natural attenuation will accomplish. The result is that landfills now incorporate means for containing and controlling leachate within the site, relying on natural attenuation only as a backup measure to protect groundwater quality. Existing landfills which have groundwater contamination levels exceeding RCRA Subtitle D limitations will be subject to remediation requirements.

Groundwater Quality Assessment

Monitoring Wells

Groundwater monitoring systems are required for new, existing, and lateral expansions of existing landfills. The monitoring is necessary to determine groundwater quality at a facility and to determine whether there has been a release of contaminants through the base of the landfill. All new landfills must have a groundwater monitoring system installed before any wastes are placed in the landfill. The schedule for installing a groundwater monitoring system at existing facilities depends on the location of the landfill with respect to a drinking water source or other state priorities. All units subject to the requirements will have to have the groundwater monitoring system in place by October 9, 1996.

Monitoring wells must be cased in a manner that maintains the integrity of the borehole and must be maintained to meet the design specifications. The number, spacing, and depths of the wells should be based on site-specific characteristics. The wells must also be constructed to facilitate the collection of groundwater samples. These two requirements are closely related. Great care must be taken when selecting well construction materials or sampling devices. Materials that may react with groundwater or contaminate samples should not be used.

The casing, associated seals, and grout protect the integrity of a borehole and minimize the hydraulic communication between zones. Materials that are not compatible with subsurface conditions can cause false or misleading detections, or non-detections, of analytes.

The techniques used to withdraw groundwater samples from a well must be based on considerations of the parameters to be analyzed in a sample. To ensure that the sample is representative of groundwater in the formation, physical alterations of the sample must be kept to a minimum. It is important to select sampling equipment that will maintain sample integrity. The sampling equipment must be constructed of inert materials that will not alter analyte concentrations or react with, sorb, or desorb the analytes.

To achieve accurate results, groundwater monitoring wells must be carefully installed and sampled.

Groundwater Monitoring and Corrective Action

The groundwater monitoring and corrective action requirements of RCRA Subtitle D have three steps: detection monitoring, assessment monitoring, and corrective action.

When contamination is detected, more extensive groundwater monitoring and possibly corrective action may be necessary.

Figure 9-14 shows a leaking landfill and one possible type of corrective action. All landfills that are required to monitor groundwater begin with detection monitoring.

Detection monitoring requires establishing background concentrations for a set of detection monitoring parameters. These indicator parameters include 47 volatile organic compounds (VOCs) and 15 metals. Unless a variance is given, these parameters must be sampled at least semi-annually during the active life of the facility and during closure and post-closure care periods.

If any of the constituents are detected at a statistically significant increase over background concentrations, assessment monitoring must begin within 90 days. Assessment monitoring may be avoided if it can be demonstrated that the increase was due to a source other than the landfill or an error in sampling, analysis, statistical evaluation, or natural variation in the groundwater.

Assessment monitoring continues until it is determined whether concentrations of contaminants exceed maximum levels under the Safe Drinking Water Act. Depending on the results, normal monitoring may resume or, if contamination levels warrant it, a program of remediation must begin. Such programs involve developing a remediation plan and often more extensive monitoring.

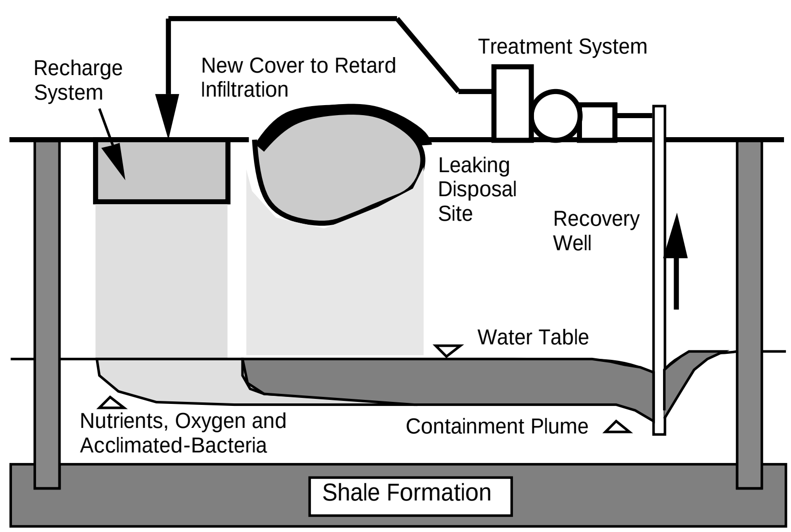
If contamination has migrated off-site, landowners and residents on land overlying the plume must be notified regarding the contamination and proposed corrective actions. Public hearings are required to evaluate the proposals.

The landfill owner may be required to implement the corrective actions and take interim measures such as the temporary supply of drinking water, if necessary. Corrective actions must continue until compliance with groundwater standards is achieved for three consecutive years.

The regulations for both groundwater monitoring and corrective actions are extensive and vary greatly among states. Individual state programs should be contacted to determine specific requirements.

Figure 9-14

Example of a Groundwater Remediation System



Source: Phil O'Leary, University of Wisconsin–Madison, Solid and Hazardous Waste Education Center, 1994

Gas Management

Because of the explosive quality of landfill gas, its migration must be monitored and limited.

Uncontrolled landfill gas migration can be a major problem at a municipal solid waste landfill. The gas must be controlled to avoid explosions and vegetation damage in the vicinity of the landfill.

RCRA Subtitle D standards limit the extent that landfill gas may migrate. Landfill gas concentrations may not exceed 25 percent of the lower explosive limit in occupied structures. This is equivalent to 1.25 percent methane in the building's atmosphere. The concentration of methane in the soil atmosphere can not exceed 100 percent of the lower explosive limit (5 percent methane) at the property line of the landfill site. Buildings at the landfill and monitoring probes located around the landfill must be tested quarterly each year for methane concentrations. Note that some states have more restrictive standards and require more frequent monitoring.

The composition of municipal landfill gas is controlled primarily by microbial processes and reactions in the refuse. Methane is usually the gas of concern. It is produced in about a 50:50 ratio with carbon dioxide. Other compounds are also produced and additional chemicals are released into the atmosphere by volatilization. Table 9-9 provides typical landfill gas composition. The oxygen and nitrogen levels shown are not products of decomposition; rather, they result from intrusion of air during gas sampling or analysis. On an air-free basis, and depending on the amount of dissolution of carbon dioxide and moisture in the landfill and the material being decomposed, the methane content typically ranges from 50 percent to 60 percent, the remainder being carbon dioxide and minor constituents as shown in Table 9-9.

Table 9-9

Typical Landfill Gas Composition

Component	Percent
Methane	47.4
Carbon dioxide	47.0
Nitrogen	3.7
Oxygen	0.8
Paraffin hydrocarbons	0.1
Aromatic-cyclic hydrocarbons	0.2
Hydrogen	0.1
Hydrogen sulfide	0.01
Carbon monoxide	0.1
Trace compounds	0.5

Source: Ham, R., USEPA, *Recovery Processing and Utilization of Gas from Sanitary Landfills*, 1979

Figure 9-15 gives typical amounts of landfill gas produced and recovered from a landfill; note the wide range in values. The total amount of gas generated in a full-sized landfill is difficult to determine because of the inherent uncertainty using isolated samples to predict total generation rates over long periods.

Landfills experience large variations in gas generation and recovery rates.

The gas that is generated will either vent to the atmosphere or migrate underground. In either case, monitoring and control equipment must be used to detect and control air pollution or damage to structures or vegetation. In addition to being a hydrocarbon source and greenhouse gas, landfill gas entering the atmosphere will carry with it trace quantities of a large number of volatile organic compounds, some of which have known detrimental health effects. Landfill gas traveling underground may enter structures, where explosive concentrations may build up, or it may displace oxygen, causing a danger of asphyxiation. Landfill gas in the soil profile may damage the vegetation on the surface of the landfill or on the land surrounding the landfill.

Why Gas Control is Needed

Methane can quickly asphyxiate a person, and concentrations as low as 5 percent are explosive. Methane displaces oxygen from the root zone and kills vegetation. Landfill operators must receive adequate safety training, and gas monitoring equipment and other safety devices must be properly calibrated and maintained.

If methane accumulates in a building it poses a severe hazard. Methane can enter a building through cracks, construction joints, subsurface utility openings, or weak spots in the basement wall or building floor. Because it is lighter than air, methane tends to accumulate near the ceiling. If the source of methane cannot be immediately controlled, the building must be evacuated or a methane alarm system must be installed and the building must be continuously vented. Following are some of the basic safety rules for dealing with methane:

When working near methane gas, safety is crucial.

