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Seminar Publication

Design, Operation, and Closure of Municipal Solid Waste Landfills

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Design, Operation, and Closure of Municipal Solid Waste Landfills

Center for Environmental Research Information
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Chapter 1
Introduction

1.1 Background

The United States is facing a major municipal solid waste management challenge. In 1990, a total of 195.7 million tons of municipal solid waste (MSW) was generated in our country (U.S. EPA, 1992a), approximately 66 percent of which was disposed in landfills (see Figure 1-1). Three factors illustrate the MSW management problems that must be addressed, especially as they relate to landfills:

- By the year 2000, it is estimated that this nation will generate over 222 million tons of MSW per year (U.S. EPA, 1992a).
- Although recycling and composting are expected to reduce the overall percentage of MSW disposed in landfills, it is estimated that at least 120 million tons of MSW will continue to be disposed in landfills in 1995 (U.S. EPA, 1992a).
- Many existing MSW landfills have closed, drastically reducing the available space for disposal of MSW.

In addition, it is now known that older municipal solid waste landfills (MSWLFs), often referred to as "dumps," historically have accepted a wide array of questionable wastes that threaten underlying ground-water resources. Many abandoned "dumps" are now Superfund sites, facing costly remediation.

Because of these MSW management and environmental crises, the need arose to develop new MSWLFs to satisfy the nation's disposal needs into the next century in an environmentally safe manner. To prescribe criteria for the design, construction, operation, and closure of reliable MSWLFs and to allow states the flexibility to define their individual landfill needs, the U.S. Environmental Protection Agency (EPA) published final MSW landfill regulations in the *Federal Register* on October 9, 1991, under authority of Subtitle D of the Resource Conservation and Recovery Act (RCRA) and Section 405 of the Clean Water Act. These new regulations, 40 CFR Part 258, established minimum design and operating criteria for all solid waste landfills that:

- Receive MSW, as defined in Part 258
- Codispose sewage sludge with MSW
- Receive nonhazardous MSW combustion ash
- Are not regulated under Subtitle C of RCRA

To assist landfill owners and operators in complying with these new requirements, EPA's Office of Research and Development, in particular the Center for Environmental Research Information in Cincinnati, Ohio, developed a series of 2-day seminars. These seminars were presented in 14 different locations during the summer of 1992. The goal of the seminars was to present state-of-the-art information on the proper design, construction, operation, and closure of MSWLFs.

This seminar publication is a documented summary of the technical information presented at the seminars. It is intended to supply the seminar information to those individuals who could not attend one of the seminars and to serve as a valuable reference to those responsible for the challenging task of designing, constructing, operating, or closing a MSWLF in compliance with federal and applicable state requirements.

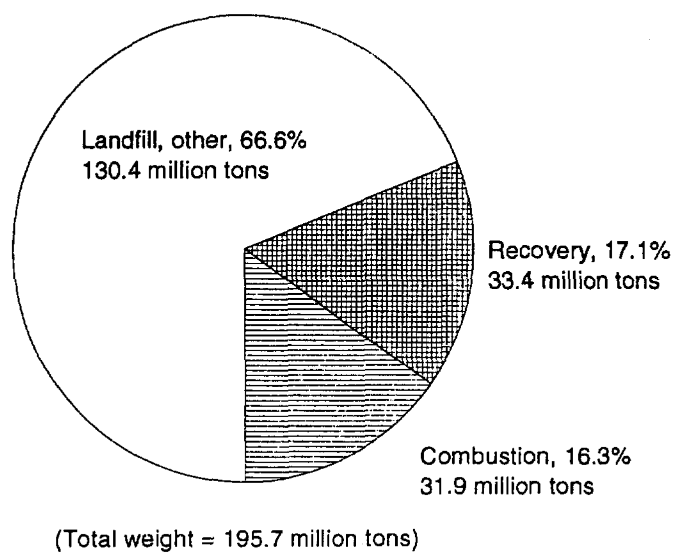


Figure 1-1. Amount of MSW generated in the United States in 1990 (U.S. EPA, 1992a).

1.2 Overview of RCRA Subtitle D MSWLF Criteria

The Subtitle D criteria established siting, design, operation, closure, post-closure care, ground-water monitoring, and financial assurance requirements for all municipal solid waste landfills that have received or will receive MSW after October 9, 1991. This section presents an overview of these MSWLF criteria. The regulations (40 CFR Part 258) and Agency guidance should be reviewed for specific issues and details of the regulation.

1.2.1 Applicability

The MSWLF criteria do not apply to landfills that ceased receiving MSW on or before October 9, 1991. If a landfill accepted MSW after October 9, 1991, but ceased accepting MSW before October 9, 1993, this landfill must comply only with the closure requirements of 40 CFR Part 258.60(a). All MSWLFs that accepted MSW on or after October 9, 1993, however, must comply with all applicable criteria. These criteria apply to MSWLFs that receive MSW, sewage sludge, or nonhazardous municipal waste combustion ash. In addition, these criteria apply to municipal nonhazardous waste combustion ash monofills. The criteria do not apply to sewage sludge monofills.

1.2.2 Implementation

The MSWLF criteria are self-implementing in states that do not have EPA-approved permit programs. Self-implementing means that MSWLF owners/operators are required to implement the requirements of the criteria and maintain adequate documentation to demonstrate compliance. The citizen suit provisions of RCRA will be relied on primarily for enforcement in these states.

The criteria provide implementation flexibility to those states that receive EPA approval of their permit programs. For MSWLFs in these states, the director of the approved state program has the authority to develop and implement alternative requirements, provided that the new requirements meet the intent of the MSWLF criteria. This provision enables states to consider site-specific factors and conditions in implementing their programs. Examples of available state flexibility are presented below in the discussion of the major provisions of the criteria (Section 1.2.4).

1.2.3 Small Landfill Exemption[1]

Some facilities might qualify for an exemption from the MSWLF design requirements. To be eligible for the exemption, a landfill must receive an average of less than 20 tons of MSW per day, and no evidence of ground-water contamination can be present at the site. In addition, the exemption applies only if:

- The facility experiences 3 consecutive months of interrupted surface transportation, or
- No practicable waste management alternative exists, and the facility receives less than 25 inches of annual precipitation.

1.2.4 Major Provisions

The new MSWLF criteria contain six major provisions, which are discussed below. A summary of changes to the effective date of each provision is presented in Table 1-1.

1.2.4.1 Location Restrictions

The MSWLF location restrictions involve the proximity of landfills to:

- Airports
- Floodplains
- Wetlands
- Fault areas
- Seismic impact zones
- Unstable areas

For new MSWLFs and lateral expansions of existing MSWLFs, all the restrictions listed above apply. For existing MSWLFs that are not expanding laterally, restrictions regarding airports, floodplains, and unstable areas apply. Existing MSWLFs that cannot meet these location restrictions must close by October 9, 1996. In states with EPA-approved programs, the director can extend the closure deadline up to an additional 2 years under certain circumstances.

1.2.4.2 Operating Criteria

The MSWLF criteria include the following operational requirements:

- Establishing procedures for excluding hazardous waste
- Applying daily cover
- Controlling disease vectors (flies, rats, etc.)
- Controlling explosive gases
- Restricting open burning
- Controlling access to the landfill
- Controlling run-on and run-off
- Protecting surface waters
- Restricting liquids
- Maintaining operating records

[1] EPA delayed the effective date for these small MSWLFs until October 9, 1995 (see 58 *Fed. Reg.* 51536, October 1, 1993).

1.2.4.3 Design Criteria

Performance-based and technology-based criteria govern the design of new MSWLFs and lateral expansions of existing MSWLFs. In states with EPA-approved programs, the director of the program can approve landfill designs that meet the performance requirements of the criteria. The performance requirements are:

- The contaminant levels in Table 1-2 shall not be exceeded in the uppermost aquifer at the relevant point of compliance, as established by the director of the program, and
- The relevant point of compliance shall not be more than 150 meters from the unit boundary and shall be on the property of the owner/operator. In states without EPA-approved programs, however, the relevant point of compliance must be at the unit boundary.

In states without EPA-approved programs; owners/operators have two options for designs of new MSWLFs and lateral expansions of existing MSWLFs:

- A standard design can be used. This design requires a composite liner consisting of an upper flexible membrane liner (FML), commonly referred to as a geomembrane, at least 30 mil thick (60 mil for high density polyethylene [HDPE]) and a lower compacted soil layer with a hydraulic conductivity of no more than 1×10^{-7} centimeters per second, along with a leachate collection system (Figure 1-2).
- An owner/operator can request that the state petition EPA for approval of an alternative design based on meeting the performance requirements discussed above.

1.2.4.4 Ground-Water Monitoring and Corrective Action

The MSWLF criteria establish requirements for ground-water monitoring and corrective action for all landfills. The criteria include a systematic process that requires routine ground-water monitoring, referred to as detection monitoring. In detection monitoring, a minimum number of indicator parameters must be tested at least annually. If statistically significant increases above background concentrations of any of the indicator parameters are detected, a more comprehensive monitoring program, referred to as assessment monitoring, must be instituted. If elevated concentrations of pollutant parameters continue or increase, the owner/operator then is required to develop and implement a corrective action program.

In states with EPA-approved programs, the director of the program has the authority to modify the ground-water

Table 1-1. Summary of Changes to the Effective Dates of the MSWLF Criteria (as of October 1, 1993) (U.S. EPA, 1993a.)

	MSWLF Units Accepting Greater Than 100 TPD	MSWLF Units Accepting 100 TPD or Less; Are Not on the NPL; Are Located in a State That Has Submitted an Application for Approval by 10/9/93, or on Indian Lands or Indian Country.	MSWLF Units That Meet the Small Landfill Exemption in 40 CFR 258.1(f)	MSWLF Units Receiving Flood-Related Waste
General effective date* (This is the effective date for location, operation, design, and closure/post-closure)	October 9, 1993	April 9, 1994	October 9, 1995	Up to October 9, 1994, as determined by state
Date by which to install final cover if cease receipt of waste by the general effective date	October 9, 1994	October 9, 1994	October 9, 1996	Within one year of date determined by state; no later than October 9, 1995
Effective date of ground-water monitoring and corrective action	Prior to receipt of waste for new units; October 9, 1994, through October 9, 1996, for existing units and lateral expansions	October 9, 1993, for new units; October 9, 1994, through October 9, 1996, for existing units and lateral expansions	October 9, 1995, for new units; October 9, 1995, through October 9, 1996, for existing units and lateral expansions	October 9, 1993, for new units; October 9, 1994, through October 9, 1996, for existing units and lateral expansions
Effective date of financial assurance requirements	April 9, 1995	April 9, 1995	October 9, 1995	April 9, 1995

* If a MSWLF unit receives waste after this date, the unit must comply with all of Part 258.
Note: See the final rule and preamble published on October 1, 1993 (58 *Fed. Reg.* 51536), for a full discussion of all changes and related conditions. All other versions of this table, including the version in 58 *Fed. Reg.* 51536, are obsolete.

Table 1-2. Maximum Contaminant Levels (MCLs) Point-of-Compliance Performance-Based Criteria

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

Source: *Federal Register,* October 9, 1991 (40 CFR Part 258.40)

monitoring requirements, including reducing the number of parameters that need to be monitored.

1.2.4.5 Closure and Post-Closure Care

After receipt of the final delivery of MSW, a landfill is required to be properly closed, and the owner/operator must provide post-closure care. The overall goals of closure and post-closure care are to minimize the infiltration of water into the landfill and maintain the integrity of the cover during the post-closure period by minimizing cover erosion.

Closure and post-closure plans for existing MSWLFs must be developed by the effective dates in the regulations. For new MSWLFs, the closure and post-closure plans must be prepared before the final receipt of MSW. The closure plan must describe the steps necessary to close all MSWLF units at any point during the active life of the landfill. The post-closure plan must include a description of monitoring and maintenance activities to be conducted during the post-closure period, as well as a description of any uses of the property during the post-closure period.

The MSWLF criteria also establish minimum requirements for a final landfill cover. At a minimum, the final cover shall consist of:

- An infiltration layer of at least 18 inches of earthen material that has a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present, or a permeability of no greater than 1 x 10^{-5} centimeters per second, whichever is less, and
- An erosion layer of at least 6 inches of earthen material that is capable of sustaining native plant growth.

In states with EPA-approved programs, the director of the program may approve alternative cover designs.

Post-closure care of the landfill and final cover system includes necessary monitoring and maintenance activities described in the post-closure plan. For MSWLFs in states without EPA-approved programs, post-closure care must be conducted for 30 years. In states with EPA-approved programs, the director of the program has the authority to decrease or increase the post-closure period.

1.2.4.6 Financial Assurance

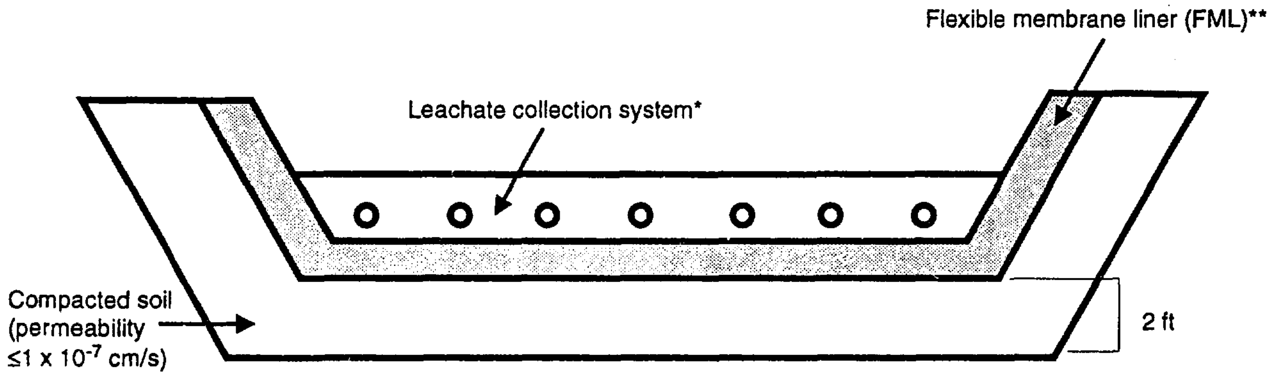
In general, all entities (including Native American tribes), except for states and the federal government, are required to provide financial assurance that a MSWLF will be properly closed and maintained. The regulations require that financial assurance be provided for:

- Closure
- Post-closure care
- Corrective action to address known releases

Many financial assurance mechanisms are available for use, including:

- Trust funds
- Surety bonds
- Letters of credit
- Insurance

EPA currently is developing financial tests to determine the financial assurance capability of municipalities and corporations. Once developed, these tests will enable public and private entities to determine their ability to provide financial assurance and the need to secure other financial assurance mechanisms.



* Leachate collection system must maintain leachate level <30 cm.
** FML must be at least 30 mil thick; FML consisting of high density polythylene (HDPE) must be at least 60 mil thick (mil = 1,000th of an inch).

Figure 1-2. Composite liner and leachate collection system design in unapproved states (adapted from *Federal Register*, October 9, 1991d).

1.3 Technical Guidance

EPA's 1992 seminars on proper MSWLF design and operation, on which this document is based, were held prior to publication of EPA's technical manual on *Solid Waste Disposal Facility Criteria* (U.S.EPA, 1993a). The reader should refer to this manual for additional technical guidance on the Part 258 regulation. The manual was developed to assist MSWLF owners and operators in achieving compliance with the revised Part 258 criteria, and includes information on the purpose, scope, and applicability of the Part 258 requirements, technical considerations relating to each requirement, and sources for further information.

Chapter 2
Landfill Siting

2.1 Introduction

The Subtitle D MSWLF siting restrictions establish minimum national siting standards for landfills. Many state regulations contain stricter landfill siting requirements, including considerations not in Subtitle D, such as restrictions on development in critical watershed areas, wellhead protection areas, sole-source aquifers, minimum buffer zones, or agricultural lands. Because states and localities currently are developing their own landfill siting programs, both state and local regulations should be consulted for possible additional requirements beyond those required by Subtitle D.

The Subtitle D siting requirements include restrictions on siting MSWLFs near or in airports, floodplains, wetlands, fault areas, seismic impact zones, and unstable areas. Some of the restrictions apply to all MSWLFs, whereas others apply to new and laterally expanding landfills but not to existing facilities, as shown in Table 2-1. These siting restrictions are discussed below.

2.2 Airport Restrictions

Airport safety as it relates to landfill siting is an issue that has been addressed by Federal Aviation Administration (FAA) policy for several years. These restrictions were developed to protect aircraft from collisions with scavenger birds that are generally associated with landfill facilities. Such collisions have caused extensive damage to aircraft and can lead to aircraft crashes during takeoffs and landings. Owners or operators of existing, new, or laterally expanding MSWLF units located (1) within 10,000 feet of the end of any airport runway used by turbojet aircraft or (2) within 5,000 feet of the end of any airport runway used only by piston-type aircraft must demonstrate that the landfill unit does not pose a bird hazard to aircraft. If this cannot be demonstrated, then the facility must close by October 9, 1996. The FAA must be notified if a new or laterally expanding landfill site is closer than 5 miles to a public airport runway.