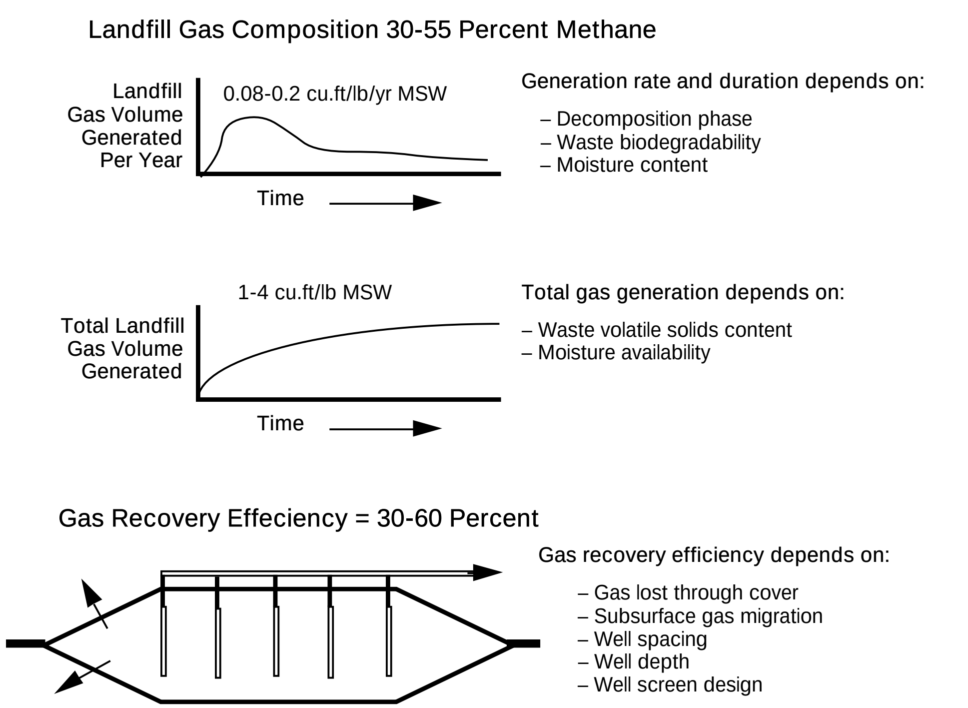
- Anyone entering a landfill vault or trench must check for methane gas, wear a safety harness, and have someone there to pull him or her to safety if needed.
- Anyone installing gas wells in a landfill must wear a safety rope to prevent falling into the borehole.
- Smoking must never be permitted while drilling or installing landfill gas wells or collection pipes, or when gas is venting.
- Gas collected from a mechanically evacuated system to minimize air pollution and reduce danger of explosion or fire must be flared.
- If it is suspected that methane gas has accumulated in a building, alert the fire department immediately. Most fire departments have equipment to detect methane and ventilate buildings.

The Mechanics of Gas Movement

Gas movement through refuse and soils is extremely complicated. The gas will tend to migrate from the landfill on a path through the refuse and surrounding soils that offers the least resistance. Gas will migrate farther through a highly permeable sand or gravel soil than it will through a less permeable

Figure 9-15

Factors Affecting Landfill Gas Generation and Recovery Rates



Source: P. O'Leary and P. Walsh, University of Wisconsin–Madison Solid and Hazardous Waste Education Center, reprinted from *Waste Age* Correspondence Course 1991-1992

silt or clay soil. The rate of migration will also be influenced by weather conditions. When barometric pressure is falling, gas will tend to be forced out of the landfill into the surrounding soil formations. Wet surface soil conditions and frozen ground may prevent gas from escaping into the atmosphere at the edge of the landfill; this may cause the gas to migrate even farther away from the landfill. Maximum migration distance of methane gas is difficult to predict. Migration distances greater than 1,000 feet have been observed.

Controlling Gas

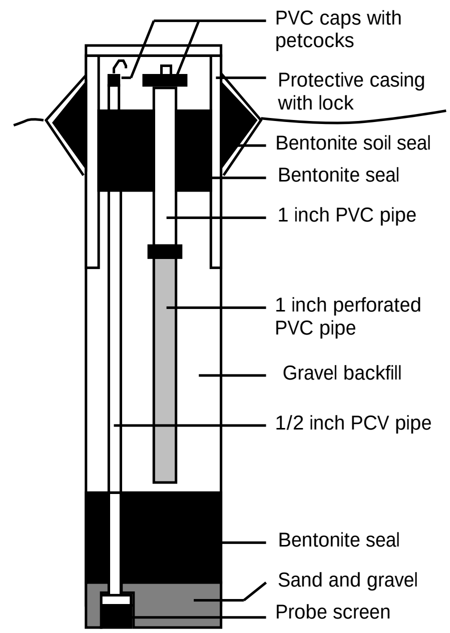
Controlling gas movement at a landfill begins with a study of the local soils, geology, and nearby area. For example, if the landfill is surrounded by a sand or gravel soil and if buildings are close to the landfill, the movement of gas into this area should be controlled by engineering methods. On the other hand, any landfill surrounded by clay may not require as stringent a control system. Note, however, that the clay cap installed at a completed landfill to exclude moisture infiltration and restrict leachate generation will, at the same time, tend to contain the landfill gas. The pressure gradient that results will force the gas to move laterally and into the areas surrounding the landfill. Even a narrow sand seam in a clay formation can transmit a large quantity of gas, especially if the gas cannot escape through the cover.

Gas Probes

Methane migration patterns and concentrations may change quickly.

Gas probes are used to detect the location and movement of methane gas in and around a landfill. A typical probe is shown in Figure 9-16. The probe is installed by boring a hole into the landfill or the ground around it. If off-site migration is a concern, the hole should extend at least 150 percent of the depth of the landfill, but not below the water table. A pipe with a perforated zone at the bottom is placed into the hole and the space between the original soil and pipe is filled with sand or gravel over the perforated portion. A bentonite slurry or other impermeable material is packed around the pipe above the perforated interval to the ground surface to prevent air leaking into the probe. At some sites, multilevel probes are installed to obtain a more accurate three-dimensional picture of gas movement.

Figure 9-16
Example of a Gas Monitoring Probe



Source: UW–Madison Solid and Hazardous Waste Education Center, reprinted from *Waste Age* Correspondence Course articles, 1991-1992

Two types of measurements are conducted. Gas pressure is measured with a gauge or manometer. Gas pressure gradients indicate landfill gas movement. The concentration of methane is also measured by using a calibrated meter on site or by taking samples for laboratory analysis.

Since the migration patterns and the methane concentrations change rapidly, frequent measurements are required to obtain an accurate picture of the gas migration pattern. At sites where there is much concern about gas migration endangering residences, daily measurements should be conducted until migration controls are put into place.

Gas Control Systems

Passive Gas Control Systems

Passive vents are sometimes used to control landfill gas migration. Passive systems rely on natural pressure and convection mechanisms to vent the landfill gas to the atmosphere. Figure 9-17 shows typical arrangements for gas venting. Recent research findings (Lofy, 1992) and field observations have confirmed that passive systems offer only limited protection. In areas where there is a significant risk of methane accumulating in buildings, passive systems may not be reliable enough to be the sole means of protection. Because of the unpredictability of gas movement in landfills, the use of passive venting is declining in modern landfill designs. Active systems are becoming more common.

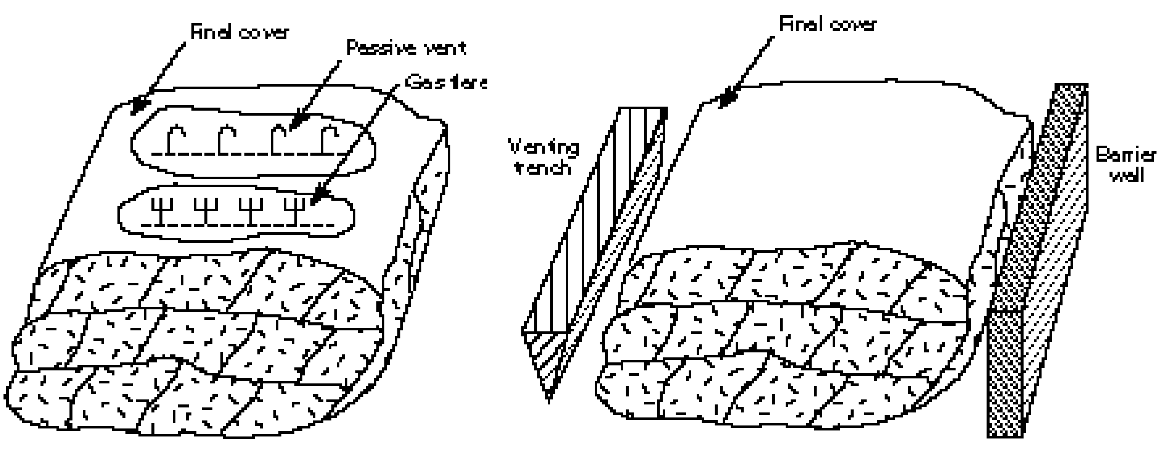
Active Gas Collection Systems

Active gas collection is more reliable than passive venting.

Active gas collection systems remove the landfill gas with a vacuum pump from the landfill or the surrounding soils. These systems may provide migration control or recover methane for use as energy. In both cases, gas recovery wells or trenches and vacuum pumps are employed. A pipe network is built to interconnect wells and blower equipment. When the primary purpose is migration control, recovery wells are constructed near the perimeter of the landfill. Depending on site conditions, the wells may be placed in the waste or in the surrounding soils, if they are reasonably permeable, as shown in Figure 9-18.

At landfills where the waste has been placed up to the property line, there may not be sufficient space to put wells and collection lines outside the waste. In such cases, interior wells, especially near the waste-soil boundary, are used.

Figure 9-17
Typical Arrangements for Passive Gas Venting



(Note: Passive vents provide limited protection. See text.)

Source: P. O'Leary and P. Walsh, University of Wisconsin–Madison Solid and Hazardous Waste Education Center, reprinted from *Waste Age* Correspondence Course 1991-1992

Borehole diameters for an active gas well are generally one to three feet. Larger diameter holes provide more surface area at the refuse-gravel interface, require less suction for gas removal, and are less prone to plugging. They are used if large amounts of gas are expected from each well, as in the case of gas recovery.

Collecting Gas for Beneficial Use

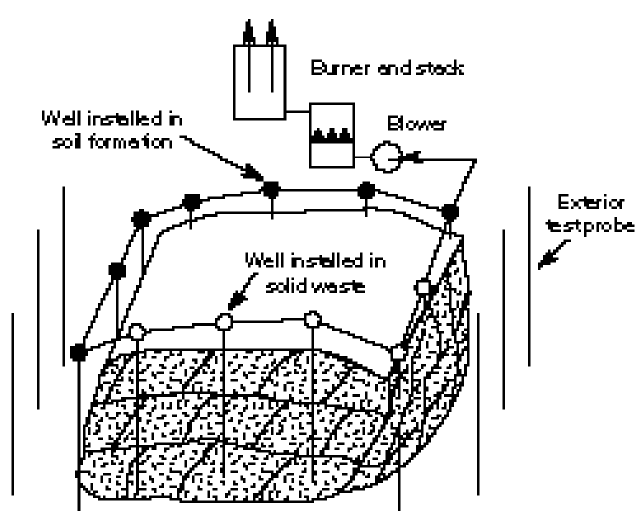
At some landfills, it is cost-effective to install gas recovery wells or trenches throughout the landfill and recover the gas for its energy value. In addition to the wells that may be constructed along the landfill's perimeter for migration control, wells or trenches may be placed in a grid pattern throughout the landfill to recover gas that might otherwise escape through the landfill cover. Depending on gas quality and user requirements, gas collected along the perimeter may be flared so as not to dilute the higher-quality gas typically collected from interior wells or trenches.

Wells are connected to a collection system that carries the gas to energy recovery equipment, as shown in Figure 9-19. Pipes connecting wells or trenches are called laterals or headers. The overall design must take settlement into consideration and should be sloped to drain gas condensate. The piping material must resist corrosion.

Collected landfill gas can be directly vented to the atmosphere in some locations, burned or flared, or directed to an energy recovery system. Venting is usually done through a stack, to provide atmospheric dispersion and to minimize the potential of odor problems. If odor problems or the presence of undesirable air contaminants justify it, the gas may be directed through a burner for combustion. If the methane concentration exceeds 15 percent and will support a flame, a supplemental fuel (such as natural gas) is not needed. This is important because supplemental fuel can greatly increase the operating cost of the landfill gas control system. When the methane gas concentration is greater than approximately 35 percent, it may be worthwhile to recover the energy from the gas. Landfill gas containing 47 percent methane has a heating value of 476 Btu / standard cubic foot; this compares to 1,030 Btu for natural gas.

Figure 9-18

Active Gas Control Systems



Source: P. O'Leary and P. Walsh, University of Wisconsin–Madison Solid and Hazardous Waste Education Center, reprinted from *Waste Age* Correspondence Course 1991-1992

Before constructing an energy recovery system, it is important to conduct tests to predict the quantity and quality of gas available. Testing is important because wide variations have been observed in gas generation rates and compositions. A pumping test is conducted by installing a gas recovery well and a number of monitoring probes in the landfill. The well is pumped until the gas flow stabilizes. Chemical characterizations of the gas are measured to determine methane content and the concentration of other chemicals; concurrently, the probes are monitored for pressure drop and methane content. The probes help define the volume of the landfill influenced by a well.

Methods of Energy Recovery

Landfill gas may contain sufficient methane to be an energy source.

The method of energy recovery depends primarily on the available energy markets. If a factory or large building is near the landfill, it may be practical to pipe the gas directly into a boiler at the facility. The landfill gas typically is passed through condensate knock-out tanks designed to remove liquid droplets by a baffle system and then injected into the furnace in combination with the regular boiler fuel, which may be coal, oil, or natural gas. A blower is needed to pull gas from the landfill and transport it at the desired pressure to the user. Using landfill gas as supplementary boiler fuel is possibly the simplest approach, but a suitable boiler is seldom available near a landfill. If the gas must be transported, the cost of a pipeline between the site and the boiler must be compared to the value of the gas.

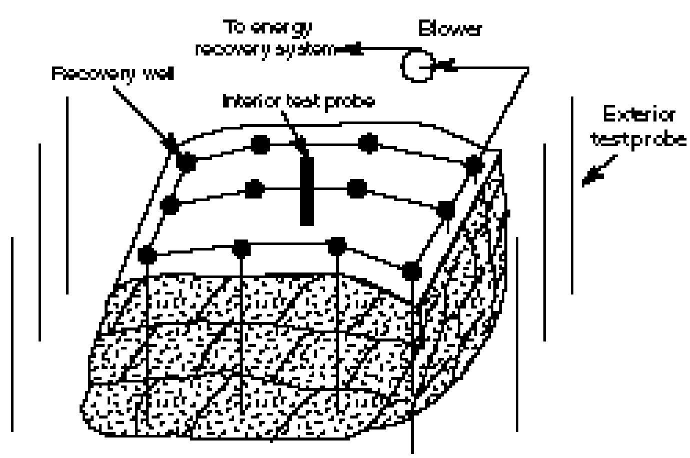
Electricity and pipeline quality gas can be produced from landfilling gas.

Often a boiler is not available as a feasible market for the methane gas. In this case, landfill gas can be directed to an engine / generator system for producing electricity. Almost all landfills have electrical service and the generated power can be used on site or sold to the electric grid. To produce electricity, the gas is compressed, dewatered, and possibly purged of particulates before it is used as a fuel in an internal combustion engine or a gas turbine.

Since the methane content of the gas will directly affect the performance of the engine or turbine, the site operator must closely regulate the gas collection system. The cost-effectiveness of generating electricity from landfill gas is limited by the price paid for the electricity by the utility and varies widely, depending on local power costs and generating capacity.

Figure 9-19

Gas Collection Systems with Wells



Source: P. O'Leary and P. Walsh, University of Wisconsin–Madison Solid and Hazardous Waste Education Center, reprinted from *Waste Age* Correspondence Course 1991-1992

Natural gas pipelines are located near many landfill sites. Several different methods including membranes, liquid solvent extraction, molecular sieves, and activated carbon adsorption, have been used to remove the carbon dioxide and other noncombustible constituents from methane landfill gas. The gas is thereby upgraded to pipeline quality and injected into the natural gas distribution network. The landfill operator is paid by the natural gas utility for the value of the methane. The market for such gas is generally excellent, but the cost of upgrading the gas to meet pipeline specifications presents problems. Generally, such gas treatment is feasible only with larger landfills. Operation problems and economic costs have limited the extent to which this option has been implemented.