Certain operational procedures at the landfill site might deter birds from inhabiting the site. A number of technologies are available, with variable success rates, to minimize food sources and discourage nesting. Waste management techniques to reduce the supply of food to birds include:

- Frequent covering of wastes that provide a source of food.
- Shredding, milling, or baling food-containing wastes.
- Eliminating wastes from the landfill that represent a food source for birds (e.g., through alternative waste management techniques, such as source separation, composting, and waste minimization).

Frequent covering of wastes that represent a food source for birds effectively reduces the availability of the food supply. Depending on site conditions, such as volume and types of wastes, waste delivery schedules, and size of

Table 2-1. Subtitle D Location Restrictions for MSWLFs

Restricted Locations	Applies to Existing MSWLFs?	Applies to New and Lateral MSWLF Expansions?	Make Demonstration to Director or Put Demonstration in Operating Record?	Must Existing Units Close if Cannot Make Demonstration?
Airports	Yes	Yes	Operating Record	Yes
Floodplains	Yes	Yes	Operating Record	Yes
Wetlands	No	Yes	Director	NA
Fault Areas	No	Yes	Director	NA
Seismic Impact Zones	No	Yes	Director	NA
Unstable Areas	Yes	Yes	Operating Record	Yes

the working face, the operator might need to apply cover several times a day to keep the inactive portion of the working face small relative to the area accessible to birds. Maintaining a small working face also concentrates spreading and compaction equipment in a small area, which further disrupts scavenging by birds.

Milling or shredding MSW tends to break up food waste into smaller particle sizes and distributes the particles throughout nonfood wastes, thereby diluting food wastes to a level that frequently makes the mixture no longer attractive as a food supply for birds. Similarly, baling of MSW reduces the surface area of the waste available to scavenging birds.

Various deterrents to bird scavenging and nesting have been used with limited short-term success. Such deterrents include the use of loud sounds at random intervals and visual deterrents, such as realistic models of predator birds. The use of physical barriers such as a canopy of fine wires or nets strung around the working face also have proved effective. Nets have been strung over sufficient landfill acreage such that the weekly operation of the facility is not affected by the presence of the nets. These nets use widely spaced wires, commonly 10 to 15 feet apart, that limit the ability of birds such as seagulls to land on the waste.

2.3 Floodplain Restrictions

Floodplains are defined as lowland and other flat areas adjacent to inland or coastal waters that are inundated during a 100-year flood. The Subtitle D regulations limit the siting of MSWLFs within a floodplain. Under Subtitle D, a landfill located in a 100-year floodplain cannot restrict the flow of the 100-year flood, reduce the temporary storage capacity of the floodplain, or result in washout of MSW. Existing MSWLFs in 100-year floodplains must close by October 9, 1996, unless it can be demonstrated that the landfill will not pose unacceptable hazards to the floodplain.

A potential problem related to floodplain siting restrictions concerns stormwater run-off control. A common method used to control offsite loss of soils from run-off is a sedimentation basin (see Section 4.4). The floodplain restrictions limit acceptable locations for sedimentation basins at existing landfills located in or adjacent to floodplains. Implementing proper sedimentation control at these facilities could be difficult if run-off sedimentation control devices cannot be sited. Nevertheless, the reasons for keeping MSWLFs and support facilities out of floodplains outweigh these drawbacks.

2.4 Wetlands Restrictions

Under 40 CFR 232.2, wetlands are defined as those areas that are inundated or saturated by surface water or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas. Wetlands are identified using three criteria: (1) the presence of characteristic vegetation, (2) inundation of the site by water for a certain number of days per year, and (3) the presence of hydric soils.

Subtitle D is consistent with EPA's objective of no net loss of wetlands in terms of acreage and function. The regulation prohibits new MSWLF units and lateral expansions in wetlands unless the owner/operator can demonstrate that no practical alternative not involving wetlands exists. Additionally, the owner/operator must show that construction and operation of the MSWLF unit will not violate applicable state water quality standards (WQS) or toxic effluent standards of the Clean Water Act and does not jeopardize an endangered species. Also, the MSWLF design must clearly demonstrate the stability and erosion potential of both native and fill soils used to construct the facility.

Subtitle D includes wetlands restoration or creation as a last option to achieve no net loss of wetlands. Successfully creating or restoring wetlands, however, is difficult. Wetlands restoration or creation is more complicated than providing a wet area; these tasks require the expertise of people in a number of broad disciplines, such as agronomists, biologists, and ecological engineers, in addition to the civil engineers and geologists who usually are involved in landfill design. Wetlands creation programs at MSWLF sites are generally onsite programs implemented during construction of a landfill cell intruding on wetlands. Federal, state, and local governments are considering stricter enforcement and interpretation regarding wetlands creation.

2.5 Restrictions in Fault Areas

A fault is a fracture or zone of fractures in geologic material along which strata on one side have been displaced with respect to strata on the other side. Subtitle D requires that no new MSWLF or lateral expansion of a MSWLF be sited within 200 feet (60 meters) of a fault area that has experienced displacement within the Holocene Epoch (the last 10,000 years). If differential movement between the two sides of a fault bridged by a landfill were to occur, the landfill's liner system may not be able to resist the movement and could fail. A sophisticated geologic study is needed to evaluate site conditions to determine if a proposed new or expanded facility is located on or near an active fault. A geologist can determine that a fault has not moved in Holocene time by examining surficial deposits for displacements. Potentially active faults can be located based on records of seismic epicenters and by examining high-altitude, high-resolution aerial photographs from the U.S.

Geological Survey (e.g., USGS Preliminary Young Fault Map MF916). In states with an approved program, an alternative setback distance of less than 200 feet might be allowed if the owner/operator can demonstrate that at this distance ground movement will not damage the structural integrity of the facility and the setback distance will be protective of human health and the environment.

2.6 Restrictions in Seismic Impact Zones

Seismic impact zones are defined as regions having a 10-percent or greater probability that maximum horizontal acceleration at the site caused by an earthquake will exceed 0.1 g in 250 years (Earth's gravitational force is 1 g). This ground movement applies to movement of lithified rock material, not soils or manmade materials such as concrete. The concern is with the potential impact of earthquake-induced lateral accelerations on the stability of the landfill and subgrade soils. Under Subtitle D, new MSWLFs and lateral expansions of landfill units cannot be located in seismic impact zones unless the owner/operator can demonstrate to the director of an approved state program that all containment structures (e.g., liners, leachate collection system) are designed to resist the maximum horizontal acceleration and that the site will remain stable.

Seismic impact zones in the continental United States are shown in Figure 2-1, which is based on ongoing work by the U.S. Geological Service (Algermissen et al., 1982, 1990). This map is based on probabilistic studies of earthquake recurrence periods and earthquake magnitude. In the western United States, earthquakes of large magnitude are frequent and can be associated with specific active faults. Such earthquake events, although large in magnitude, tend to affect a relatively small geographic area. Thus the probability of seismic ground movements occurring in a given location in the West is closely tied to the area's proximity to active faults. Conversely, very few earthquakes of large magnitude occur in the eastern United States, but those that do occur affect a large geographic area. Thus the seismic impact zones in the eastern United States are not, for the most part, defined by the proximity of the site to active faults. The exact source or mechanism for earthquakes in much of the eastern United States is not understood at present.

Within seismic impact zones, the design of a MSWLF must consider the stability of the landfill, its support structures, and the underlying soils. The evaluation of landfill stability should focus on the effect of earthquake-induced horizontal accelerations on the slope stability of the landfill during operation and the post-closure period. Such evaluations are particularly important given the low friction angle of the surface of geomembrane liners used in MSWLF lining systems. The evaluation of the site's subgrade stability should identify zones of saturated, loose sands that could possibly liquefy during an earthquake. This liquefaction is caused by the generation of shear-induced excess pore water pressures within the sands, which produce a "quick" condition in the sand. This quick condition can lead to a loss of bearing capacity in the subgrade soils and subsequent failure of the MSWLF liner system.

The EPA's Risk Reduction Engineering Laboratory, located in Cincinnati, Ohio, is currently developing a technical guidance document on designing municipal solid waste landfills in areas affected by seismic activity. The document, *RCRA Subtitle D Seismic Design Guidance for Municipal Solid Waste Landfill Facilities*, should be available in early 1995.

2.7 Restrictions in Unstable Areas

The final Subtitle D siting restriction for MSWLFs pertains to unstable site subgrades. Unstable MSWLF sites have subgrades susceptible to natural or human-induced events or forces that could produce settlement or displacement capable of impairing the integrity of the landfill. These areas might include poor foundation conditions (e.g., highly compressible soil layers), sites susceptible to mass movements (e.g., landslides), and karst terrain that may have hidden sink holes. Under Subtitle D, if a MSWLF is located in an unstable area, the owner/operator of the landfill must demonstrate that engineering measures have been incorporated into the unit's design to ensure the integrity of the landfill's structural components.

One example of siting in an unstable area is siting a MSWLF over a thick, extensive clay layer. A landfill site with a 60-foot natural clay layer, and therefore a low permeability site, ordinarily would be considered a good landfill site because leachate impacts would be minimized. But the design of an MSWLF sited on compressible clays also must include an evaluation of the impact of long-term settlement on the integrity of the liner and leachate collection system to ensure that the strains in the liner system remain acceptable and that flow directions in the leachate collection system are not reversed. Additionally, as MSW is placed in the landfill, the weight acting on the clay increases and water is squeezed from the compressible clay. This process reduces the volume of the clay and produces settlement of the landfill. The amount of settlement in a given area increases as the weight of the waste increases and as the clay beneath the area compresses. A highly compressible clay beneath the area therefore will increase settlement. Clay properties are time and moisture dependent and influenced by freezing. Initially, the clay might not be strong enough to support a large amount of waste, but over time, as the weight of the waste squeezes the water out of the clay beneath it, the clay may become stronger and might be capable of supporting the waste. Thus, the rate

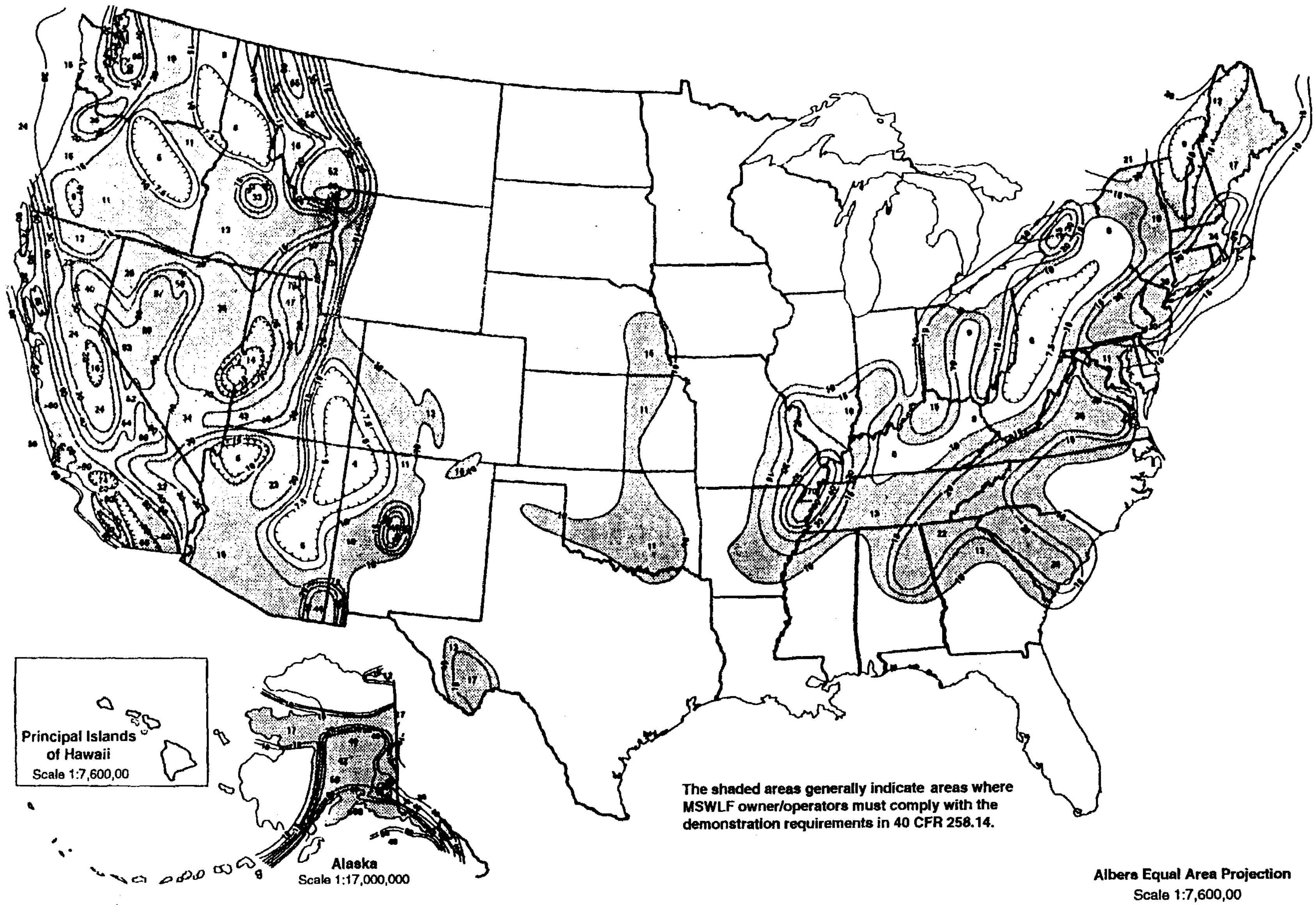


Figure 2-1. Seismic impact zones (U.S. EPA, 1993a).

of waste placement at such a site might be an important consideration.

A stability analysis should be undertaken when a landfill is sited in an unstable area to demonstrate that the subgrade can support additional MSW loads. MSWLF designers typically use a unit waste weight of 1,400 pounds per cubic yard when performing this stability analysis. But the contents of many communities' waste stream have changed since this rule of thumb was developed (e.g., many elements, such as "white" metals, and tires now are recycled rather than disposed). Unit weights of MSW as high as 2,500 pounds per cubic yard have been measured, which would significantly affect the results of a stability analysis. Actual MSW density measurements in the field might be required to confirm the stability analysis at a particular site.

A different type of stability concern arises when considering karst terrain, which can include sink holes, caves, and large springs that result from the dissolution of limestone or other soluble rock. Two significant problems exist with siting an MSWLF in karst terrain: (1) hidden sink holes can collapse and significantly damage the waste containment system; and (2) detection of leakage from the MSWLF unit is difficult, because leachate can move rapidly through hidden conduits within the limestone beneath the site. Subtitle D does not preclude siting MSWLFs in karst areas, but does require the designer to evaluate karst conditions and potential impacts.

2.8 Closure of Existing Landfills if Siting Restrictions Cannot Be Met

Existing landfills that do not meet the airport, floodplain, or unstable area siting restrictions must close by October 9, 1996, and conduct required post-closure activities unless the owner/operator can demonstrate that no alternative exists for disposal or that the landfill presents no immediate threat to human health or the environment. In such cases, the deadline for closure might be extended for 2 years by the director of an approved state program.

Chapter 3
Design Criteria

3.1 Introduction

This section discusses the specific MSWLF design criteria contained in Subtitle D and presents guidelines for meeting the regulatory requirements. These requirements are applicable to both new and lateral expansions of MSWLFs, although some small landfills that receive less than 20 tons per day (TPD) of waste on average are exempted. Chapter 1 discusses small landfill exemptions in more detail.

Two specific design criteria are presented in Subtitle D: (1) in approved states, the liner design must ensure that the allowable values in Table 1-2 will not be exceeded in the uppermost aquifer at the relevant point of compliance; or (2) a composite liner system must be used with a leachate collection system that is designed and constructed to maintain less than a 30-centimeter depth of leachate over the liner. Sections 3.2 and 3.3 below describe the design criteria that must be met, as well as the practical and technical considerations that affect landfill design for these criteria; Section 3.4 discusses the design issues related to leachate collection systems.

The owner/operator first determines whether the MSWLF is in an approved state. In an approved state, the owner/operator would follow the design standards of the state. In an unapproved state, the owner/operator would choose the composite liner or use the petition process provided for in Subtitle D to seek approval of an alternative liner design.

3.2 Liner Design: Point-of-Compliance Method

Subtitle D is a major departure from previous hazardous waste regulations that have addressed waste containment systems. Hazardous waste regulations and related minimum-technology guidance provide very specific requirements for liner components (e.g., compacted clay liners and geomembranes). Subtitle D allows for consideration of performance standards when designing a MSWLF. In this manner, the designer is able to consider site-specific factors in the design. Such factors include:

- The hydrogeologic characteristics of the facility and surrounding land.
- The volume and physical and chemical characteristics of the leachate.
- The quantity, quality, and direction of ground-water flow.
- The proximity and withdrawal rate of ground-water users.
- The availability of alternative drinking water supplies.
- The existing quality of the ground water.

Under Subtitle D, the relevant point of compliance of a designed MSWLF can be as far as 150 meters from the waste management unit boundary in a state with an approved landfill management program, as long as the area within the 150-meter buffer zone belongs to the facility. In states without an approved program, the point of compliance must be at the waste management unit boundary. Ground water beyond the point of compliance must comply with either the MCLs for pollutants listed in Table 1-2 or existing background levels of pollutants, whichever is greater.

Practical application of the point-of-compliance criteria to the design of a MSWLF liner system depends on the designer's ability to model accurately the rate of pollutant movement through the liner system and site stratigraphy. Contaminant transport at the landfill site (e.g., advection, diffusion, soil adsorption—see Chapter 5) must be studied carefully to determine the direction, speed, and concentration of contaminant flow. Because contaminant transport in ground water can be very complicated, the accurate prediction of contaminant movement will increase significantly the cost of design and site characterization.

EPA's Environmental Research Laboratory in Athens, Georgia, is currently developing a computer software model, MULTIMED (U.S. EPA, 1990a), for use in evaluating liner designs based on point of compliance. This software model requires contaminant-specific transport factors that have been applied to only a few of the contaminants listed in Table 1-2. The point-of-compliance evaluation proposed by EPA uses the Hydrologic Evaluation of Landfill Performance (HELP) (U.S. EPA, 1984) computer model to estimate the rate of liquid loss through the bottom of the landfill. The MULTIMED computer model then predicts the rate at which the contaminant moves through the partially saturated soil beneath the liner system.

3.3 Liner Design

If a state does not have an EPA-approved MSWLF program, or if the designer cannot justify a point-of-compliance design, newly designed or laterally expanding municipal landfills must use the composite liner alternative. This liner system consists of an upper geomembrane liner and a lower compacted soil liner. The geomembrane must be at least 30 millimeters thick, except for HDPE geomembranes, which must be at least 60 millimeters thick. The compacted soil liner must be at least 2 feet thick and have a hydraulic conductivity of less than 1×10^{-7} centimeters per second.

The geomembrane liner (GML) minimizes the exposure of the compacted soil liner to leachate, thus significantly reducing the volume of leachate reaching the soil liner. Reducing membrane penetration is vital to controlling the escape of leachate into ground water. One way to reduce membrane penetration is to institute a comprehensive construction quality assurance program, which is discussed later in Section 3.3.1.5. The leakage rate through a hole in the geomembrane of a composite liner can be calculated based on the following empirical function:

$$Q = 3a^{0.75}h^{0.75}K_d^{0.5}$$

where:

- Q = Leachate leakage through a hole in the GML of the composite liner (m^3/s)
- a = Area of hole (m^2)
- h = Hydraulic head of liquid applied to the membrane (m)
- K_d = Hydraulic conductivity of the compacted clay (m/s)

The hydraulic conductivity of the compacted soil liner is an important factor in leakage control. For example, a 1-square-centimeter hole in a geomembrane with 12 inches of liquid head can have a leakage rate as high as 3,300 gallons per day. The presence of a compacted soil liner with a conductivity of 10^{-7} centimeters per second underneath the geomembrane can reduce this rate to 0.2 gallons per day. Even if the conductivity changes to 10^{-6} centimeters per second, the leakage rate still would be less than 4 gallons per day, providing a dramatic improvement over the use of a geomembrane alone.

3.3.1 Design and Construction Considerations for Geomembrane Liners

Many factors must be considered for a successful geomembrane design and installation, including:

- Selection of proper membrane materials.
- Proper subgrade preparation.
- Membrane transportation, storage, and placement.
- Proper installation conditions (weather, temperature, etc.).
- Seaming and tests.
- Application of construction quality assurance (CQA).

The following sections explain in detail the requirements and considerations associated with these factors.

3.3.1.1 Membrane Materials and Properties

A GML must provide excellent chemical resistance and reliable seams at a competitive cost. HDPE liners provide significant chemical resistance at a moderate cost. HDPE, however, is difficult to seam and requires a rigorous CQA program to ensure seam integrity. Alternative geomembrane polymers include polyvinyl chloride (PVC) and polypropylene. These polymers have excellent biaxial stress-strain properties, but do not have substantial chemical resistance. Therefore, they are useful as cover membranes because their biaxial strength allows them to withstand significant waste subsidence, while their lack of direct contact with leachate reduces the need for a liner with substantial chemical resistance. Available data on MSWLF leachate quality indicate that leachate typically has a pH range between 5.5 to 7.0 and low concentrations of organic compounds. Based on these data, the chemical resistance of all the polymers mentioned above is excellent.

3.3.1.2 Subgrade Preparation

The surface of the compacted soil liner must be smooth and strong enough to provide continuous support for the geomembrane. The surface of the soil must be relatively free of rocks, roots, and excess water. EPA studies (U.S. EPA, 1988) show that stones at the surface that are smaller than 3/4 inches and are not angular will not penetrate most geomembranes.

3.3.1.3 Geomembrane Transportation, Storage, and Placement

Rolls or pallets of geomembranes are shipped to the job site by truck. Geomembranes such as PVC are commonly prefabricated into large panels, folded, and shipped secured to a pallet. Geomembranes such as

HDPE and polypropylene must not be folded and are shipped to the job site as rolls.

Once at the job site, the geomembranes should be stored such that direct contact with the ground is avoided. This requirement could be met by placing a protective surface (e.g., a geotextile) over the ground or having the geomembrane rolls wrapped in plastic at the factory. The stored geomembrane also should be protected from excessive exposure to dust, water, and heat.

To limit scratching of the underside of the geomembrane, rolls of geomembranes should be handled by placing a steel lifting tube through the center of the roll and lifting the membrane with a beam that prevents cables from touching the roll. The geomembrane then should be unrolled into its final position with a minimum amount of dragging and shifting.

3.3.1.4 Geomembrane Seaming and Testing

Most geomembrane liners are seamed thermally. Thermal seaming requires both proper weather conditions and a clean surface on both membrane surfaces. If the surface of a membrane is wet, water can vaporize and form bubbles in the seam, which significantly reduces the strength of the seam and might lead to leakage. Ambient temperature also is an important factor that should be considered during installation. Thermal seaming should be performed when the ambient temperature is between 40°F and 104°F. The most common reason for poor geomembrane seaming is the presence of dust. Therefore, dust control during the seaming process is critical.

Geomembrane seaming is important in maintaining membrane integrity, and a seam testing program should be established for quality control. Seam testing methods can be categorized into two groups: nondestructive testing, which usually is performed in the field, and destructive testing, which can be conducted either in the field or a laboratory. For different seaming styles, different testing methods can be applied. Many handbooks and manuals describing these testing methods are available (U.S. EPA, 1989b, 1991b). Figure 3-1 shows different seaming configurations. The most common thermal seams currently used are the extrusion and double-wedge seams. These seams are described in greater detail below.

Double hot-air wedge seams (two parallel seams with an air channel in between) can be nondestructively tested by applying air pressure (normally 30 pounds per square inch) to the channel. If the channel can hold the pressure for five minutes, the seam is acceptable. Sometimes when the test is conducted, the pressure fluctuates in response to ambient temperature variations (such as when weather conditions change from sunny to overcast). As long as the pressure fluctuation does not exceed 3 to 4 pounds per square inch, the seam should be acceptable. For a long seam (i.e., over 100 feet), additional gages might need to be installed to measure each section of the seam.

Extrusion seaming requires careful quality control to prevent long-term problems. During the seaming, the surface of each membrane must be abraded at the seaming area. The two sheets are then welded together to form a proper seam. Overgrinding of the surface must be avoided. In general, the grinding depth should be controlled to less than 10 millimeters. If more than 1/4 inch of the abraded surface is visible after seaming, the finished seam must be rejected. This type of seam can be nondestructively tested by applying soapy water to the surface of the seam and then putting a vacuum box over the seam. A vacuum is applied inside the box; if bubbles appear at the seam area, the seam must be redone.

Destructive testing for all seam types includes the shear test and the peel test, as shown in Figure 3-2. The shear test demonstrates that the seam develops the full tensile strength of the parent membrane. A sample is cut across a seam and placed on an extension machine for testing. The shear test does not judge the quality of the seam but instead measures the product of the seam strength and seam area. A poor-quality seam with a large weld area might develop the strength required and pass the test. A peel test, in which the force is focused on the leading edge of the seam, can truly evaluate the quality of a seam. Statistically, a minimum of one sample for every 500 feet of the liner seam must be taken.

3.3.1.5 Construction Quality Assurance (CQA)

To minimize holes in a liner (caused by product defects, transportation, installation, seaming, etc.) and to meet the required standards, a CQA program should be established for the liner installation (U.S. EPA, 1986, 1992b). The program is a planned system of activities performed by landfill owners or their representatives (CQA inspectors) to ensure that the facilities are constructed as specified in the design. The program should be developed during the landfill design stage, and the state should review a facility's CQA program before a permit is issued for construction. CQA is distinct from Construction Quality Control (CQC), which is performed by the installer to ensure the quality of the work.

Several elements in the CQA program are important to its overall success, including:

- *Responsibility and Authority*: CQA personnel are given responsibility and authority by the landfill owner to represent his or her interests to ensure that the liner meets design specifications.
- *Personnel Qualifications*: The CQA inspector must have extensive experience and knowledge about the work performed in the field. A program administered

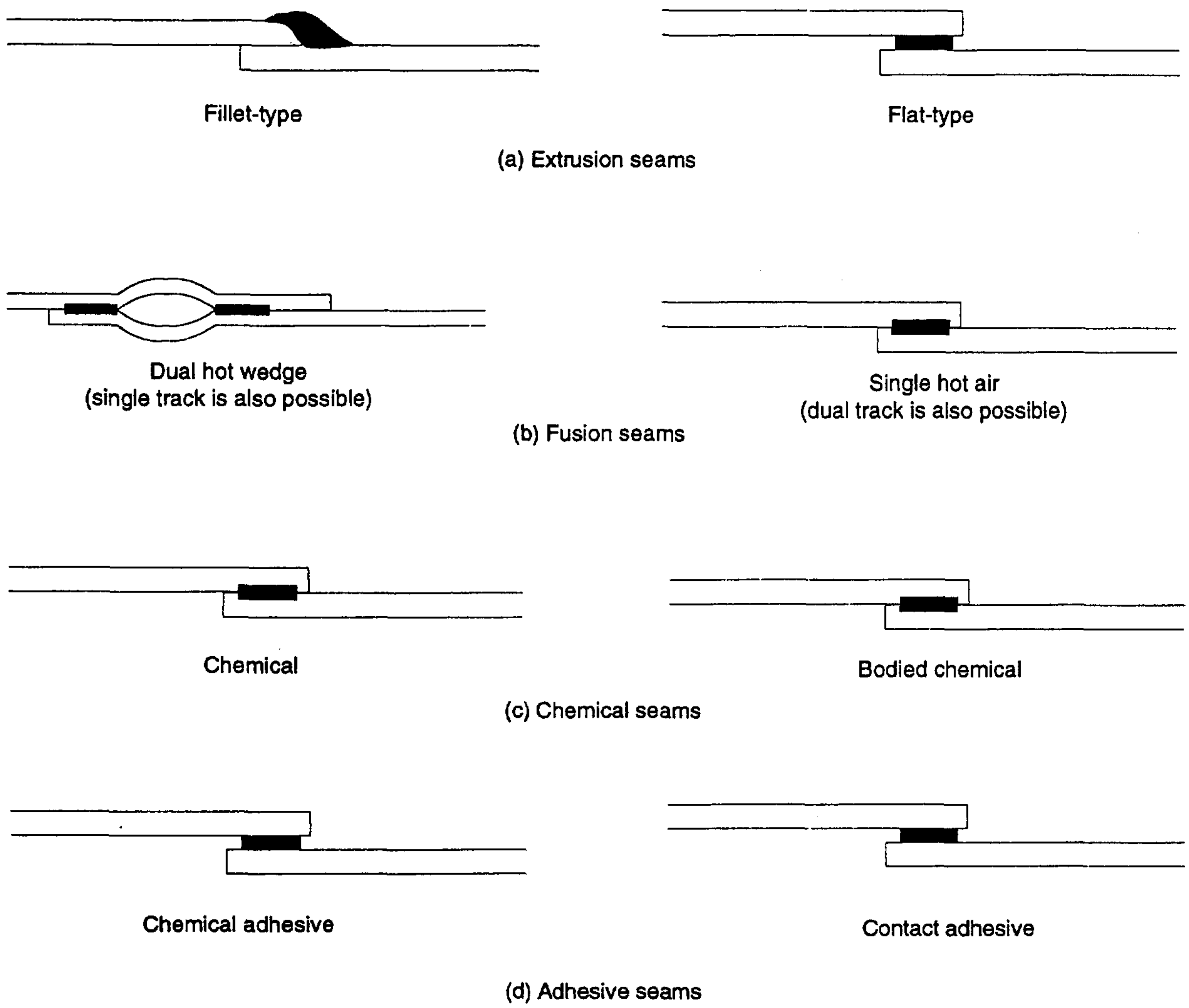


Figure 3-1. Various methods available to fabricate geomembrane seams (U.S. EPA, 1989b).

by the National Institute for Certifying Engineering Technicians (NICET) gives formal exams and provides certification of CQA inspectors for membrane installation. Many large landfill owners/operators now require CQA personnel to have certification.

- *Inspection Activities*: The CQA program must clearly define the testing program and acceptance criteria for all significant components of the MSWLF. For the liner system, the CQA program should specify the frequency of testing to be performed on the compacted soil and geomembrane liner, outline the sampling strategy, and define the specific tests to be performed.
- *Sampling Strategies*: CQA testing is performed using a combination of statistical and judgmental sampling strategies. Typical statistical sampling strategies include defined interval testing, such as one destructive seam test per 5,000 feet of seam, or one moisture/density test per 5,000 cubic yards of soil liner. Judgmental testing allows the CQA inspector to call for testing when the quality of workmanship is suspect.
- *Documentation:* Most states now require documentation that a CQA program was performed before a permit to operate the MSWLF is issued. All CQA activities must be clearly documented so that a third party can understand and verify the testing and inspection program.

An average CQA program for a landfill with a single composite liner costs approximately $4,500 to $6,000 (1994 dollars) per acre. These costs can vary widely depending on site conditions.

3.3.2 Design and Construction Considerations for Compacted Soil Liners

Clay is a difficult engineering material with which to work because of its highly moisture-dependent physical properties. As a basic landfill liner, clay must meet certain

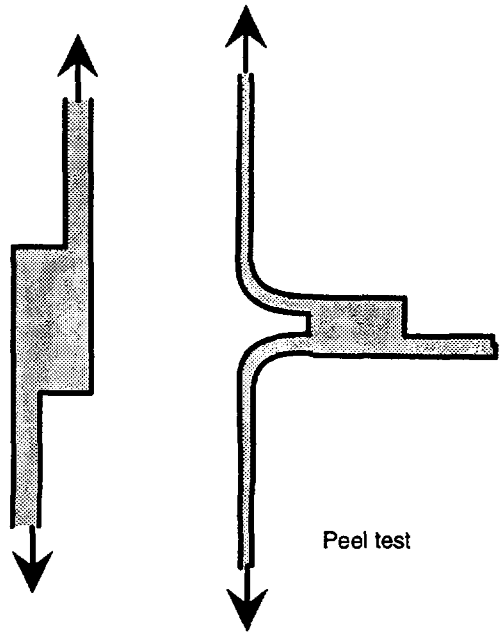


Figure 3-2. Seam strength tests (U.S. EPA, 1989b).

criteria to protect ground water from leachate contamination. The clay soil liner must be constructed to provide a minimum 2-foot layer of compacted clay with a hydraulic conductivity of less than 10^{-7} centimeters per second. To meet this requirement, the following steps should be taken during construction of a compacted clay liner:

- Destroy soil clods
- Eliminate lift interfaces
- Conduct proper compaction
- Meet moisture-density criteria
- Avoid desiccation

Each of these requirements is discussed below.

3.3.2.1 Soil Clod Destruction

Soil clod size has significant impact on the permeability of compacted clay. For example, if two clay samples, one with 3/4-inch soil clods and the second with 1/5-inch soil clods, are compacted with equal force and have equal water content, the first sample might have a hydraulic conductivity of 10^{-4} centimeters per second and the second sample might have a hydraulic conductivity of 10^{-7} centimeters per second (see Figure 3-3). Clod size in raw clay liner material can be controlled by passing the clay through a sieve of the desired size. Another way to destroy soil clods is to increase soil moisture. Clods will soften and break apart at a high moisture content.

3.3.2.2 Lift Interface Prevention and Proper Compaction

Clay liners are constructed by compacting the clay in horizontal layers commonly called lifts. During construction of a clay liner, if a new lift is applied directly to the unscarified surface of a previous lift, a zone of high permeability and low strength forms at the interface. Moisture moving through the liner could then spread quickly across this interface to a lower lift. To avoid formation of interface flow paths, the surface of the previous lift must be scarified before another compacted clay lift is added. A fully penetrating sheepsfoot roller can be used to compact the new lift intimately to the previous lift. "Fully penetrating" means that the height of the feet on the compaction wheels is greater than the thickness of the loose soil placed to form the new lift.