As gas emission control becomes more common for environmental and regulatory reasons, gas use will also probably become more common even if the income, for example, from electricity sales, is too low to justify the project on a financial basis alone. Although the energy available from landfill gas represents a small fraction of the total energy usage in the area, it can be important because it is available locally and continuously. Electricity and natural gas pipeline production from existing landfill gas recovery systems can often supply the electrical needs for 5,000 to 20,000 homes.

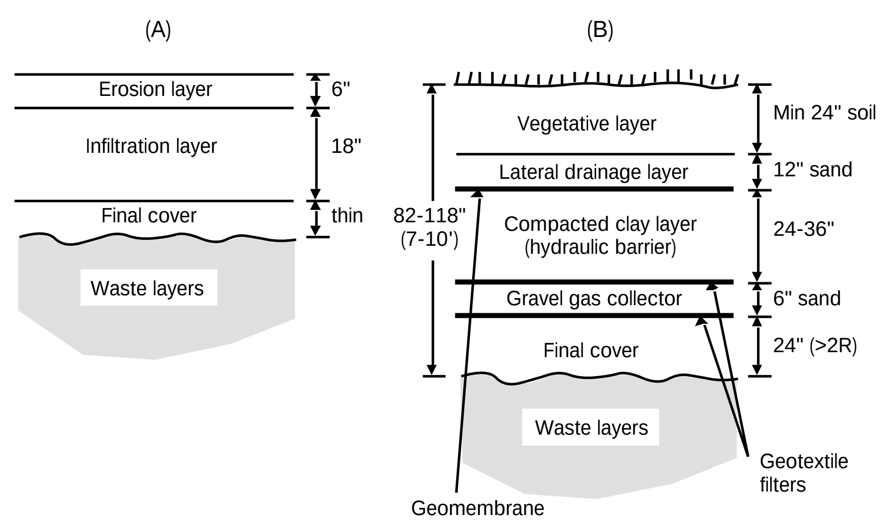
The USEPA has promulgated New Source Performance Standards and Emission Guidelines for landfills pursuant to mandates in the Clean Air Act. These rules will require landfills to collect landfill gas and prescribe design standards and performance limits for gas extraction systems.

Final Cover System

RCRA Subtitle D specifies the type of final landfill cover.

To close an MSW Landfill, RCRA Subtitle D requires that the final cover system be composed of an infiltration layer that is a minimum of 18 inches thick and overlain by an erosion layer that is a minimum of 6 inches thick, as shown in Figure 9-20, drawing A. This requirement is applicable for existing, new, or lateral expansions of existing landfills. Figure 9-20, drawing B, shows a cover with additional layers incorporated into its design to promote lateral drainage of infiltration and to provide a zone under the cover for gas movement.

Figure 9-20
Examples of Final Covers



Source: J. Spear, 1994

As with other design features, states may have additional requirements.

Over the long term, the infiltration layer should minimize liquid infiltration into the waste. The infiltration layer must have a hydraulic conductivity less than or equal to any bottom liner or natural subsoils present to prevent a "bathtub" effect. In no case can the infiltration layer have a hydraulic conductivity greater than 1 x 10^{-5} cm / sec regardless of the permeability of underlying liners or natural subsoils. To meet the infiltration layer performance standard at a landfill with a flexible membrane bottom liner, it is likely that the final cover will also need to incorporate a flexible membrane liner. As with other design features, the state may have additional requirements.

Design Considerations

Design criteria for a final cover system should be selected to do the following:

- minimize infiltration of precipitation into the waste
- promote good surface drainage
- resist erosion
- prevent slope failure
- restrict landfill gas migration or enhance recovery
- separate waste from vectors (animals and insects)
- improve aesthetics
- minimize long-term maintenance
- otherwise protect human health and the environment.

The cover system should be designed to provide the desired level of long-term performance with minimal maintenance.

Reduction of infiltration in a well-designed final cover system is achieved through good surface drainage and runoff with minimal erosion, transpiration of water by plants in the vegetative cover and root zone, and restriction of percolation through earthen material. The cover system should be designed to provide the desired level of long-term performance with minimal maintenance. Surface water runoff should be properly controlled to prevent excessive erosion and soil loss. The vegetative cover should not contain deeply rooted plants that could damage the underlying infiltration layer. In addition, the cover system should be stable geotechnically to prevent failure, for example, sliding that may occur between the erosion and infiltration layers, within these layers, or within the waste.

Erosion Control

When designing the final cover system, it is common to use the universal soil loss equation or a similar model to predict erosion and aid in design. This helps specify the interrelationships between vegetation, slope, soil used, and climatic conditions. To minimize major erosion and post-closure care problems, the maximum slope is typically 4:1 (4 parts horizontal to 1 part vertical); however, 5:1 is better. A slope of 3:1 is likely to lead to long-term maintenance problems, but it may be feasible in some areas if the site is well maintained and the slope is not too long. Diversion channels consisting of berms or swales are used approximately every 200 feet to intercept runoff before it has a chance to accumulate and cut erosion gullies. Down spouts should be used to convey runoff down long, steep slopes.

Vegetation

Selection of vegetation is important in ensuring long-term, maintenance-free operation of the cover. Good vegetation will improve erosion control through rapid growth and the formation of a complex root system. Vegetation commonly used includes vetches and fescues; however, it is a good idea to check with the local highway department for suggestions regarding vegetation for erosion control in the climate at hand. Table 9-10 describes recommendations for establishing vegetation on a landfill cover.

Other Design Considerations

In addition to the major issues of gas and leachate control and final cover, many other elements of landfill design require attention.

Roads

Each design element is important to the long-term success of the landfill.

Traffic control and roads are important. On-site routing of trucks to the working face should be planned to minimize waiting times at the site. A permanent road from the public road system to the site should be provided. The road should be 15 feet wide for small operations and 20 to 24 feet wide for larger landfills. Grades should not exceed 7 percent uphill and 10 percent downhill for loaded vehicles (Sittig, 1979).

Special working areas should be designated on the site plan for inclement weather or other contingency situations. Access roads to these areas should be of all-weather construction.

Table 9-10

Steps for Planting and Maintaining Vegetation on Landfills

1. Select an end use.
2. Determine depth of cover.
   Cover soil must be at least 60 cm deep for grass establishment and 90 cm for shrubs and deeper for trees.
3. Establish an erosion control program.
   The soil on recently covered landfills must be stabilized soon after spreading to prevent erosion.
4. Determine the soil nutrient status.
   Before or during the grass and ground cover experiments, soil tests should be made for pH, major nutrients (nitrogen, potassium, and phosphorus), conductivity, bulk density, and organic matter.
5. Determine soil bulk density.
   Cover soil is frequently compacted by landfill equipment during spreading operations to bulk densities that will severely restrict plant root growth.
6. Amend soil cover.
   The soil over the entire planting area should be amended with lime, fertilizer, and/or organic matter according to soils tests before planting. These materials should be incorporated into the top 15 cm of soil.
7. Select landfill-tolerant species.
   Grasses and other ground covers can be selected for planting in the soil cover by evaluating the results of the experimental plots established earlier to determine landfill-tolerant species.
8. Plant grass and ground covers.
   It is generally desirable to embed the seed in the soil. Mulches can be used as an alternative to embedding the seed but is less likely to be effective.
9. Develop the tree and shrub growth.
   Trees and shrubs should not be planted for 1 or 2 years after grass has been planted. If the grass cannot grow because of gases from the landfill, other deeper-rooted species are not likely to thrive either.

Source: Adapted from Gilman, et al., *Standardized Procedures for Planting Vegetation on Completed Sanitary Landfills,* 1983

Hauling routes to the site should use major highways as much as possible. Potential routes should be studied to determine the physical adequacy of roadways for truck traffic, as the landfill may cause a significant increase in truck traffic on nearby roads. Local authorities may require that the roads be improved to handle the higher traffic counts and heavier vehicles.

Storm Water Drainage

RCRA Subtitle D further specifies run-on and runoff controls for controlling drainage into and out of the landfill working face.

Runoff from rainfall and snow melt must be planned for by developing drainage channels within the site. Sloped areas within the landfill will cause larger volumes and higher peak runoff flows from the site than would occur naturally. The runoff should be directed into channels that are capable of carrying most storm loads without overflowing or flooding adjacent areas. Generally, drainage structures are designed for 25-year storms. RCRA Subtitle D further specifies run-on and runoff controls for controlling drainage into and out of the landfill working face.

To minimize siltation problems downstream, a detention basin should be considered. Runoff directed into the basin is released at a slow rate after most sediment has settled to the bottom of the basin. This arrangement also provides an opportunity to test runoff water for chemical contamination before it is discharged to a stream or lake.

Utilities

The landfill will need electrical service for buildings, pumps, and blowers. A source of water for the employees must be provided for sanitary and possibly shower facilities. If a public water supply utility is located nearby, a supply line can be connected to the service building. A water supply well can be drilled in rural areas, but regulations may specify a setback distance between a landfill and a well; in such cases, the well may be located far away from the service building.

Scales

Most large landfills are equipped with scales for weighing incoming loads. Charges to users can be prepared from the weight records. The filling rate and compaction density can be more accurately monitored with scales than with truck counts and gate volume estimates.

A building will be needed for a scale attendant. Note that although the weighing system can be fully automated, a full-time attendant is needed to monitor waste sources. The service building for equipment maintenance and for employee headquarters may also be at this location.

Regulatory Approvals

Achieving regulatory approval is the culmination of a long-term effort that begins early in the development process. Chapter 1, on public education, and Chapter 2, on siting, should be consulted for suggested approaches to facilitate public participation. Projects lacking public review or input until the design is completed may face substantial delays in the approval process. The final task in developing the plan is to obtain approval from regulatory agencies. The designer should maintain a close liaison with regulatory people throughout the design process to ensure compliance with regulatory standards.

Several different agencies usually must issue approvals.

After submitting applications and plans, the agency reviewing the proposal may have additional questions to be answered by the developer. Additional permits may be needed from local agencies, state agencies other than the one dealing specifically with landfills, and federal agencies, such as the U.S. Army Corps of Engineers and the U.S. Fish and Wildlife Service.

Many states have a requirement mandating preparation of an environmental impact statement. The purpose of the environmental impact statement is to disclose the nature of the proposed project, assess current and possible future environmental conditions, and to describe alternatives to the proposed action.

OPERATING THE LANDFILL

Documented operating procedures can be crucial if questions arise in the future regarding the adequacy of site construction.

The landfill operational plan should serve as the primary resource document for operating the site. It shows the technical details of the landfill and the procedures for constructing the various engineered elements.

Since a landfill is constructed and operated over a number of years, it is important that personnel periodically review the plan and refresh their memories to ensure conformance with the plan over the long term. If operating procedures must be modified, the changes must be noted so that an accurate record is maintained. Documented operating procedures can be crucial if questions arise in the future regarding the adequacy of site construction.

After receiving the required approvals for the site design, preparation and construction of the site can begin. Table 9-11 provides site preparation and construction tips.

Table 9-11

Site Preparation and Construction Steps

1. Clear site.
2. Remove and stockpile topsoil.
3. Construct berms.
4. Install drainage improvements.
5. Excavate fill areas.
6. Stockpile daily cover materials.
7. Install environmental protection facilities (as needed).
   - landfill liner with leachate collection system
   - groundwater monitoring system
   - gas control equipment
   - gas monitoring equipment
8. Prepare access roads.
9. Construct support facilities.
   - service building
   - employee facilities
   - weigh scale
   - fueling facilities
10. Install utilities.
    - electricity
    - water
    - sewage
    - telephone
11. Construct fencing.
    - perimeter
    - entrance
    - gate and entrance sign
    - litter control
12. Prepare construction documents. (continuously during construction)

Source: P. O'Leary and P. Walsh, University of Wisconsin–Madison Solid and Hazardous Waste Education Center, reprinted from *Waste Age* Correspondence Course 1991-1992

Providing Financial Assurance

Before opening a landfill, the owner and operator must provide financial assurance for closure and 30-year post-closure care. Refer to the section later in this chapter on financial assurance for more detailed information.

Program to Detect and Exclude Hazardous Waste

The owner or operator is required to implement a program to detect and exclude regulated hazardous wastes and PCBs from disposal in the landfill. This program must include the following elements:

- performing random inspections of incoming loads or other prevention methods

- maintaining inspection records
- training facility personnel
- notifying appropriate authorities if hazardous wastes or PCB wastes are detected.

Inspections

Random inspections of incoming loads are required.

An inspection is typically a visual observation of the incoming waste loads by an individual who is trained and qualified to identify regulated quantities of hazardous waste or PCB wastes that would not be acceptable for disposal at an MSW landfill. An inspection is considered satisfactory if the inspector knows the nature of all materials received in the load and is able to discern whether the materials are potentially regulated hazardous wastes.

Random inspections provide a reasonable means to adequately control the receipt of inappropriate wastes. The frequency of random inspections may be based on the type and quantity of wastes received daily, and the accuracy and confidence desired in conclusions drawn from inspection observations. Since statistical parameters are not provided in the regulation, a reasoned, knowledge-based approach may be taken. A random inspection program may take many forms, such as inspecting every incoming load one day out of every month or inspecting one or more loads from transporters of wastes of unidentifiable nature each day.

Inspection frequency also can vary depending on the nature of the waste. For example, wastes received exclusively from commercial or industrial sources may require more frequent inspections than wastes collected exclusively from households. Priority can also be given to inspecting haulers with unknown service areas, to loads brought to the facility in vehicles not typically used for disposal of municipal solid waste, and loads transported by known previous offenders.

To provide the facility owner or operator the opportunity to refuse or accept wastes, loads should be inspected before actual disposal of the waste at the working face of the landfill. Inspections can be conducted on a tipping floor of a transfer station before transferring the waste to the disposal facility. Inspections may also occur at a tipping floor located near the facility scale house, inside the site entrance, or near, or adjacent to, the working face of the landfill.

Alternative Methods for Detection and Prevention

While the regulations explicitly refer to inspections as an acceptable means of detecting regulated hazardous wastes and PCB wastes, preventing the disposal of these wastes may be accomplished through other methods. These methods may include receipt of household wastes and processed (shredded or baled) wastes that are screened for the presence of the excluded wastes before processing.

Cover Material Requirements

RCRA Subtitle D standards require the owner or operator to cover solid waste with six inches of an earthen material at the end of each operating day.

RCRA Subtitle D standards require the owner or operator to cover solid waste with six inches of an earthen material at the end of each operating day. Six inches of cover will prevent exposing the waste to birds, insects, and rodents, which represent the principal transmission pathways of human disease. Cover material also reduces the exposure of combustible materials to ignition sources, reduces odors, and controls blowing litter. Removing the waste from sight also reduces scavenging. The use of alternative material of alternative thicknesses for daily cover may be allowed in certain jurisdictions.

Air Criteria

RCRA Subtitle D standards prohibit routine open burning of solid wastes. Infrequent burning of agricultural and silvicultural waste, diseased trees, or debris from land clearing or emergency cleanup operations is allowed subject to state and federal air pollution control regulations. Any burning area should be far enough from the landfill to avoid burning other solid waste.

The USEPA has promulgated New Source Performance Standards and Emission Guidelines for landfills pursuant to mandates in the Clean Air Act. These rules will require landfills to collect landfill gas and prescribe design standards and performance limits for gas extraction systems.

Access Control

Public access to landfills must be controlled by use of artificial barriers, natural barriers, or both to prevent unauthorized vehicular traffic and illegal dumping of wastes. These barriers can include fences, ditches, berms, trees, etc. Access should be controlled by gates that can be locked when the site is unsupervised.

Run-on and Runoff Control Systems

Site drainage is always critical in a good sanitary landfill design.

Site drainage is always critical in a good sanitary landfill design. As much water as possible should be diverted off the landfill to minimize operational problems and the formation of leachate.

Landfill operators are required to have a run-on control system to prevent flow onto the active portion of the landfill during the peak discharge from a 25-year storm event. The goal of the run-on system is to collect and redirect surface waters entering the landfill boundaries.

A runoff control system from the active portion of the landfill must be able to control at least the volume of water that results from a 24-hour, 25-year storm. The runoff control system should be designed to collect and control any water that may have contacted any waste materials. The runoff must be managed in compliance with the point and nonpoint source requirements of the Clean Water Act.

Small Vehicles and Safety

Many landfill operators find that allowing public access at the disposal face interferes with site operation and can lead to unsafe conditions. Separate waste collection facilities such as 40-cubic-yard containers can be located near the site entrance for private citizens. Such facilities provide disposal service to the public, while eliminating possible interference with operations. On a regular basis, the area should be inspected and litter picked up to prevent unsightly conditions.