3.3.2.3 Moisture-Density Requirements

Clay becomes less permeable when it is compacted at a high moisture density. Its shear strength, however, decreases under high moisture-density conditions and might become so low that the clay cannot support the compaction device. Compaction criteria for landfill liners differ from compaction criteria for other purposes (e.g., building foundations). Traditionally, compaction criteria are based on strength for load-carrying capacity. For MSWLF liners, however, compaction criteria are designed to produce low permeability. Clay liners must be installed when the moisture content of soils is 2- to 6-percent wetter than soils used for other construction purposes. Figures 3-4 and 3-5 illustrate this concept.

3.3.2.4 Desiccation Prevention

Desiccation of the clay liner is difficult to avoid. A dry environment or freezing of the liner can cause the liner to lose moisture. The potential for soil-liner desiccation increases if a capillary break exists beneath the liner. A capillary break can be formed by a natural sand layer or a leachate detection layer. The capillary break prevents the clay liner from drawing moisture up from deeper soil layers to replenish moisture lost through surface evaporation. Therefore, caution should be taken to avoid desiccation when a sand layer is installed for leak detection under compacted clays. When a compacted clay liner freezes, permeability decreases after the liner thaws. Each freezing cycle reduces the permeability of the clay liner up to an order of magnitude. A layer of soil can be used to protect clay liners from desiccation and freezing. The soil layer can be removed for subsequent work.

3.4 Leachate Collection System

A leachate collection system is designed and constructed to collect leachate and convey the leachate out of the landfill for treatment. This system must ensure

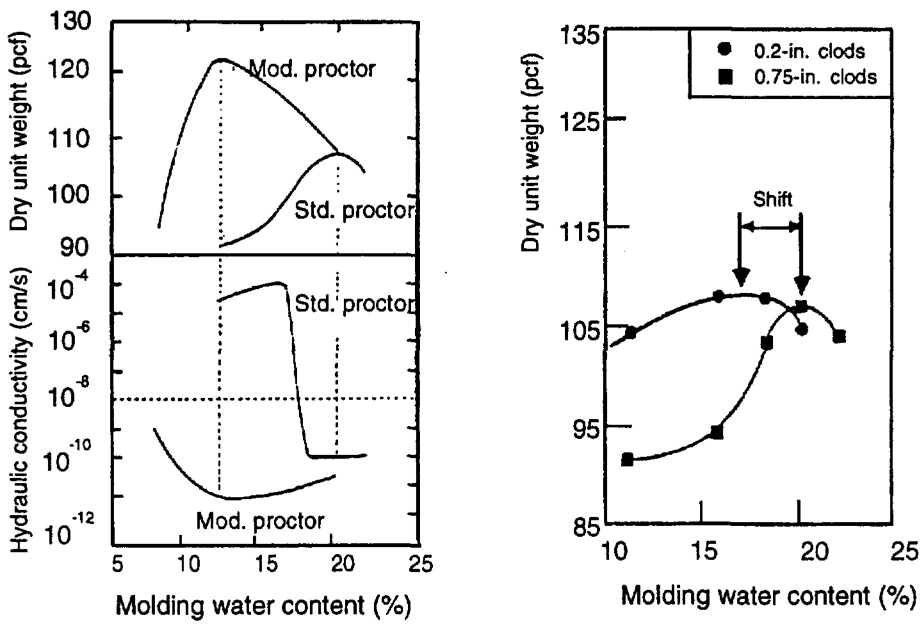


Figure 3-3. Comparison of the hydraulic conductivity of soil with different clod sizes (U.S. EPA, 1989b).

that less than 30 centimeters of leachate (the amount of leachate the liner must be designed to maintain, according to Subtitle D) accumulates over the composite liner to minimize possible contamination of ground water. When designing and constructing a leachate collection system, the following components must be considered:

- Area collector—the drain that covers the liner and collects leachate.
- Collection laterals—the pipe network that drains the area collector.
- Sump design—the low point where the leachate exits the MSWLF.
- Stormwater/leachate separation system—a system for minimizing leachate generation.

These components must be designed to handle larger leachate flows associated with initial operations and to resist problems such as biological clogging that can destroy the long-term flow capacity of the system.

3.4.1 Area Collector

The area collector, also called the blanket drain, covers the surface of the membrane liner and collects leachate. The area collector system is commonly built with at least a 12-inch layer of sand having a hydraulic conductivity greater than 10^{-2} centimeters per second. An alternative type of blanket drain can be constructed using a geonet. This alternative synthetic system has a high transmissivity (the product of layer thickness and permeability) and reduces the required thickness of a collection system, allowing more space for waste storage. Geonet systems are especially suitable for use on a side slope because they eliminate the need to operate heavy equipment directly on the liner system (such as during the construction of a sand collection system). Many types of geonet material are commercially available. One type, foam net, however, is not recommended because it can be compressed by the solid waste load and lose its ability to collect leachate.

One of the disadvantages of geonets is that they have limited hydraulic storage capacity and, therefore, no buffer capacity for stormwater flow into the system. A sand collection system is thus more suitable for a collection system located at the bottom (rather than the side slope) of the landfill. A sand collection system not only supplies stormwater buffer capacity but also forms an operational liner cover that prevents construction or operation equipment from directly contacting the composite liner underneath.

3.4.2 Collection Laterals

In general, the regulatory limit of a 30-centimeter maximum liquid head over the liner cannot be achieved using an area collector alone—collection laterals are needed. Collection laterals are perforated pipes that direct leachate to sumps so that the leachate can be removed from the landfill. During landfill operation, leachate passes through the area collector, into collection laterals, and drains to a sump where it is removed from the MSWLF.

Spacing of the collection lateral pipes depends on the permeability of the collector, the slope of the liner, and the assumed impingement rate of leachate (see Figure 3-6). The lower the permeability, the closer the

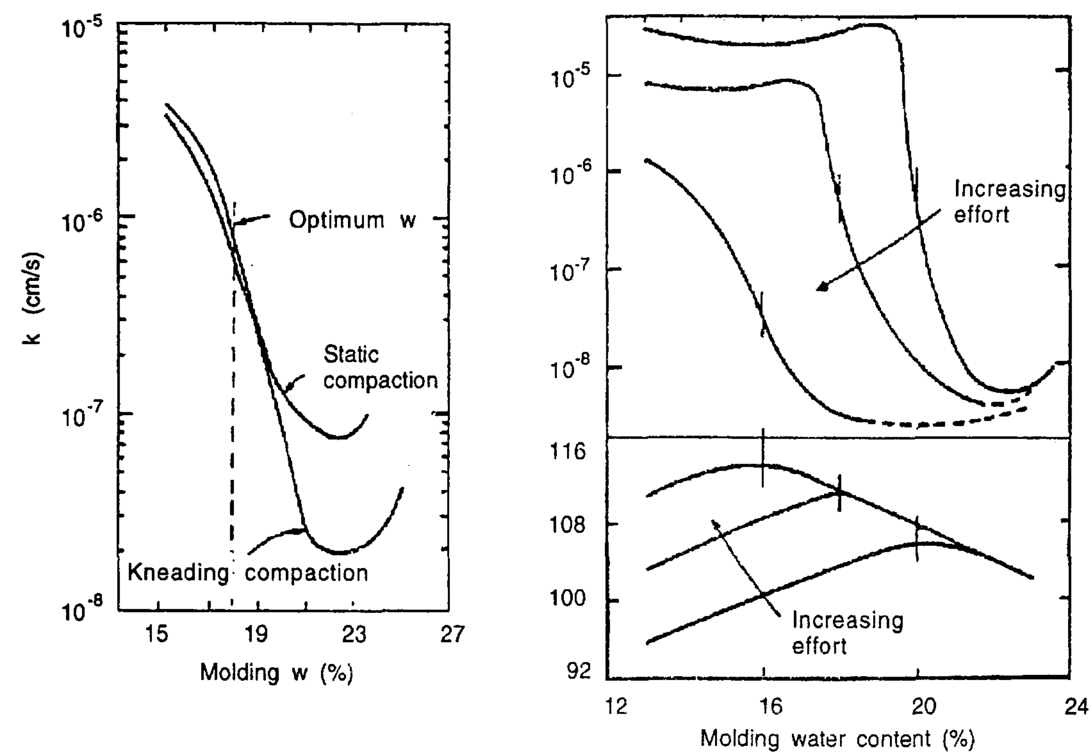


Figure 3-4. Influence of soil moisture content and compactive energy on soil permeability (U.S. EPA, 1989b).

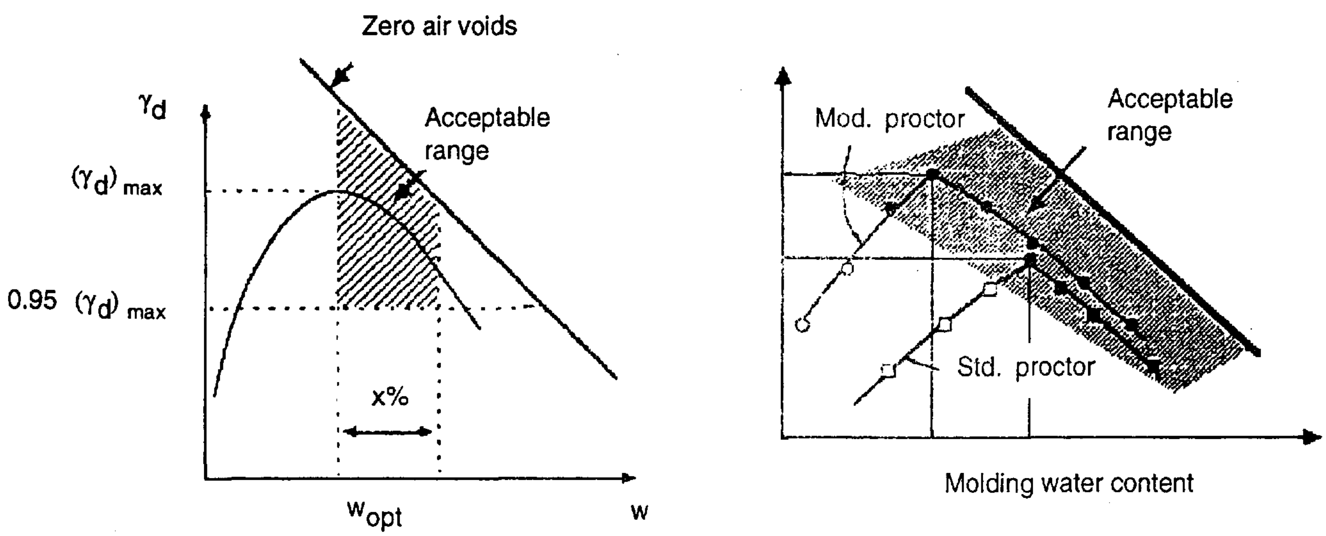


Figure 3-5. Moisture-density acceptance criteria for soil compaction (left: conventional criteria; right: permeability criteria) (U.S. EPA, 1989b).

space should be between pipes. The slope of collection laterals should be greater than 2 percent to achieve adequate flow velocity to help clean the pipes and ensure that settlement of the foundation caused by the weight of the waste will not reverse the slope of the pipe. The horizontal spacing of the collection pipes is calculated using the mounding equation shown in Figure 3-7. Design impingements (the number of inches of rainfall per minute) should be based on realistic operational conditions; a 24-hour, 25-year storm probably will generate excessive head (greater than the 30 centimeters allowed by Subtitle D) on the liner during the actual storm event.

3.4.3 Sumps

As mentioned earlier, sumps are low points in the liner constructed to collect leachate. Commonly, the

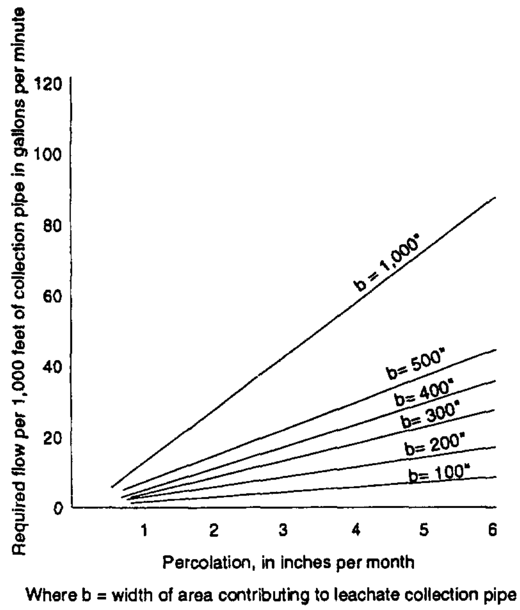
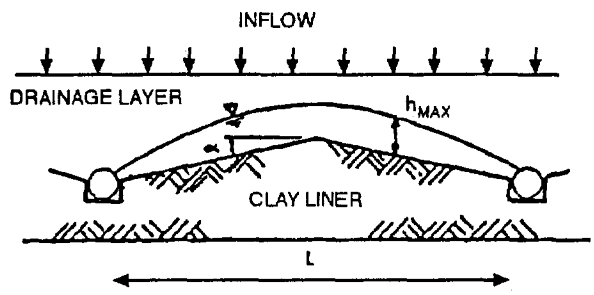


Figure 3-6. Required capacity of leachate collection pipe (U.S. EPA, 1989b).



$$h_{max} = \frac{L\sqrt{c}}{2}\left[\frac{\tan^2\alpha}{c} + 1 - \frac{\tan\alpha}{c}\sqrt{\tan^2\alpha + c}\right]$$

where:

c = q/k
k = permeability
q = inflow rate

Figure 3-7. Mounding equation used to calculate horizontal spacing of collection pipes (U.S. EPA, 1989b).

composite liner system is depressed in areas to create these sumps (see Figure 3-8). It is difficult to test the seaming in such sumps because of the slopes and corners on which the seams occur. Because of the difficulty in seam testing sumps, sump areas often are designed with an additional layer of geomembrane. Alternatively, many sumps now are being constructed using premanufactured units made of HDPE, with large-diameter HDPE pipe or HDPE manholes. Although more costly, the premanufactured sumps can be thoroughly field-tested.

3.4.4 Stormwater/Leachate Removal

During the design of the leachate collection system, the effect of stormwater on the landfill must be considered. Stormwater increases the amount of liquids requiring removal from the landfill and is the largest potential source of liquid reaching the sump. The stormwater removal problem is managed by using an impingement rate (see Section 3.4.2) based on the storm event for which the landfill was designed. The volume of stormwater treated as leachate, however, can be reduced significantly by including a stormwater/leachate separation system in the MSWLF design. Such systems divide the MSWLF into subcells using interior berms or using the slope of the liner as an interim stormwater system (see Figure 3-9). Rain falling into a subcell that contains no MSW is removed from the cell as stormwater. Before MSW is placed in a subcell, the stormwater removal system is disconnected from that subcell, and the barrier to the leachate collection system is removed. In this manner, the volume of leachate requiring treatment over the life of the cell can be reduced dramatically. This procedure provides a significant cost savings to the operator because leachate treatment costs average approximately $0.15 per gallon. See Section 4.4 for a further discussion of stormwater collection.

3.4.5 Biological Clogging

Biological growth on sand drains and geonets can cause clogging of the leachate collection system (U.S. EPA, 1991a). This clogging directly affects the liner's ability to maintain a hydraulic head of less than 30 centimeters. The biological growth occurs because of the high biological oxygen demand (BOD) level of the leachate being removed. This growth does not attack the liner or drainage system, but does clog the drainage elements. Current EPA-sponsored research shows that sand drains and geotextiles are particularly prone to clogging. The potential for clogging of the leachate collection system can be reduced using coarse stone around the collection pipe and providing cleanouts for the primary leachate collection pipes. Based on EPA research and similar findings in Germany and Italy, wrapping geotextiles around gravel drains surrounding the collector pipes is not recommended.

Figure 3-8. Depression of composite liner system to create sumps (provided by Greg Richardson).

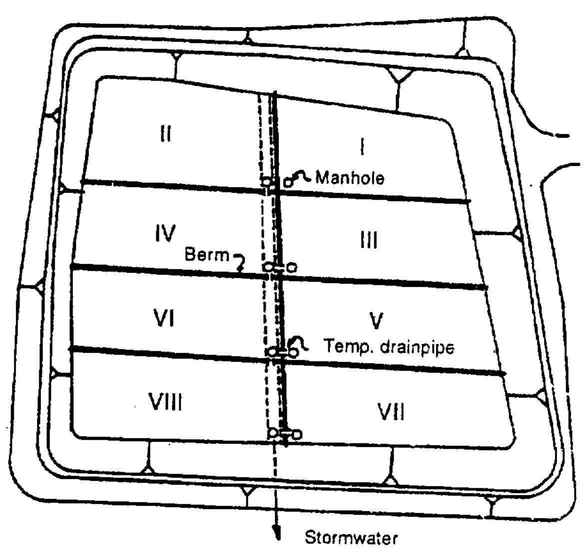


Figure 3-9. Leachate-stormwater separation system using interior berms (U.S. EPA, 1992c).