Additional Controls

Good housekeeping procedures are necessary for landfill operations. RCRA Subtitle D requirements and many state regulations mandate controls on operation. For details regarding the regulations, see 40 CFR Part 258 and the appropriate state regulations. A well-planned and maintained landfill effectively controls for the following:

- **Aesthetics:** Although making the site pleasing to look at is cosmetic, it is not frivolous. Addressing aesthetic concerns may include using fences, berms, plantings, or other landscaping to screen the landfill's daily operations from roads or nearby residents, and providing an attractive entrance with good roads and easy-to-read signs.
- **Wind-Blown Paper:** On-site litter control is accomplished by using fences to stop blowing paper and plastic. Frequent manual or mechanical litter pick up is also needed.
- **Insects:** Flies and mosquitoes are the most common insects of concern to neighbors. They are best controlled by covering the solid waste daily

and eliminating any open standing water, such as in appliances stored for recycling or in surface depressions.

- **Rodents and Wildlife:** Rats were once a problem at open dumps, but at sanitary landfills, burying all food wastes with daily cover material usually eliminates rat problems.
- **Birds:** Birds can be a nuisance or even cause problems with planes if the landfill is near an airport. Federal Aviation Administration (FAA) should be notified if the landfill is within five miles of an airport runway used by jet aircraft. Methods to discourage birds include use of noise makers, wire grids, and liberal use of cover soil. The best approach is to keep the working face small and to provide adequate cover.

The landfill operator must be trained and equipped to handle a wide variety of conditions and situations.

- **Odors and Fires:** Odors are best controlled by daily cover, as well as by adequate compaction. Daily cover also forms cells that reduce the ability of inadvertent fires to spread throughout the landfill. Any burning or smoking waste should be dumped off to the side and extinguished before placing it in the working face. Fire-fighting equipment and an emergency water supply should be available on site or arranged for with local authorities.
- **Noise:** Equipment should be operated behind berms, which shield the surrounding area from noise as much as possible. Access should be designed to minimize the impact that landfill site traffic has on nearby neighborhoods.
- **Dust and Tracking:** Roads should be watered in dry periods to keep dust to a minimum. Roads should be crowned and well-drained to minimize mud tracking. Adequate wheel-cleaning and mud knock-off areas should be provided. Entrance roads should be paved or have all-weather surface concrete or asphalt to keep mud tracking on-site and should be cleaned whenever a mud buildup occurs.
- **Scavenging:** While recycling at a landfill may be desirable, scavenging (or uncontrolled picking through waste to recover useful items) is not desirable. Because scavengers have been injured, sometimes fatally, while picking through the wastes, the practice should be prohibited. Salvaging, which is the controlled separation of recoverable items, should be distinguished from scavenging. Any salvage operations should be kept away from the landfill, usually at the gate area, and residues should not be allowed to accumulate.
- **Gas and Leachate:** Particularly important to the protection of public health and the environment is the control of gas generated by the decomposition of solid wastes, and of leachates that form as water migrates through the solid wastes. Because of their importance, methods to control both gas and leachate were considered in earlier sections of this chapter.

Landfill Equipment

Equipment at sanitary landfills falls into three functional categories: waste movement and compaction, earth cover transport and compaction, and support functions. Selection of type, size, quantity, and combination of machines required to move, spread, compact, and cover waste depend on the following factors (ASCE, 1976):

- amount and type of waste to be handled
- amount and type of soil cover to be handled
- the distance the cover material must be transported
- weather conditions
- compaction requirements

- site and soil conditions: topography, soil moisture, and difficulty of excavation
- supplemental tasks such as maintaining roads, assisting in vehicle unloading, and moving other materials and equipment around the site.

Many factors must be considered when selecting landfilling equipment.

The amount of waste is the major variable influencing the selection of an appropriate-size machine. Table 9-12 shows equipment needs. Heavier equipment provides more compaction, all else being equal, but also provides more flexibility in handling and compacting a variety of materials using thicker compaction lifts. The condition in which the waste is received may affect choice of equipment. For example, landfills accepting only shredded wastes are operated much like landfills handling unprocessed wastes, although there may be less need for daily soil cover, and it will be easier to compact the waste. For landfills handling baled waste, the bales are often moved with forklifts and no compaction equipment is needed.

Table 9-12

Equipment Needs by Daily Tonnage

Approximate Population	Daily Wastes Tons	Equipment Number	Equipment Type	Equipment weight, lbs	Accessory[a]
0-20,000	0-50	1	Tractor, crawler	10,000-30,000	Dozer blade Front-end loader (1-2 cu/yd) Trash blade
20,000-50,000	50-150	1	Tractor, crawler	30,000-60,000	Dozer blade Front-end loader (2-4 cu/yd) 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 (2-5 cu/yd) 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 (2-5 cu/yd) 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.

Source: G. Tchobanoglous, *Integrated Solid Waste Management: Engineering Principles and Management Issues, 1993*

The degree of compaction is critical to extending the useful lifetime of a landfill. For achieving high, in-place waste densities, a compactor may be necessary. A minimum in-place compaction density of 1,000 pounds per cubic yard is recommended. The number of passes that the machine should make over the wastes to achieve optimum compaction depends upon machine wheel pressure, waste compressibility, and compaction layer thickness. In general, three to five passes are recommended to achieve optimum in-place waste densities, as shown in Figure 9-21. Although additional passes will compact the waste to a greater extent, the return on the effort diminishes beyond six passes.

Figure 9-21 also shows the relationship between the waste layer thickness for compaction and the compacted waste density found in a field test for a particular type of machine and operating procedure. Each landfill will have different results, but the shape of the curves will be similar. Note the rapid decrease in density above a compacted layer thickness of about 1-1/2 feet. Thus, the best solid waste compaction results from compacting the waste in layers one to two feet thick.

The working face slope will affect the degree of compaction achieved. As the slope increases, vertical compaction pressure decreases. The highest degree of compaction is achieved with the least slope. However, the feasibility of a nearly flat working face grade has to be weighed against the larger area over which the solid wastes and cover soil must be spread.

Waste Handling and Compaction

There are several factors to consider when making decisions about waste handling and compaction, shredding and baling of wastes, and the types of equipment used for compacting the wastes.

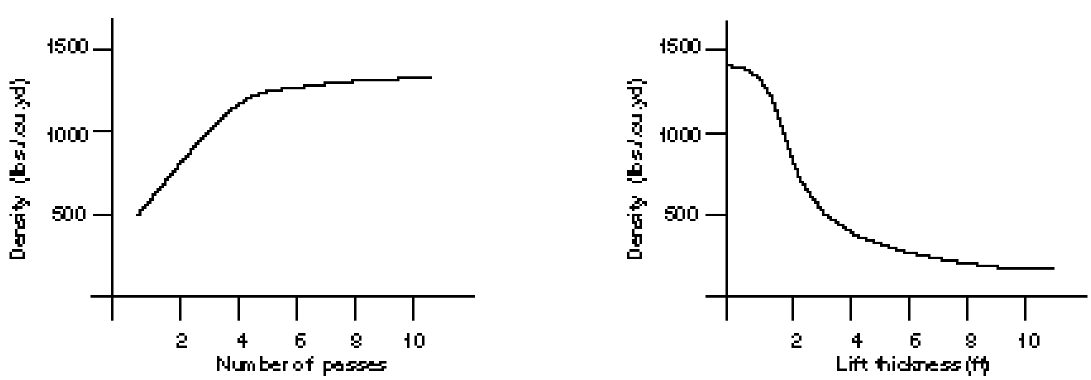
Shredding and baling are options for processing waste before it is landfilled.

Waste Shredding

In shredding of solid waste, incoming refuse is mechanically processed into small uniformly sized pieces. Shredding can take place immediately before landfilling or it can be done at a transfer facility prior to transport. While shredding may be undertaken as the sole processing technique used before disposal, it also can be one step in a process that includes the mechanical separation and removal of recyclable or reusable materials from the waste stream.

After compaction, shredded refuse has a greater density than compacted, unprocessed MSW. This can result in preserving landfill space and reducing

Figure 9-21
Waste Densities



Source: P. O'Leary and P. Walsh, University of Wisconsin–Madison Solid and Hazardous Waste Education Center, reprinted from *Waste Age* Correspondence Course 1991-1992

the amount of required cover material. In addition, landfill settlement and stabilization may be more uniform over time in the landfilled area. These benefits must be compared with the significant capital and operating costs of the shredding equipment, the space required to process the waste, and the historically significant potential for worker injury and equipment downtime caused by explosions from crushing compressed gas containers and by the ignition of explosive gases by sparking metal.

The benefits of waste shredding must be evaluated with several other factors in mind.

Baling Solid Waste

The baling of municipal solid waste involves the compaction of refuse into high-density blocks that are stacked and covered with cover material in a landfill. Depending on the equipment used, the bales can have a density between 1,000 to 1,900 pounds per cubic yard. In certain circumstances, baling municipal solid waste before disposal may result in landfill space savings as a result of increased compaction density and reduced cover material requirements. Baling wastes can also reduce the amount of blowing litter.

Landfill Handling and Compaction Equipment

Steel-wheeled compactors are designed specifically for compacting solid wastes. Wheels are studded with load concentrators of various designs. This equipment gives maximum compaction of solid wastes. Steel-wheeled compactors are best suited to medium or large sanitary landfills, which can support more than one machine, since these units are suitable only for compaction work.

Track-type tractors or dozers may be used for handling and compacting waste, as well as for cover excavation and compaction. Such units can also be used for site preparation, road construction, and maintenance. These are the most versatile units and are preferred for small operations in which one unit must perform a variety of functions.

Earth Movers

Rubber-tired loaders or dozers provide more speed and maneuverability than track-type units and can haul cover efficiently and apply it up to approximately 1,000 feet from the working face. Rubber-tired scrapers are efficient for excavating and transporting soil for cover when it is more than 1,000 feet from the working face. Where the soil is hard to excavate (e.g., clay or frozen soil), scrapers can be pushed with a bulldozer.

Draglines are also efficient earth movers but are only able to deposit soil within the area reached by the boom and are not suitable for transporting cover material. Backhoes are well suited for small, specialized excavation at the landfill, such as for a leachate collection system. Dump trucks can be used at landfills in conjunction with excavation equipment for moving cover material. Motor graders are useful for road construction and maintenance, for construction of berms and drainage ways, and for landscaping.

Equipment Maintenance and Backup

Proper maintenance of landfill equipment is important.

Equipment maintenance is clearly an important task. Regular maintenance reduces breakdowns and identifies equipment problems early, before more costly and time-consuming repairs are needed. Provision must also be made for backup equipment, perhaps by keeping additional equipment available.

Adverse Weather

Wet weather problems are especially serious with soils that have a high silt or clay content. When wet, these soils usually become muddy and slippery. Provision should be made to continue operating areas less susceptible to such problems. Procedures to minimize and clean mud tracking on roads are especially important during wet weather.

Cold weather brings many problems in starting and operating machinery, keeping employees comfortable, and obtaining cover material. Equipment manufacturers can offer recommendations for cold weather starting and operation, and excavation of well-drained and stockpiled cover soil can improve cold weather operations.

Windy conditions can require the use of extra or specially placed fencing and use of a lower or more protected working face. Unloading wastes at the bottom of the working face can help because the wind cannot pick up materials as easily as when wastes are deposited at the top of the working face.

Fencing and the area downwind of the working face should be cleaned at least daily.

In addition to fencing at the perimeter of the active area, portable fences are often used to catch litter immediately downwind of the working face. Fencing and the area downwind of the working face should be cleaned at least daily.

Dust can be a nuisance at landfills, both to employees and to neighbors. Water wagons can be used to control dust. Calcium chloride is also used for dust control, because it absorbs moisture from the air.

Personnel and Safety

To maintain an efficient landfill operation, employees must be carefully selected, trained, and supervised. Proper landfill operation depends on good employees. Along with equipment operators, other necessary employees may include maintenance personnel, a scale operator, laborers, and a supervisor. People will also be needed to keep financial and operating records. Good employee training and supervision must include attention to safety. Operating a landfill presents many challenges; accidents are expensive and have hidden costs often several times the readily apparent costs.

Solid waste personnel work in all types of weather, with many types of heavy equipment, with a variety of materials presenting diverse hazards, and in many different types of settings. The types of accidents possible at landfills include injury from explosion or fire, inhalation of contaminants and dust, asphyxiation from poorly vented leachate collection system manholes or tanks, falls from vehicles, injury associated with operating heavy earth-moving equipment, injury from attempting to repair equipment while engines are operating, exposure to extreme cold or heat, and traffic accidents at or near the site.

Safety guidelines specific to the operation of landfill equipment are shown in Table 9-13. Educational films and written material on safety at the landfill are available from the federal government and from equipment manufacturers. Assistance in setting up a safety program is available from insurance companies with worker's compensation programs, the National Safety Council, safety consultants, and federal and state safety programs.

Table 9-13

Safety Suggestions for Sanitary Landfill Equipment Operators

- Check equipment before starting.
- Use steps and hand holds.
- Keep steps clean.
- Inspect area before moving.
- Operate from driver's seat.
- Wear seat belts.
- Never mount moving equipment.
- Authorized passengers only.
- Keep bucket or blade low.
- Check blind areas.
- Keep enough clearance.
- Avoid side-of-hill travel.
- Avoid excessive speed.
- Do not crush sealed containers.
- Go carefully over bulky items.
- Check work area.
- Park on level ground.
- Lower attachments to ground when parked.
- Never jump from equipment.
- Avoid leaving equipment unattended.
- Always have adequate lighting.
- Clean equipment before repairing.
- Remain in seat during equipment adjustments.

Source: P. O'Leary and P. Walsh, University of Wisconsin–Madison Solid and Hazardous Waste Education Center, reprinted from *Waste Age* Correspondence Course 1991-1992

Quality Control and Record Keeping

During all construction, a quality control program should be followed to ensure the landfill conforms to the design and operating plans. An inspector should be on site to approve construction work as each structure or construction sequence is completed. Compliance with specifications should be checked by soil tests before waste is placed over the liner. Grades and elevations can be measured with surveying equipment to document the as-built features of the landfill.

RCRA Subtitle D requirements and many state regulations establish record-keeping requirements.

RCRA Subtitle D requirements and many state regulations establish record-keeping requirements. For details regarding the regulations, see 40 CFR Part 258 and the appropriate state regulations.

Operational records that should be maintained include waste quantity by tons or, preferably, by volume (since landfill capacity is by volume), cover material used and available, equipment operation and maintenance statistics, and environmental monitoring data. Data on waste loadings will allow the site operator to predict the useful, remaining site life; any special equipment that may be needed; or personnel requirements. Financial records are also crucial for maintaining sound operations. To ensure and document adherence to the design and operating plans, many sites now have engineers or certification personnel always on hand, or at least during major construction and periodically thereafter.

Community Relations

An important and often overlooked aspect of landfill operation is sustaining good community relations. The landfill manager must maintain a dialog with neighbors, municipal leaders, community activists, and state governmental representatives in an effort to build trust through honest communications. While community relations activities do not guarantee continued support for the landfilling operation, poor relations almost certainly will result in complaints and problems.

CLOSING THE LANDFILL AND PROVIDING POST-CLOSURE CARE

The landfill must be closed in accordance with an approved closure plan. The goal of closure and post-closure care is to ensure the long-term protection of human health and the environment. The owner or operator must close the landfill in a manner that will minimize the need for maintenance and will be protective of human health and the environment.

Financial Assurance for Closure and Post-Closure Care

Federal standards require that landfill owners and operators, including municipalities that operate landfills, have financial assurances in place to cover the costs of closure and post-closure. Financial assurance is also required when corrective action is necessary to clean up releases of hazardous constituents to groundwater. Several mechanisms are allowed, including trust funds, surety bonds, letters of credit, insurance, a state / tribal approved mechanism, state / tribal assumption of responsibility, and use of multiple mechanisms. USEPA will issue a rule that would allow a local government financial test.

Design and operating procedures affect the cost estimates for financial assurance.

The closure and post-closure cost estimates used to determine the amount of coverage required must be based on the cost of closing the landfill at the point of the landfill's active life when the extent and manner of its operation would make closure and post-closure care the most expensive. Furthermore, cost estimates must reflect the costs that a third party would incur in conducting the closure and post-closure activities. The closure and post-closure cost estimates must be updated yearly to account for inflation and updated whenever changes to the closure and post-closure plans or changes at the facility increase the cost of closure and post-closure. Whenever the cost estimates increase, the owner or operator must increase the level of financial assurance provided. Critical technical issues that must be faced by the designer include the following:

- the degree and rate of post-closure settlement and stresses imposed on soil liner components
- the long-term durability and survivability of cover system
- the long-term waste decomposition and management of landfill leachate and gases
- the environmental performance of the combined bottom liner and final cover system.