Chapter 4
Landfill Operations

4.1 Introduction

The Subtitle D operational requirements for landfills are designed to ensure the safety of people on the landfill site—facility operators, haulers, and the public—and to protect the environment. Subtitle D regulations also require that records be kept of the operation and that these records be available to regulatory personnel. Further, Subtitle D regulations require landfill owners or operators to implement measures to:

- Exclude hazardous waste and PCBs
- Provide daily cover
- Control onsite disease vectors
- Provide routine methane monitoring
- Eliminate most open burning
- Control public access
- Institute run-on/run-off controls
- Control discharges to surface waters
- Eliminate disposal of most liquid wastes
- Keep records that demonstrate compliance

To meet the requirements of liners and leachate collection systems, landfill design and construction have become increasingly complex. Because of this complexity in landfill design, facility integrity easily can be jeopardized by careless or inappropriate operations by an unknowledgeable operator. Therefore, facility operators should be fully aware of landfill operational requirements and the reasons for these requirements, particularly because the reason for some of the procedures might not be readily apparent. Communication about design and operation must be maintained in two directions. Design concepts must be communicated clearly and understood by operators to ensure the facility is operated as designed. At the same time, landfill designers and regulators should obtain feedback from the facility operators, who must implement the day-to-day operational requirements. A complex, sophisticated design that cannot be operated in the field will not achieve its intended purpose.

This section discusses the Subtitle D operational requirements. It also includes information on procedures that are not specifically required by the regulation but might be helpful in efficiently operating the landfill in a safe and environmentally sound manner. Some of these suggested procedures might reduce liability and help prevent problems requiring costly remediation. Because state regulations vary and might be more restrictive than Subtitle D, which sets only minimum standards, any operating plan developed must be coordinated with the appropriate state agencies.

More specifically, this section discusses waste identification and restriction, including inspections, source control, and segregation of hazardous wastes; daily cover materials, such as soils, geotextiles, and other materials, as well as cover costs; run-on/run-off controls; operational safety concerns; landfill gases, including gas accumulation, migration, collection, and treatment; and the management of special wastes, including medical wastes, sewage sludge, and incinerator ash.

4.2 Waste Identification and Restriction

Owners/operators of MSWLFs must develop a program to exclude regulated quantities of hazardous wastes from the landfill, as described in Section 4.2.1. Even with such a program, however, the owner/operator still might find that some unacceptable hazardous wastes have been delivered to the landfill site. These wastes must be segregated and handled appropriately, as discussed in Section 4.2.2. Section 4.2.3 outlines the recordkeeping and notification requirements for hazardous wastes found at MSWLFs.

4.2.1 Exclusion of Hazardous Wastes, PCBs, and Liquids

4.2.1.1 Why These Wastes Must Be Excluded

Hazardous and other inappropriate wastes must be excluded from MSWLFs for four reasons: (1) regulatory requirements; (2) protection of ground water from potential contamination; (3) incompatibility with other materials in the landfill; and (4) potential adverse impact on leachate treatability. Excluding hazardous and other inappropriate wastes from the landfill helps ensure that the wastes coming into the landfill are compatible with other wastes and materials at the site. If waste that reacts with water or leachate, for example, contacts the landfill liner, it could cause the liner material to fail. Restricting hazardous wastes also helps ensure that leachate remains treatable. Toxic wastes in the landfill, for example, could impair biological treatment of leachate (e.g., by destroying bacteria that normally biodegrade the leachate). Also, treatment is most effective when leachate is relatively uniform; if hazardous wastes, with their numerous components, were disposed in the landfill, the leachate quality could become highly variable.

The Subtitle D regulations require that landfill owners/operators implement a program for detecting regulated quantities of hazardous wastes and PCBs to prevent these wastes from being disposed in MSWLFs. Wastes are classified as hazardous either because they are listed as hazardous in 40 CFR Part 261 or because they exhibit hazardous characteristics, including toxicity (i.e., materials that fail the Toxic Characteristic Leaching Procedure [TCLP] test, 40 CFR Part 261, Appendix II); reactivity (materials that may be explosive or react violently with water); corrosivity; and ignitability. The definition of hazardous waste includes many specific compounds and some sludges from various industrial processes. Hazardous waste does not include material from: conditionally exempt small quantity generators, which are those generators that generate less than 100 kilograms per month of hazardous waste; household waste; and hazardous household waste. PCBs, which are regulated under the Toxic Substances Control Act, also must be excluded from municipal solid waste landfills.

Other wastes that must be excluded from MSWLFs include liquid wastes in bulk containers and uncontained liquid wastes. Small, household-type containers are acceptable, as are leachate and landfill gas condensate liquids returned (i.e., recirculated) to the landfill if the facility has a composite liner and leachate collection system.

Two methods can be used to exclude hazardous wastes from the landfill: random inspections and source control. These methods are discussed below in detail.

4.2.1.2 How To Ensure Wastes Are Excluded

Random Inspections

Unfortunately, the high cost of hazardous waste disposal at a properly licensed hazardous waste facility can be an economic incentive for illegal disposal at MSWLFs. One purpose of waste identification and random inspections is to discourage illegal dumping.

Subtitle D regulations state that random inspections for hazardous wastes must be performed unless the landfill owner takes other measures to exclude hazardous wastes. The regulations also state that facility operators must be trained to recognize hazardous wastes and PCBs. Subtitle D regulations do not specify how often inspections must be conducted or how they should be performed. Safety considerations during inspections are discussed in Section 4.5.4. Suggestions for conducting inspections are discussed below.

There are different ways of recognizing and identifying wastes that should be excluded from landfills. One of the most obvious ways is to look for Department of Transportation (DOT) and other descriptive labels that often identify whether the material is hazardous or nonhazardous and specify what a container holds. Manifest forms that might accompany the waste also can be reviewed.

Inspections can be performed in several ways. In a simple inspection, the operator can visually inspect waste by looking into an open truck to view its contents. If a more complete inspection seems warranted, the hauler should be instructed to dump the load onto a concrete pad, where normal disposal operations are not obstructed and such that subsequent handling of the waste is not inhibited. If some of the materials in the waste are not acceptable, they should be separated and managed as restricted waste. A typical flow sheet of activities to be followed during a waste inspection is shown in Figure 4-1.

Any unidentified waste could be an excluded waste and should be handled by properly trained personnel using appropriate techniques. If any waste is suspected of being hazardous, it should be stored as a hazardous waste until proved otherwise. If the contents of a container are unknown, proper protection, such as a face mask and protective clothing, should be worn. The potential risks should be understood when investigating an unknown waste.

Inspections should focus on loads that are more likely to contain unacceptable wastes, such as loads from commercial or industrial establishments and unknown haulers; other factors also might serve as a warning. For example, drums or other containers are not normally used to dispose of municipal solid waste, but are often used for liquids. Generally, a waste containing at least 20 percent solids would pass the paint filter test and would be defined as a solid (sludge can be disposed of in a landfill provided it is sufficiently dewatered and passes the paint filter test). Another warning sign is a waste with an oily appearance, which might indicate the presence of PCBs.

Source Control

Source control can be used as an alternative to conducting random inspections. With source control, a landfill receives wastes only from household and other sources

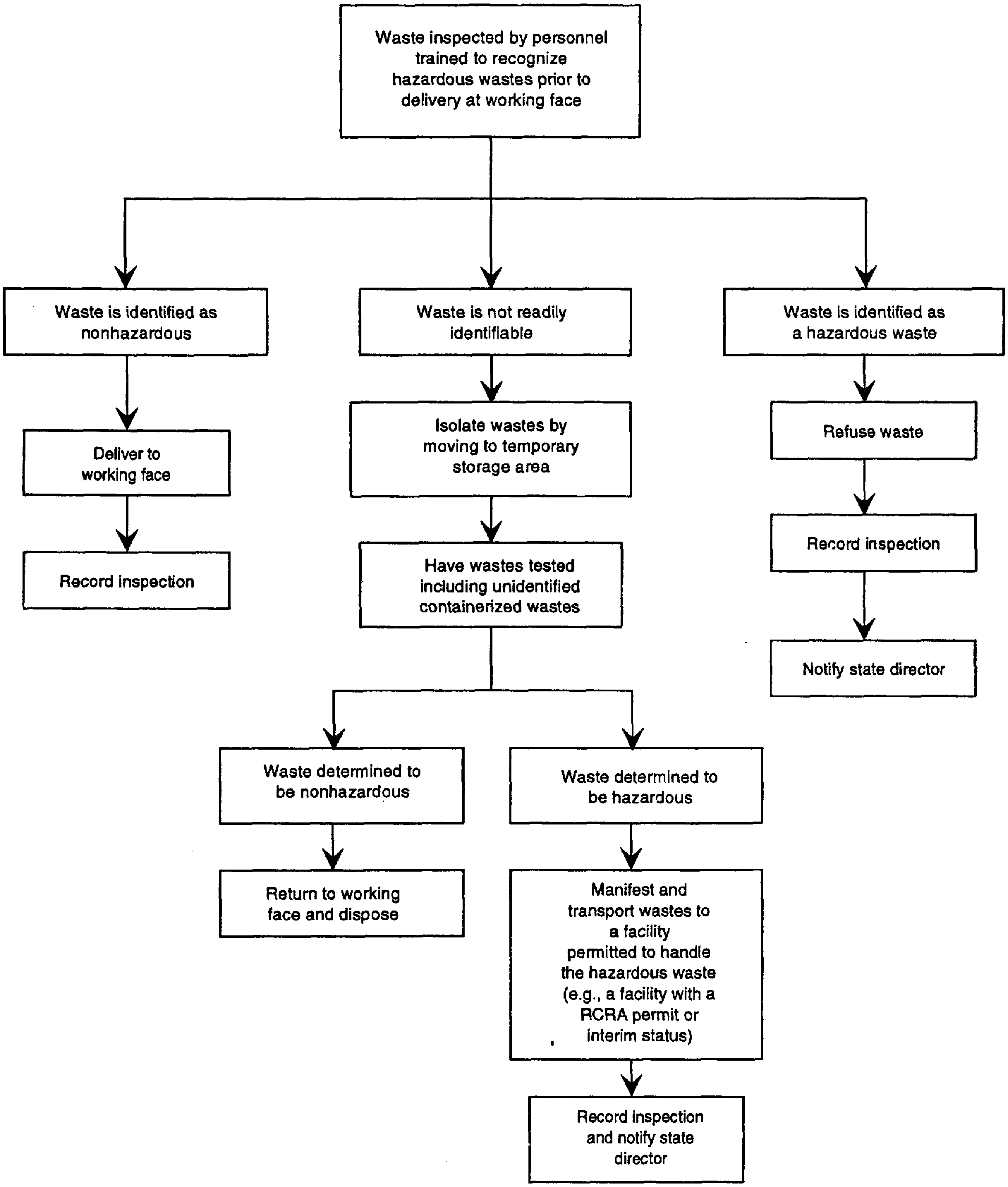


Figure 4-1. Hazardous waste inspection decision tree (U.S. EPA, 1993a).

that have been screened previously. The screening process would identify potential sources, determine if and when they might have unacceptable material, and establish programs to segregate excluded wastes generated from these sources. Wastes whose characteristics are unknown should be tested. Where possible, waste characteristics should be identified before the wastes are brought to the site. Source control is probably most suitable for very small, rural landfills. If the source of the waste cannot be controlled, random inspections should be conducted.

4.2.2 Segregating Hazardous Wastes

If hazardous wastes are found on site in the possession of the hauler, the hauler is still responsible for proper disposal. The landfill operator can reject any waste until it is identified and determined to be acceptable at the site. If hazardous wastes are identified on site and the hauler and/or source of the wastes cannot be identified, the landfill owner/operator is responsible for proper disposal.

Hazardous wastes identified at a landfill site can be stored for up to 90 days at the facility without a permit if the wastes are containerized and the date received is visibly marked on the container. Further, a temporary storage area must be designated, and the stored containers must be marked "Hazardous Waste." In addition, the landfill owner must designate an employee as an emergency coordinator whose phone number, along with the telephone number of the fire department, must be listed next to the facility phone.

The temporary storage area for hazardous wastes should be fenced off, with restricted access only. The area should be designed to protect soil and ground water, as well as people. Both unidentified and hazardous wastes should be kept in this protected area.

To transport the material off site, the landfill owner should either obtain an EPA identification number for transporting the waste or hire a licensed hauler to remove the wastes. The wastes should be packaged according to DOT regulations and labeled properly. If hazardous wastes are identified relatively frequently, the landfill owner might consider having a standing contract with a licensed hauler. These contractors are available at short notice to pick up hazardous waste loads. Such an arrangement might be more economic for very small facilities than training facility operators to handle hazardous wastes.

4.2.3 Recordkeeping and Notification

If hazardous wastes are found at the site either during an inspection or afterwards, the operator is required to record that information and notify the appropriate state or EPA personnel. The proper authorities must be notified of the results of any inspections, including when hazardous waste is rejected or returned to the hauler. Records must include the date, time the waste was received, the name of the hauling firm and the driver, the source of waste, the hauler identification number, and any observations made, as well as results of the inspection. Particularly at large facilities, the landfill operator also should consider instituting additional recordkeeping for conventional wastes and for haulers that come to the landfill regularly.

Many landfill owners already collect much of the information noted above. Alternatively, the information can be collected easily at the weigh station. These records are valuable not only to meet regulatory requirements, but also for long-term planning. In addition, these records can be valuable if hazardous wastes are found in a particular hauler's waste load. Knowledge of the content of previous loads that this hauler has brought to the site and the sources of these loads might help identify where problem wastes might be located in the landfill. The information also can be used with data from other facilities to track wastes from sources to disposal areas.

4.3 Daily Cover Material

4.3.1 Purpose of Daily Cover

Daily cover is placed each day over the waste received in a landfill to control disease vectors such as rodents, insects, and birds and to control odors, litter, and scavengers. A daily cover placed between individual landfill cells also helps create a firebreak, preventing fire from spreading throughout the landfill. If a landfill fire starts, it is almost impossible to stop. Water might successfully douse the fire but could create additional leachate. Excavating the burning area also might work for small fires or small landfills, but excavation can introduce oxygen into the landfill waste, possibly increasing the intensity of the fire.

Daily cover has other benefits as well. Leachate generation and gas migration can be controlled (by controlling infiltration) with an appropriate cover. Vehicle access also is improved if daily cover is provided, although the required 6 inches of daily cover might not be sufficient to support loaded trucks. Also, a tidy landfill with well-covered waste helps improve public perception of the landfill.

4.3.2 Soil Covers

Six inches of soil compacted on the waste generally is sufficient to control vectors, litter, and other potential problems (see Figure 4-2). The daily cover soil typically is spread with a bulldozer and compacted. Waste should be compacted before covering. If the waste is not compacted or is poorly compacted, the cover soil will fill

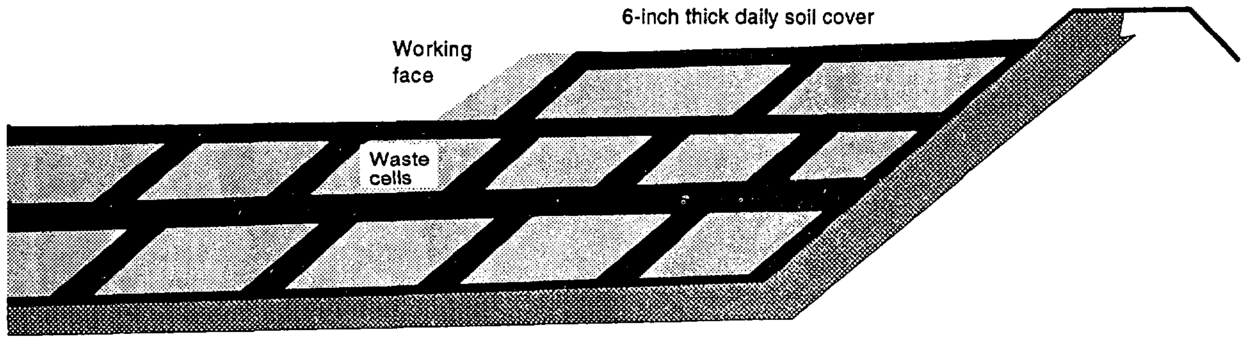


Figure 4-2. Daily soil cover for landfill operations (provided by ABB Environmental Services).

in the voids in the waste material and more cover soil will be required. Excessive cover soil is not only an unnecessary expense, but also uses up landfill space. Two types of soil covers are typically used: coarse, permeable soils (sands), and fine-grained, low-permeability covers (silty clays). Each type has distinct advantages, discussed below. For any type of soil cover, a small working face minimizes the amount of cover material needed.

4.3.2.1 Sand Covers

Sandy soils have been used for years as daily cover. They are easy to use and are relatively inexpensive, making them an ideal cover material. Unlike some other cover types, sandy soils do not create erosion problems on the site and provide a good traveling surface for vehicles. Sand is not difficult to handle when it gets wet, as is often the case with other materials. Gas movement in the landfill is not restricted by sandy soils. Sand covers do have some disadvantages, however. Sand allows percolation of rainfall into the landfill, thereby increasing the amount of leachate.

4.3.2.2 Silty Clay

Another type of soil cover is a silty clay material. This material has the advantage of restricting water infiltration into the landfill, a key factor in minimizing leachate production, which is desirable at some landfills. Working with a clay cover, however, is more difficult than working with sand. Silty clay is very difficult to obtain and use during the winter in northern climates. Also, because this type of cover restricts vertical leachate percolation, leachate within the landfill can migrate laterally and possibly break out on the side slopes of the landfill.

The selection of a cover is a compromise and is highly facility-specific. Some landfill owners use sand as a daily cover but use an intermediate cover consisting of a more silty soil for areas that have reached final slope or grade limits (as specified in the landfill permit). This silty soil is intended to remain as a cover for an extended period of time and is designed to inhibit water infiltration into the landfill. A silty soil cover should be seeded to protect against erosion.

4.3.2.3 Costs of Soil Covers

Soil cover costs can vary significantly depending on whether the soil material can be obtained onsite or needs to be brought in from another location. The real cost of using soil for daily cover involves two components: (1) the cost of obtaining and applying the soil cover, and (2) the revenue lost by filling potential landfill capacity with cover soil. The impact of 6 inches of daily cover soil on landfill capacity is shown in Figure 4-3. The graph presented is based on a specific working face size and waste density, but the general shape of the curve reflects the impact of cover soil on all landfills. (It does not reflect additional soil that might be necessary to fill waste voids). As the graph shows, a considerable amount of landfill space can be lost to daily cover. At a small landfill, where a relatively small amount of waste is handled each day (perhaps 20 or 50 cubic yards), as much as 25 percent of the landfill capacity might be filled by daily cover. Even at larger landfill sites, as much as 14 to 16 percent of the waste volume can be occupied by daily cover.

Approximately 0.2 cubic yards of soil are required to cover 1 square yard of waste to a depth of 6 inches. At an estimated cost of cover soil between $3 and $6 (1992 dollars) per cubic yard, the direct costs of daily cover soil for a landfill are approximately $0.60 to $1.20 per square yard. In addition to this direct cost, however, the 0.2 cubic yards per square yard of cover soil is also a loss of landfill capacity. The value of landfill space varies between landfills, but assuming a tipping fee of between $10 and $20 per cubic yard, the potential value of the lost landfill airspace would be between $2.00 and $4.00 per square yard of waste covered. Therefore, the actual cost of daily soil cover—the cost of the cover and the cost of lost landfill space—would be between $2.60 and $5.20 per square yard covered. An evaluation of the cost

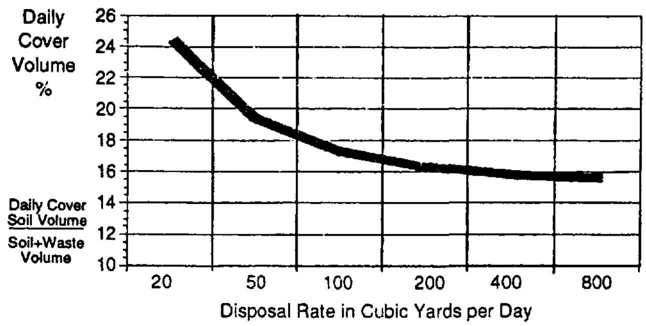


Figure 4-3. Impacts of daily soil cover on landfill capacity (U.S. EPA, 1992c).

of daily soil cover that includes the value of lost airspace has increased the attractiveness of alternate cover materials.

4.3.3 Alternative Cover Materials

Alternative cover materials could reduce the expense of daily cover. As long as the alternative material meets the intent of the 6-inch soil cover requirement for controlling disease vectors, fires, odors, litter, and scavengers, an alternative material can be used, subject to approval by the director of an approved state program, and based on a performance demonstration. Whether it is advantageous to use alternative covers will depend on a number of factors: the cost of materials and labor, whether the cover meets the particular landfill's requirements, and whether it is functionally equivalent to sand or other soil materials.

4.3.3.1 Geosynthetics

One possible alternative to soil covers is geosynthetic sheets, which are usually geotextiles and are sometimes geomembranes. Geosynthetics are relatively impermeable, do not take up any landfill volume, and inhibit vectors, litter, and scavengers. The sheets often are placed over the waste at the end of a day's operation and removed the next day prior to operation. Geosynthetic sheets have limited effectiveness in controlling odors, and concentrated odors can be released when the sheet is removed from the working face. The sheets also have minimal effectiveness in controlling landfill fires.

Before a geosynthetic is placed over the landfill, the waste should be well compacted. The geosynthetic can be dragged over the top of the working face by attaching the ends of the sheet to bulldozer blades or other suitable equipment. If mechanical equipment is not available, a group of workers can place the sheet, but this approach generally would be effective only on small working faces. After placement, the sheet should be anchored with sandbags, tires, or other means to keep it from being lifted by wind. The number of times a geosynthetic can be reused will depend on its continued integrity and its ability to remain relatively clean. A sheet left on the landfill and subsequently filled over could create a barrier to both the downward migration of water (leachate) and the upward migration of gas. Therefore, when a sheet is to be left in place it should be shredded sufficiently to avoid these barrier problems. The cost of using geosynthetics for daily cover has been reported to be between $1.50 and $3.00 (1992 dollars) per square yard. The range in cost to a large degree reflects the number of times a geosynthetic can be reused.

4.3.3.2 Foams

Different types of foam material are available at varying costs. Some foams are a plastic-like material that will become relatively rigid when placed. These foams can be placed at a depth of 1 to 2 inches and left for extended periods. Other foams do not become rigid and are suitable for shorter periods. Foams can be placed either with specialized vehicles or by hand. Some types of foams are difficult to place in wet weather or just before rain is expected because the rain will break apart the foam, although some foam manufacturers claim their foam will remain intact under these conditions. One advantage of a foam cover is that when waste is placed on top, the foam collapses, minimizing lost landfill space. Foams also do not inhibit the movement of gas or leachate. The cost of foam covers is reported to be about $1.50 to $2.00 (1992 dollars) per square yard.

4.3.3.3 Other Types of Alternative Daily Covers

Other materials, including some waste materials, have been used for covering MSWLFs. Various sludges have been used as covers, including industrial sludges. Some facilities have used pulp and paper mill sludge for cover, in part because of the relatively low permeability of these materials. Alternative cover materials often are tried because they can cost much less than soil covers.

4.3.4 Temporary Waivers for Daily Covers

Temporary waivers for daily covers can be granted by directors of approved state programs for extreme seasonal climatic conditions. Under these conditions, cover material might be frozen during parts of the year, or other conditions might exist that make daily covering impractical.

4.4 Run-on and Run-off Control

4.4.1 Run-on Control

Run-on water from outside the landfill that runs toward the landfill should be prevented from entering the containment area. Subtitle D regulations require a control system for run-on to prevent flow onto the active portion of the landfill during the peak discharge from a 25-year storm. The run-on requirement determines the size of ditches, dikes, culverts, etc. If run-on is not prevented from entering the landfill, it can percolate into the landfill and increase the amount of water and leachate that must be managed. Uncontrolled run-on also can cause potentially expensive erosion problems.

4.4.2 Run-off Control

Run-off from precipitation falling within the landfill itself must be managed to prevent the escape of contamination from the containment area and avoid erosion of the cover system. Subtitle D regulations require a system to collect and control the accumulated flow of water resulting from a 24-hour, 25-year storm at a minimum. This system must not discharge pollutants into surface-water bodies in violation of the Clean Water Act. Run-off must be controlled in two ways. First, run-off from active portions of the landfill, where it could contact waste or leachate, must be managed as leachate. The size of the leachate collection, transport, storage, and treatment systems must be sized to handle this run-off as well as the daily leachate generated. Keeping active landfill cells small and controlling grading to divert run-off from working areas also helps minimize the amount of run-off collected. Second, on inactive portions of the landfill, any rainfall that does not percolate into the ground or through the cover can be discharged as stormwater without having to be collected as leachate, thus reducing leachate collection costs (see Section 3.4). This uncontaminated run-off must be managed to control erosion using perimeter ditches, berms, siltation fences, hay bales, sedimentation basins, or other mechanisms, described below. An example of run-off control formed by waste slope and containment sideslope is presented in Figure 4-4.

4.4.2.1 Perimeter Ditches

Perimeter ditches commonly are used to control run-off and consist of a ditch upgradient of the landfill to keep run-on from entering the landfill site. Ditches downgradient of the site also are used to collect clean run-off from covered portions of the landfill. If a ditch has a relatively steep slope, riprap, pavement, or other surface might have to be placed on the slope to prevent erosion. On very steep slopes, gabion steps can be used to control the run-off velocity. Ditches should be oversized where possible to avoid overflowing. Ditch overflows can cause numerous problems. For example, landfill dikes can be eroded by ditch overflows, allowing water to flow into the landfill.

4.4.2.2 Berms

Temporary berms (dikes) can be used within a landfill for run-off control. These berms are small earthen structures, constructed of one or two feet of soil, that direct run-off away from the operating face, where the run-off could become contaminated. The berms should redirect the run-off at a shallow slope and slow velocity so that the berms themselves do not create an erosion problem.

4.4.2.3 Siltation Fences and Hay Bales

Siltation fences consist of a 2- to 3-ft wide geotextile fabric that is placed horizontally and supported by wooden posts. These fences slow the flow of water and retain sediment as the water filters through the geotextile. Hay bales perform a similar function. These fences or bales can be used temporarily for erosion control on the landfill cover or around the perimeter of the landfill before permanent grass growth is established. Siltation fence posts located within the landfill containment area should be installed carefully to avoid puncturing the landfill liner.

4.4.2.4 Sedimentation Basins

A sedimentation basin is an area that allows water to stand long enough to allow sediment in the water to settle out and accumulate in the bottom of the basin. The size of the basin depends on the drainage area upgradient of the basin. Periodically, the basin must be dredged to remove the sediment. Sedimentation basins (and ditches) quickly tend to become overgrown with aquatic plants if they are not maintained, reducing their effectiveness.

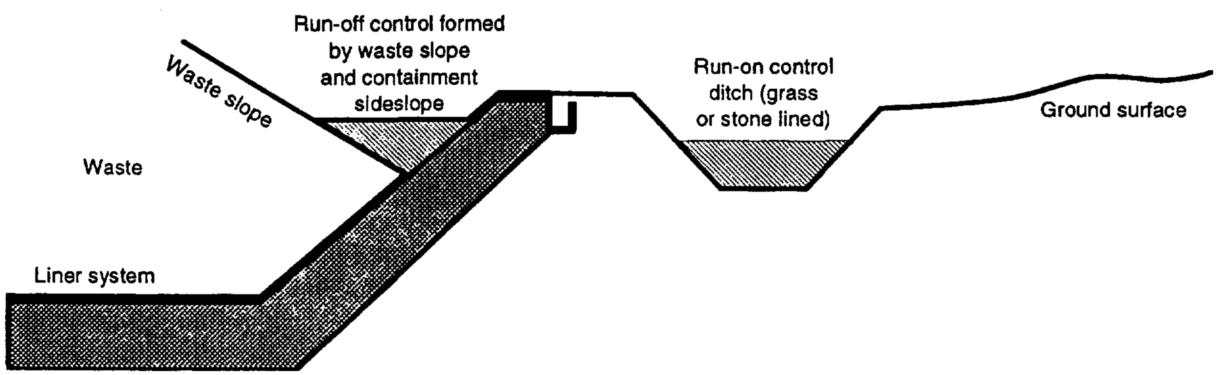


Figure 4-4. Example of run-on/run-off control structures (provided by ABB Environmental Services).

4.4.3 Factors To Consider in Selecting Run-on-Run-off Control Methods

Structures to control run-on and run-off generally must be designed for a storm of a particular intensity and duration. Because it is possible that the intensity and duration of the design storm might be exceeded during the active life of the facility, the ramifications of a larger storm on the environmental integrity of the landfill should be considered during the design process. Where possible, ditches and storage basins should be oversized if the overflow of these structures is likely to cause serious environmental damage. For example, if a perimeter ditch were to overflow and allow water to enter the landfill, leachate volumes could increase, or possible erosion of the cover soil could occur. Overflowing of a ditch also could erode the ditch banks, resulting in a diversion of water from the ditch into the landfill. Excess storm flow within a landfill and consequent increased leachate generation could cause an overflow of the leachate storage pond. The risks of these occurrences should be weighed against the costs of increasing the capacities of the control structures.

Some general suggestions regarding run-on and run-off control include: minimize the area from which run-off needs to be collected; use temporary berms to divert clean run-off to areas from which run-off does not require collection; and divert clean run-off from the leachate collection area to avoid collecting this water. The method used for controlling run-on and run-off depends on the options available; if run-on/run-off is being collected with the leachate and is pumped to a large-capacity treatment plant, then disposal is rapid and perhaps inexpensive; installing extensive run-on/ run-off control structures might not be necessary. If leachate and run-off are trucked to a disposal facility, berms or other onsite run-on/run-off collection methods could significantly minimize costs.

Design and operating considerations also should be investigated when determining run-on/run-off control methods. For example, the effect of run-off diversion on leachate generation from other areas of the landfill, now or in the future, should be considered. Also, if leachate is seeping through the cover from closed portions of the landfill, run-off from these portions must be considered contaminated and handled appropriately.

4.4.4 Leachate Storage

Treatment options for leachate include onsite treatment and discharge, and treatment at offsite facilities, with leachate transported by truck or pipeline. The onsite leachate storage requirements depend on the quantity and rate fluctuation of leachate generation, the limitations of the treatment system, and the rate at which leachate can be withdrawn from the storage facility. The size of a storage facility needed often depends on the amount of anticipated precipitation and the size of the portion of the landfill from which precipitation will be collected. A landfill that relies on a small, onsite treatment facility or trucking to an offsite treatment plant might require a greater storage capacity than a facility that can pump large quantities of leachate directly to a large treatment facility. The landfill should have sufficient storage capacity to handle the expected run-off from a 25-year, 24-hour storm plus the volume of leachate estimated to be generated during the storm and drawdown period, as required by Subtitle D regulations. Oversizing a storage basin provides additional security against overflowing, but the additional surface area can increase the amount of rainfall that is collected. Minimizing run-on and run-off can help reduce storage capacity needs.

4.5 Safety

4.5.1 General Operations

Operator personnel should be trained in workplace safety, including Occupational Safety and Health Act (OSHA) training programs, first aid, and emergency response. A health and safety plan also should be developed for the landfill operation. This plan should include risks and associated symptoms of exposure to types of wastes that are commonly brought to the landfill. It also should address other, less common wastes that may come to the site, such as municipal and industrial sludges or other industrial wastes. Employees should be aware that this plan is available to help them determine proper response should they suspect a certain substance is present. The health and safety plan also should include an evacuation plan and telephone numbers and names of contact persons at hospitals, first aid operations, and the local fire department.

A contingency plan should be developed to address potential landfill operation problems. This plan should identify who is in charge during emergencies, who should be contacted, and under what circumstances, and when the site should be closed. If the operators cannot handle a problem, the contingency plan should indicate which experts can be called. Having protocols for these issues ahead of time will reduce problems if an emergency occurs.

If an operational activity requires a person to be at a remote part of the landfill, he or she should have some kind of communication device, such as a two-way radio. Using the "buddy system" is also recommended; at least two people should be assigned to potentially dangerous tasks so that if someone is injured, for example, the other person can offer them assistance or summon help.

4.5.2 Access Restrictions

One of the Subtitle D regulatory requirements is restriction of public access to the landfill. This requirement pertains to restriction of access *to* the site as well as restrictions *on* the site. To restrict access to the site, perimeter fencing, gates, or other devices should be installed. How far a fence needs to extend depends on how easily the site can be accessed. Natural barriers such as a thick grove of trees, slopes, or banks can be used to prevent access to the landfill site or operating equipment. Separate dumping areas at the entrance to the landfill, such as boxes or dumping platforms, can be used to keep the public away from active landfill operations. If recycled materials are collected at the landfill, separate dumping areas could be incorporated into the recycling area.

4.5.3 Traffic Control

Other access control devices, including barriers, gates, and signs, should be used to direct the public to their destination once they are on the landfill site. Considerable traffic moves around the landfill, and the routes of traffic and people should be controlled. Trucks usually have back-up alarms, but people generally become desensitized to frequently sounded alarms, so alarms alone should not be relied on exclusively for traffic safety. Public access and traffic restrictions not only help control public exposure to potential hazards but also help prevent illegal dumping during operating and non-operating hours.

4.5.4 Personnel Equipment

Protective face masks and outer suits, chemical-resistant gloves and boots, and other safety equipment should be readily available if any chemicals are handled on site. Face masks should be fit-tested to ensure proper sealing. Other types of safety equipment include safety glasses and various types of face shields. Air packs might be needed if maintenance is performed in areas that could contain contaminated air or have oxygen-deficient atmospheres.

4.5.5 Hazardous Waste Inspections

The operator conducting hazardous waste inspections at the landfill site must understand the materials he or she might encounter and must be able to handle unexpected situations or emergencies. The Subtitle D regulations require that facility personnel be trained to recognize hazardous wastes and PCBs. This training should include the proper ways to conduct inspections to identify these wastes and provide an overview of Subtitle D, state regulations, OSHA safety regulations, and any applicable local regulations.

An important part of operator training is to identify the common types of MSW that are disposed of in the landfill. Many MSWLF sludges are nonhazardous, and operators should be able to recognize them. If an unusual waste (i.e., one with which the operator is not familiar) is brought to the landfill, an inspection is probably warranted.