Procedures for Site Closure

The primary objectives of landfill closure are to establish low-maintenance cover systems and to design a final cover that minimizes the infiltration of precipitation into the waste. Installation of the final cover must be completed within six months of the last receipt of wastes.

Long-term maintenance and post-closure costs are important considerations when closing a site.

The procedures for placing the cover over the landfill are usually defined during site design. If no cover design is available, specifications must be prepared. See the section in this chapter on cover design for more information. Table 9-14 shows the procedures to follow when either the entire landfill or a phase of it has been filled to capacity. Phased closure is recommended. Construction techniques ensuring that quality closure is achieved, especially with regard to final cover and vegetation, will minimize long-term upkeep problems. After cover placement, the area should be immediately planted with vegetation to prevent erosion.

Table 9-14

Procedures for Site Closure

Preplanning:

- Identify final site topographic plan.
- Prepare site drainage plan.
- Prepare vegetative cover and landscaping plan.
- Identify closing sequence for phased operations.
- Specify engineering procedures for the development of on-site structures.

Three Months Before Closure:

- Review closure plan for completeness.
- Schedule closing date.
- Prepare final timetable for closing procedures.
- Notify appropriate regulatory agencies.
- Notify site users by letter if they are municipalities or contract haulers; by published announcements if private dumping is allowed.

At Closure:

- Erect fences or appropriate structures to limit access.
- Post signs indicating site closure and alternative disposal sites.
- Collect any litter or debris and place in final cell for covering.
- Place cover over any exposed waste.

Three Months After Closure:

- Complete needed drainage control features or structures.
- Complete, as required, gas collection or venting systems, leachate containment facilities, and gas or groundwater monitoring devices.
- Install settlement plates or other devices for detecting subsidence.
- Place required thickness of earth cover over landfill.
- Establish vegetative cover.

Source: P. O'Leary and P. Walsh, University of Wisconsin–Madison Solid and Hazardous Waste Education Center, reprinted from *Waste Age* Correspondence Course articles, 1991-1992

Post-Closure Care

Post-closure care of the landfill begins upon completion of the closure process. The post-closure care period can be 30 years, but some jurisdictions can choose to shorten or lengthen the post-closure care period. During this period the landfill owner is responsible for providing for the general upkeep of the landfill, maintaining all of the landfill's environmental protection features, operating monitoring equipment, remediating groundwater should it become contaminated, and controlling landfill gas migration or emissions.

General Upkeep

A closed landfill requires long-term maintenance.

After closure, the landfill site will appear inactive, but biological activity in the landfill will continue. As a result, the landfill cover continues to settle as the waste consolidates. Poorly compacted waste will settle the most. Settlement will cause depressions in the cover and stresses on the cover. The depressions need to be filled with cover soil to limit infiltration through the top of the landfill. Where flexible membranes are part of the cover, extensive repair work may be needed if the settlement results in the membrane tearing. A few years after closure, the settlement rate will slow, necessitating less repair work of this type.

The vegetative cover on the landfill must also be maintained. In the long run weeds and areas of dead vegetation will result in damage to the landfill cover. The grass cover should be mowed periodically. The frequency will depend on local conditions. Reseeding areas where the vegetative cover has died is also necessary. Failure to reseed may result in excessive erosion and damage to the cover.

Road and Drainage Structure Repairs

Settlement may affect the access roads, which must be maintained so equipment can reach monitoring points on the landfill without damaging the cover. Access roads may also experience settlement and erosion problems. Periodically, the access roads should be regraded and repaired in order to maintain their long-term usefulness.

Drainage patterns on the landfill may change as settlement occurs. Channels, culverts, and risers must be annually inspected to determine their condition. Repair work should be done each year where drainage patterns have changed or erosion has damaged the structures.

Periodic monitoring and reporting will be necessary if the discharge is regulated under a National Pollutant Discharge Elimination Permit (NPDES).

Surface waters released from the closed landfill site must be properly managed. Any detention basin constructed to control peak runoff rates and sediment flow must be maintained. This may include the need to dredge the sedimentation basin. Periodic monitoring and reporting will be necessary if the discharge is regulated under a National Pollutant Discharge Elimination Permit (NPDES).

Leachate Treatment

Leachate will continue to be generated after the landfill is closed. The quantity should diminish if a good cover was placed over the landfill. Providing cover maintenance will also reduce leachate generation. The chemical composition will also change as the landfill becomes more biologically stabilized with pollutant concentrations slowly diminishing. Leachate collection and treatment generally will be necessary throughout the entire post-closure care period. Pumps and other leachate collection equipment must be operated and serviced. Every few years, leachate lines must be cleaned with sewer cleaning equipment. On-site leachate treatment facilities must be maintained and operated. Where leachate is transported off-site, arrangements for trucking and treatment must be continued.

Groundwater Quality Monitoring

Groundwater and landfill gas monitoring must continue after a landfill is closed.

The groundwater under the landfill must be monitored during the post-closure care period. If contamination is detected, RCRA Subtitle D specifies a procedure for more intensive monitoring and corrective action. The extent of groundwater contamination must be determined. Plans must be prepared and approved for the corrective action. Following implementation of the corrective action, less frequent monitoring can resume if groundwater quality improves to within specified limits.

Landfill Gas Monitoring

The management of landfill gas was described in a previous section. The operation of landfill gas control and monitoring systems will need to continue for many years after the landfill closes. Failure to operate and maintain the system may result in damage to the vegetative cover of the landfill and off-site migration of landfill gas. RCRA Subtitle D requirements specify that gas monitoring probes around the landfill be tested on a quarterly basis each year. Where landfill gas migration is detected near occupied structures, more frequent monitoring is recommended. If regulatory standards for migration are exceeded, improved migration control and landfill gas recovery facilities may be necessary. At sites that do not have control systems, the landfill may need to be retrofitted for gas control. See the landfill gas section in this chapter for more information.

REFERENCES

Brunner, D. R. and D. J. Keller, 1972, *Sanitary Landfill Design and Operation*. USEPA. SW-65ts.

Conrad, et al. 1981. *Solid Waste Landfill Design and Operation Practices.* USEPA Draft Report Contract.

Ehrig, H. J. 1989. "Water and Element Balances of Landfills," in *Lecture Notes in Earth Sciences: The Landfill*.

Farquhar, G. J. and F. A. Rovers. 1973. "Gas Production During Refuse Decomposition," *Water, Air, and Soil Pollution*, Vol. 2.

Fenn, D. G., K. J. Hanley, and T. V. DeGeare. 1975. *The Use of the Water Balance Method for Predicting Leachate Generation from Solid Waste Disposal Sites*. USEPA.

Gilman, E. F. , Franklin B. Flower, and I. A. Leone. 1983. *Standardized Procedures for Planting Vegetation on Completed Sanitary Landfills.* USEPA. EPA-600/S2-83-055.

Ham, R. 1979. *Recovery Processing and Utilization of Gas from Sanitary Landfills*. USEPA.

Lane, W. N. and R. R. McDonald. 1981. "Land Suitability Analysis for Sanitary Landfill Siting." *Proceedings, Fourth Annual Madison Conference of Applied Research and Practice on Municipal and Industrial Waste.* University of Wisconsin–Madison Extension.

Stanforth, R., R. Ham, M. Anderson and R. Stegmann. 1979. "Development of a Synthetic Municipal Landfill Leachate," *Journal of the Water Pollution Control Federation*, Vol. 51.

Tchobanoglous, G.; H. Theisen; and S. Vigil. 1993. *Integrated Solid Waste Management: Engineering Principles and Management Issues.* NY: McGraw-Hill.

USEPA. 1994. *Solid Waste Disposal Facility Criteria: 40 CFR Part 258: Technical Manual.* Available from the National Technical Information Service (NTIS). To order, call NTIS at 703/847-4650 and ask for publication number PB94-100 450.

USEPA. 1994. SW-846.

USEPA. 1993. *Technical Guidance Document: Quality Assurance and Quality Control for Waste Containment Facilities. EPA/600/R-93/182.*

USEPA. 1994. *Characterization of Municipal Solid Waste in the United States: 1994 Update.*

USEPA. 1992. *Characterization of Municipal Solid Waste in the United States: 1992 Update.*