Hazardous wastes and PCBs must be handled safely. Health and safety procedures for handling these wastes are published and maintained by OSHA. OSHA also provides a 40-hour course on health and safety for hazardous waste site workers that provides training for people conducting hazardous waste investigations. This course might provide more information than that required for municipal landfill personnel, but it does have some applicable information. Also, the Red Cross provides good first aid and CPR courses. Local fire departments and safety crews also will have helpful information.

The National Institute for Occupational Safety and Health (NIOSH) *Pocket Guide to Chemical Hazards* (Department of Health and Human Services, no date) is a valuable document that should be kept at a landfill site. This document includes characteristics of many substances as well as chemical names, synonyms for the chemical name, exposure limits, physical descriptions, incompatibility with other substances, and personnel protection that should be worn when handling different types of materials.

4.5.6 Gaseous Conditions

Potential safety problems, such as explosion or asphyxiation risks, exist when landfill gases such as methane and other toxic materials are generated. The landfill area is susceptible to gas accumulation. Gas enters leachate pipes and then can infiltrate manholes, pump stations, garages, operators' quarters, or other spaces near the landfill.

The Subtitle D regulations require onsite methane monitoring. (A more detailed discussion of methane and other landfill gases is presented in Section 4.6.) Monitoring for oxygen also should be conducted when anyone enters a confined space to ensure enough oxygen is present. Also, some monitoring devices, such as draëger tubes, can identify the specific gases and approximate concentrations present.

All structures within the landfill site should be vented, especially if they are anywhere near potential routes of gas movement. Belowground structures (e.g., leachate pump stations) that are likely to pick up gas should be vented before entry. Entry procedures should be developed for confined spaces, which pose a risk to workers if not vented properly. A number of such spaces, including manholes, will need to be accessed periodically for sampling, maintenance, or cleaning. For example, when a worker enters a leachate manhole, air can be pumped in to ensure that the manhole has an adequate atmosphere.

The worker probably should enter the manhole with an air pack, and another worker should have a hoist available to help remove the person entering the manhole in an emergency. If a worker collapses while in the manhole, a second worker should *not* enter the manhole to rescue the victim, because the rescuer might collapse, too. The victim should be removed from the manhole using the hoist, or a worker with a clean air supply should descend to retrieve the person. Rescue procedures should be established before a confined space is entered.

4.6 Landfill Gas Monitoring and Management

4.6.1 Gas Generation

Gas generation is a biological process in which microorganisms decompose organic wastes to produce carbon dioxide, methane, and other gases. Gases of concern are generated mostly by the anaerobic process, in which microorganisms generate gas in an environment deficient in oxygen. The ability of a landfill to generate gas depends on many factors, including waste composition, moisture content, pH, and nutrient availability. If the landfill is very dry, little gas will be generated. When older, well-covered landfills have been excavated, little waste decomposition (and therefore gas production) has been noted.

In some landfills, seasonal temperature changes also might influence gas generation. In the colder months, the rate of gas generation can decrease significantly in shallow landfills. Gas generation also can vary significantly throughout a landfill because of the distribution of different wastes types in the facility. Pockets of high microbial activity can be interspersed with other areas where little decomposition and gas generation occur.

Initially, when waste is placed in a landfill, conditions are aerobic. Atmospheric oxygen is present, and the organic materials in the waste begin to break down, producing mainly carbon dioxide and water. These aerobic processes are exothermic (heat-producing), and the landfill temperature begins to rise. As a landfill ages and more waste is placed in it, the oxygen is depleted, and anaerobic (oxygen-deficient) conditions eventually predominate. The organic materials in the waste break down into organic acids, which then further break down into methane and carbon dioxide.

Generation rates for gases vary among landfills and within each individual landfill. Theoretically, between 7 to 9 cubic feet of gas can be generated per pound of dry organic matter. In general, from 0.05 to 0.2 cubic feet of gas per year can be generated for every pound of refuse. Pressure in the landfill builds up as the gas is generated, and pressures of 1 to 3 inches of water (and as high as 6 inches in some cases) have been measured. It is this pressure that drives the gas from the landfill into the atmosphere, into the soil, and, potentially, into surrounding structures.

Figure 4-5 presents a graph showing landfill gas composition over time. Initially, the distribution of gases in the landfill is representative of the distribution of gases in the atmosphere—about 80 percent nitrogen, 20 percent oxygen, with some carbon dioxide and other compounds. Then the microorganisms present in the landfill begin to break down the organic material. Oxygen becomes depleted, the carbon dioxide level increases, and aerobic conditions begin changing to anaerobic conditions. Initially, the methane content is very low in the landfill, but becomes higher over time, whereas the carbon dioxide content tends to fall slightly. These gases tend to migrate as one mixed gas, rather than as segregated methane and carbon dioxide. Over longer periods, as the organic matter in the landfill is consumed, the rate of all gas generation ceases.

4.6.2 Characteristics and Potential Hazards of Landfill Gases

Potential hazards posed by landfill gas include explosions, asphyxiation, offsite gas migration, and disruptions of cover systems. Major constituents of landfill gas include methane, carbon dioxide, and hydrogen sulfide. Other compounds also can be present, including trace amounts of volatile organic compounds. Methane is the constituent of most concern. It is colorless and odorless, and therefore cannot be detected by smell. It is lighter than air and highly combustible. Methane will combust

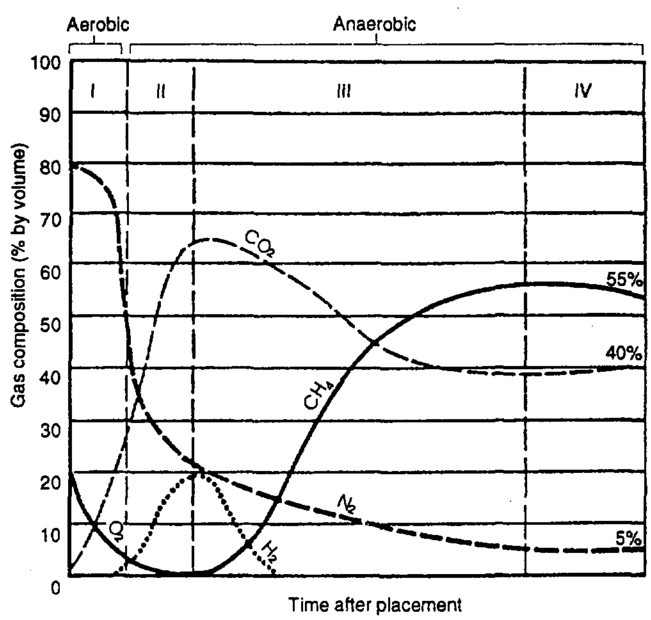


Figure 4-5. Changes in landfill gas composition over time (U.S. EPA, 1993d).

if its presence in air is between 5 and 15 percent. At lower than 5 percent methane content, not enough methane is present to allow combustion. At greater than 15-percent, not enough oxygen is available. Five percent is defined as the lower explosive limit (LEL) for methane. The 15 percent limit is the upper explosion limit (UEL). Subtitle D requires that landfill gas (methane) must not exceed 25 percent of the LEL in facility structures, such as operators' quarters, garages, pump stations, and any other facilities, and must not exceed the LEL, or 5 percent methane, in soil at the facility boundary. Methane monitoring at the facility boundary should include monitoring with soil gas monitoring probes.

Carbon dioxide is a very common gas, colorless and odorless, heavier than air, and noncombustible. Although carbon dioxide is heavier than air and methane is lighter than air, they are generated together, tend to travel together, and generally are found in a relatively uniform mixture throughout the landfill. Carbon dioxide is a concern because it can displace air in structures, creating an unbreathable and potentially asphyxiating atmosphere.

Hydrogen sulfide is a colorless gas but has a relatively strong odor, like that of rotten eggs. The odor can begin to be observed at about 5 parts per billion. The gas is an immediate danger to life and health at about 300 parts per million. Unfortunately, high concentrations of hydrogen sulfide cannot be differentiated from low concentrations by smell. OSHA/NIOSH recommends an action level of 10 to 20 parts per million for hydrogen sulfide, the level at which the owner/operator must take measures to protect worker safety.

In addition, because of its sulfur content, hydrogen sulfide can be transformed into sulfuric acid when combined with oxygen. Sulfuric acid is extremely corrosive and has caused many problems with pump stations and metallic devices in the leachate collection system.

4.6.3 Landfill Gas Migration

Landfill gas migrates in response to pressure, concentration, and possibly temperature gradients. Because gas generation causes gas pressure to build, a gradient is established that seeks to equalize itself. Gas migration in the landfill follows the path of least resistance. The degree to which gas migrates vertically or horizontally depends on many factors, including the nature of the landfill design, surrounding soils, type of waste, degree of waste segregation in the landfill, and the type of daily or final cover used at the facility. With a sand and gravel soil cover of relatively high permeability, gas tends to vent equally and vertically, perhaps through the cover onto the surface, and at a relatively uniform rate. With a low-permeability cover, gas tends to migrate horizontally. If a low-permeability cover is placed on the landfill, the gas no longer has a pathway for upward release. If lateral resistance to migration is less than vertical resistance, the gas tends to move laterally and might collect in low spots, such as basements, manholes, and pump stations adjacent to the landfill, resulting in oxygen-depleted and potentially explosive environments. Any structures on or near the landfill must be monitored to ensure that gas is not accumulating in that area. These migration concepts are shown in Figures 4-6 and 4-7.

Gas generally is transported through the unsaturated portion of the soil (i.e., that portion not filled with water) or fractures in rock. But because gas is soluble, it can migrate through saturated soil under sufficient pressure. For example, in some large, old landfills, relatively impermeable waste often was placed directly on the ground with no leachate collection system or drainage beneath the waste. These landfills can generate significant amounts of gas. At one facility, the pressure was so high that it drove the gas into the ground water. The gas then exited from the ground water into unsaturated soil at the site perimeter, where pressures were lower.

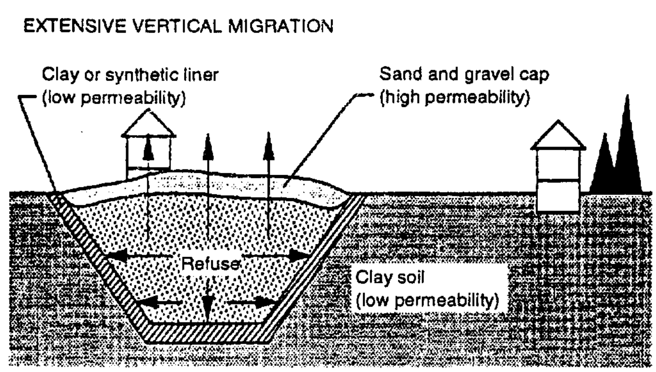


Figure 4-6. Landfill conditions that result in vertical gas migration (EMCON, 1981).

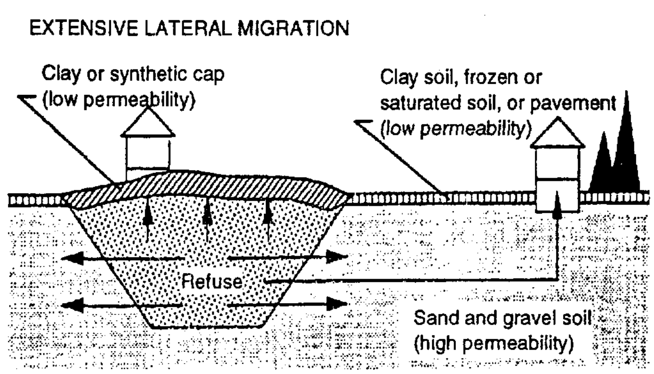


Figure 4-7. Landfill conditions that result in lateral gas migration (EMCON, 1981).

4.6.4 Landfill Gas Monitoring

Subtitle D requires a routine monitoring program for methane. This program should be based on facility-specific soil conditions. A landfill built in relatively permeable soils (sands and gravels) probably should be monitored for methane more frequently than one constructed in relatively impermeable (clay) soils. Also, nearby pipelines, sewer lines, water lines, and other utilities, even those not associated with the landfill, can become primary pathways for gas migration and thus might require monitoring. These structures are conducive to gas migration because they frequently are surrounded by special pipe-bedding soil, which is often much more permeable than native soil. Utilities associated with the landfill, such as leachate manholes and pump stations, also might contain methane. Elevated methane concentrations found in these locations might not trigger reporting or remediation activities, however.

If methane limits are exceeded, the landfill owner/operator is required to take several steps to protect human health and the environment. First, protective procedures must be undertaken immediately, and the appropriate state authorities must be notified. If a high methane gas level is detected in a structure, such as operators' quarters, the structure should be evacuated and the gas vented. If methane levels are exceeded in a pump station or elsewhere where personnel access might be required, proper confined entry procedures must be taken before the structure is entered. These procedures would include checking for oxygen as well as explosive conditions, using protocols for ventilating the space and emergency rescue, when necessary.

The owner/operator also must implement a remediation plan when methane limits are exceeded. The plan should address the nature and extent of the migration, where it was found, and what levels were monitored. It is useful to record soil characteristics (e.g., sandy soils) and note if the water table has dropped below normal during a dry season (which could increase pathways for gas migration). If soil conditions vary within the landfill, gas could be migrating in the permeable soils but not in other soils. A review of operations might help the owner/operator identify the potential causes of gas migration. For example, has there been a change in the landfill operation, such as a different area being worked or failure of the leachate or gas removal system? Closure activities also could alter available pathways for gas migration.

In addition to monitoring for gas in facility structures, owners/operators should install gas monitoring wells to measure belowground gas. Facility structures could include basements, manholes, and pump stations. Some of these structures, such as manholes and pump stations in which leachate is exposed to the atmosphere, would be expected to have some methane present. Elevated levels of methane found in these locations might not trigger remedial action, however.

Locations for gas monitoring wells, or probes, should be selected based on a review of the landfill's design, site geology and hydrology, and other features relevant to gas migration such as subsurface sewer or utility pipe locations. Wells should be placed in transmissive geologic strata at locations that allow gas to be measured near both the solid waste boundary (to identify gas migration) and the facility's property boundary (for compliance monitoring).

Homogeneous soils are perhaps best monitored with continuously screened wells. Heterogeneous soils, however, might require well clusters to be installed with discrete screened intervals to monitor different geologic strata. Well construction details will vary according to the geologic stratigraphy to be monitored at the well location. When multilevel monitoring well clusters are used, the screened intervals must be sealed from one another so that specific strata can be monitored discretely. The screened intervals can be constructed from slotted PVC well screen or from pipe into which holes have been drilled. Because these monitoring points are intended to be somewhat permanent, they must be protected from damage by vehicular traffic, either using wells with surface casing and protective posts or installing flush-mounted (e.g., roadbox) wells.

Typical gas monitoring wells are shown in Figures 4-8 and 4-9. These devices are similar in construction to ground-water monitoring wells, except that the screened area of the gas probe is located in the soil above the ground-water table, rather than in the ground water itself. Gas probes should be purged before sampling similarly to ground-water monitoring wells (see Chapter 5). At least one or two pore volumes of air should be purged from the well before sampling. Alternatively, the well can be purged until a constant gas concentration is evident in the monitoring equipment. Ambient temperature, barometric pressure, and gas pressure in the probe should be measured before a gas sample is taken for analysis.

Portable methane meters and explosimeters are used most commonly to monitor gas concentrations. They are relatively simple, durable devices that can be hand-held while gas measurements are taken. Methane meters indicate the percentage of methane present, whereas explosimeters measure the combustibility of the gas as the percentage of the LEL (see Section 4.6.2). Either device can be used for compliance monitoring. An oxygen meter also is commonly used with these devices. For more sophisticated analysis, a portable gas chromatograph can be used, or samples can be collected and sent to a laboratory to determine the gas constituents by gas chromatography analytical methods. All instruments must be properly calibrated. Other gases, such as

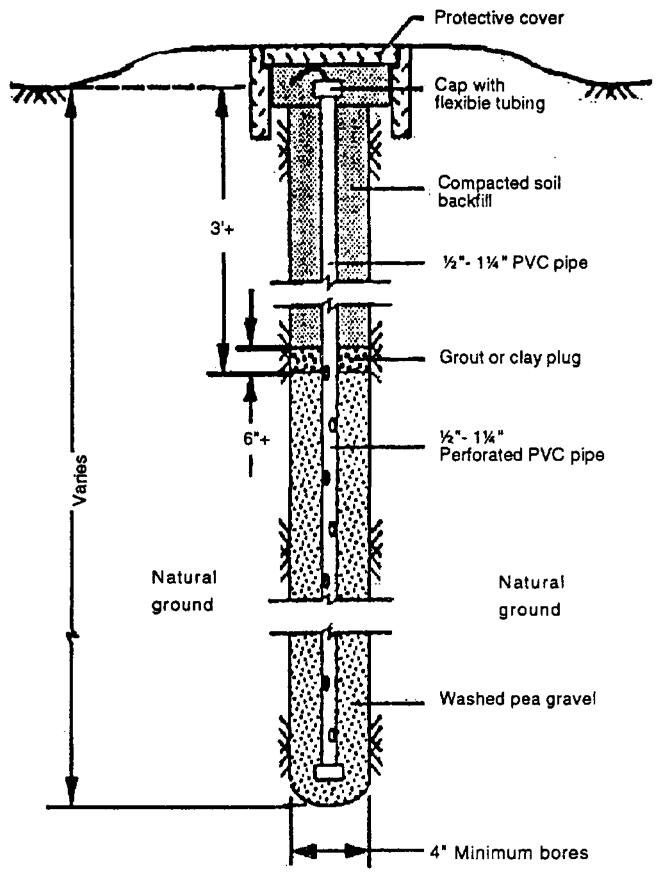


Figure 4-8. Typical single screen gas monitoring probe (EMCON, 1980).

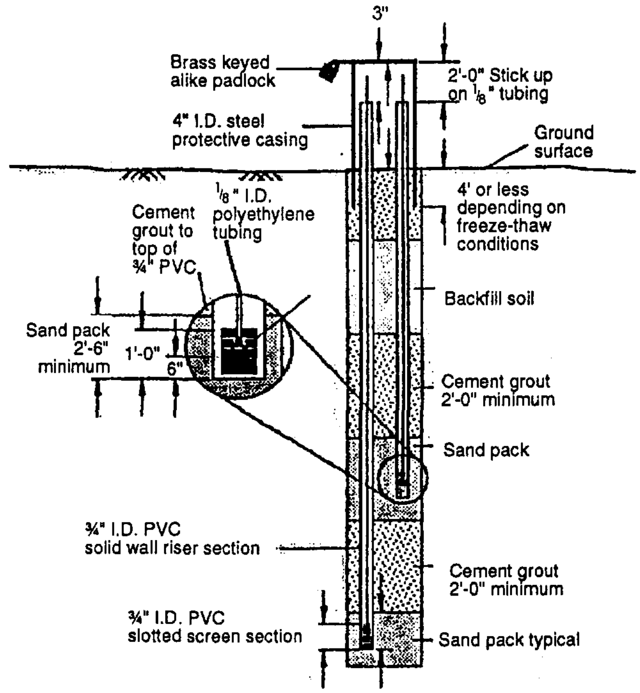


Figure 4-9. Typical multiple screen gas monitoring probe (E.C. Jordan Co., 1986).

carbon dioxide, can interfere with the accuracy of readings by some meters. Consultation with the manufacturer of the equipment to determine its limitations is recommended.

Other indicators of gas migration, besides actual sampling, include the odor of hydrogen sulfide, the presence of stressed vegetation on closed portions of the landfill, or a grass kill where the grass is otherwise growing well. Dead or dying vegetation is a good indication that methane is seeping through the soil and replacing the oxygen in the soil, because such conditions interfere with vegetation growth.

4.6.5 Gas Collection

On May 30, 1991, EPA published proposed regulations (40 CFR Parts 51, 52, and 60) which included standards of performance for new MSWLFs and emissions guidelines for existing MSWLFs pursuant to sections 111(b) and 111(d) of the Clean Air Act. Under the proposed regulations, MSWLFs emitting greater than 150 megagrams per year (167 tons per year) of nonmethane organic compounds would be required to design and install gas collection systems. The final regulations are expected in late 1994. These regulations could apply to hundreds of new and existing MSWLFs across the country and will likely result in subsequent state regulations that will also establish limitations on emissions from MSWLFs.

During landfill operations, and more frequently during and after landfill closure, operators might need to control gas movement. Two different systems can be used to collect vented gas—passive and active collection systems. With either type, redundancy in the gas collection system is important for ensuring continued operation of the system. Redundancy protects against the loss of system components caused by settlement and failure of the entire system from a single malfunctioning component. Redundancy can include additional gas extraction wells and header pipes (see Section 4.6.5.2).

4.6.5.1 Passive Collection Systems

Passive gas collection systems allow gas to be released without using mechanical devices such as blowers or pumps. The systems can be used outside or within the landfill. Perimeter trenches and pipes vented to the atmosphere can act as a passive system by intercepting lateral migration of gas through the soil. A trench is dug around the landfill to the depth of the water table (if shallow), and is backfilled with pervious stone and pipes, which act as a passive barrier.

Depending on the types of soil at the facility, a more solid and less permeable barrier might be needed on the trench side away from the landfill to improve passive venting within the trench. If the soil is sandy with a permeability similar to that of the trench, a flexible membrane liner placed on the outside of the trench will help stop gas migration and allow the gas to pass up through the vent. For facilities with a deeper water table, a slurry wall can be used as a remedial measure to stop gas migration.

Figure 4-10 presents a typical passive vent used at landfills with both intermediate and final cover systems. A perforated collection pipe is placed in a granular vent layer above the waste. Typically, coarse sand is used for the vent layer, but geotextiles and geonets can be combined as an alternative. This pervious pipe is connected to a vertical riser pipe, which is connected to a 90-degree elbow (gooseneck) through which gas is vented. A barrier layer placed above the vent layer causes gases to stop at the geomembrane or the clay surface and migrate laterally to the pipes and up to the atmosphere. Vents can be independent or connected in a system of lateral header pipes. Piping should be buried deep enough to prevent frost-heaving. Care must be taken to protect these vents; if they are broken the piping will provide a conduit for surface water into the waste.

The advantage of passive gas collection systems is that they are relatively inexpensive and require little maintenance. If a passive system is not working properly and vents are connected with a header pipe in a portion of the landfill, the system can be converted to an active gas collection system.

4.6.5.2 Active Collection Systems

If a passive system is insufficient to manage landfill gas problems, an active collection system might be necessary. In an active system, power is applied to create a vacuum or positive pressure, forcing gas from the landfill. Most active gas collection systems use negative pressure and apply a vacuum to pull gas out of the soil in the landfill via extraction wells, extraction trenches, or a venting layer.

Although positive pressure systems are not commonly used, a positive pressure system could be used in a trench around the landfill perimeter to create a higher pressure zone. This higher pressure zone would tend to force air back toward the landfill, thereby redirecting any gas migrating through the ground upwards into the atmosphere.

Typically, active gas collection systems are designed based on pilot test results that are used to determine spacing and operating flow parameters for gas extraction wells or trenches. As a rule of thumb, extraction wells should be approximately 200 feet apart. A better way to determine gas well locations is to conduct a pilot pumping test, similar to a pumping test for ground water. For a pilot extraction test, a pilot well is installed, along with vacuum pressure monitoring wells at about 25, 50, and 100 feet away from the extraction well. As gas is pulled out of the extraction well, vacuum pressures in piezometers are monitored to determine how far away from the extraction well gas movement occurs. From these data, the permeability of air flow in the waste, the radius of influence of the extraction wells, and maximum flow rates per unit length of well or extraction trench length can be determined.

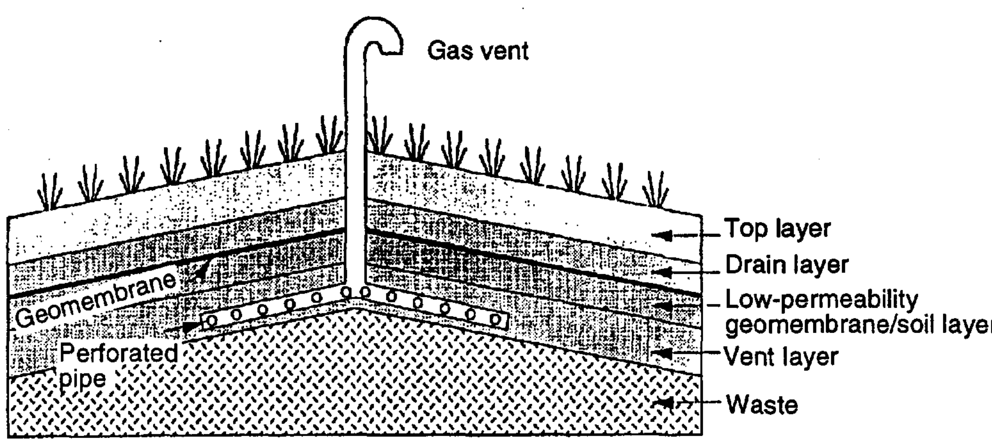


Figure 4-10. Typical passive gas collection system for venting of landfill gas (U.S. EPA, 1992c).

Figure 4-11 illustrates a gas extraction well that can be used within the landfill or around the perimeter. Gas wells or header systems should be equipped with a valve that regulates flow and serves as a sampling port. Such a valve is important because gas generation can vary throughout different parts of the landfill. Additionally, over time, the flow from certain areas might need to be adjusted. By monitoring gas quality (e.g., methane content) and measuring gas pressures, the operator can assess more readily the seasonal and long-term changes in gas production and distribution within the landfill and make appropriate adjustments.

Gas extraction wells should be sealed to minimize atmospheric releases. Depending on the age of the landfill and the location of the wells, differential settlement can occur, leading to well damage. Efforts to design the extraction system with flexible connections and materials capable of withstanding strain will help maintain system integrity. Also with differential settlement, low spots in the collection or header pipes can develop, and the pipe can fill with gas condensate, which effectively plugs the pipe. Condensate traps, spaced 300 to 500 feet apart, should be included in the design of the gas collection system. These traps will allow the condensate, which migrates with the gas, to drop out of the gas collection pipe, thus preventing pipe plugging. For every million cubic feet of gas that is generated, about 50 to 600 gallons of condensate might be generated, depending on the vacuum pressure of the system and the moisture content of the waste. Condensate is one of the few liquids that can be disposed in Subtitle D landfills.

Blowers used to pull gas from the landfill generally operate from 300 to 2,000 cubic feet per minute and apply 10 to 100 inches of negative water pressure at the well heads. The size of the blower and the amount of head are design parameters that should be based on actual pilot field data to ensure proper system design and operation. Blower capacity should be matched against future needs for gas management as a facility expands over time or as needs change, such as when landfill cells are added to or disconnected from the gas recovery system.

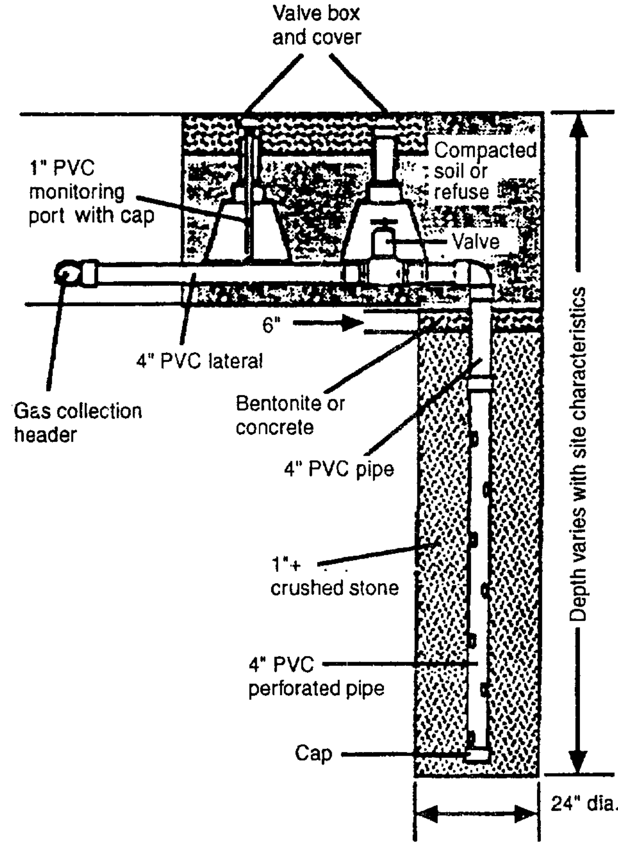


Figure 4-11. Schematic of gas extraction well (SCS, 1980).

4.6.6 Gas Treatment

If landfill gas is collected in an active system, the gas must be treated. Gas treatment usually involves either thermal destruction of organic compounds by flaring or gas processing and energy recovery.

4.6.6.1 Flaring

A flare is a controlled combustion unit. Flaring is a common treatment method when enough methane (e.g., greater than approximately 20 percent by volume) is present in the gas. Flaring reduces odors and often is a much more effective method for odor control than passive venting. Most flares designed today are enclosed flares, which allow longer residence times, elevated combustion temperatures, and greater thermal destruction efficiency than open flares.

Generally, gas enters the flare system from the landfill through a valve located upstream of the blower (Figure 4-12). The blower outlet exits through a pipe to the flare stack, which contains instruments to verify temperature and flame presence and to prevent burnback of gas into the blower. These instruments use passive safety mechanisms, such as flame arresters and liquid-filled flashback units, or active protection systems, such as thermocouples (to detect combustion flashback), self-actuated valves (to shut off gas entry), and auto-shutdown sensors. If for any reason the flame goes out, a flame detector will immediately sense that no flame is present and will shut down the self-actuated valve, thus preventing uncombusted gas from escaping into the atmosphere. A flare should include both passive and active safety systems; if one of these systems malfunctions, the other system can take over. The stack is generally purged before flare startup, and, typically, propane is used for ignition and pilot fuel. The flare stack also can include equipment for monitoring air quality exiting the system, which might be required by some state permits.

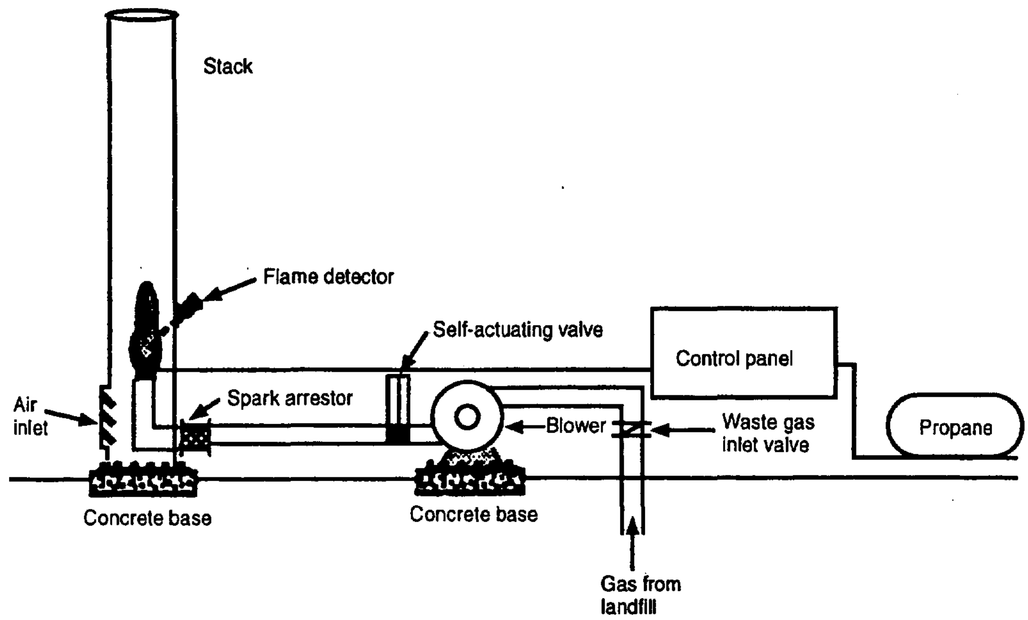


Figure 4-12. Schematic of a landfill flare system with blower (ABB Environmental Services, 1990).

4.6.6.2 Gas Processing and Energy Recovery

Gas also can be processed by removing water and impurities, including carbon dioxide. The heat value of unprocessed landfill gas is about 500 Btu per standard cubic foot. This heat value is about half that of natural gas, primarily because only about half of landfill gas is methane. Processing increases the heat value of the gas to approximately 1,000 Btu per cubic foot. At this level, gas can be directed into a pipeline and sold to a utility as natural gas.

Energy recovery is being used at some landfills, particularly larger landfills where the magnitude of the operation and the potential life of the project make energy recovery economically viable. Whether energy can be recovered at a reasonable cost depends on the quality and volume of the gas. At a small landfill, gas with a heat value of 500 Btu per pound can be used to run a modified internal combustion engine or a generator to convert gas to electrical energy. At a larger landfill, moisture and carbon dioxide removal (through scrubbing and gas polishing with carbon or polymer adsorption) enables the gas to be used to run boilers and turbine generators for energy recovery.

Generally, landfills closed for fewer than 5 years are the best candidates for energy recovery because over time, even with proper conditions, the ability of a landfill to generate gas decreases. With optimum conditions, however, an area of a landfill might produce gas for 15 years or more, depending on the rate of gas generation, the water content of the waste, and the manner in which the landfill was closed. Modern closure requirements for landfills are intended to limit moisture infiltrating the landfill. To what degree these requirements will affect long-term gas generation is unknown, but they should lead to a reduced period of gas generation after closure.

4.7 Special Wastes

By definition, a number of wastes are classified between what is commonly considered municipal solid waste and what constitutes potentially hazardous waste. Although these wastes do not, in general, pose a public health or environmental problem if managed properly, they might require special handling procedures. These wastes include materials such as medical wastes, sewage sludge, and municipal solid waste incinerator ash.

4.7.1 Medical Wastes

Most medical wastes, such as disposable clothing, bandages, syringes (sharps), and other disposable instruments, come from hospitals and clinics. Medical waste is not directly regulated under Subtitle D. Certain RCRA Subtitle C listed hazardous wastes may be generated by medical facilities, or certain medical wastes may exhibit hazardous characteristics which would require special packaging, storage, labeling, transport, and disposal procedures. Many state regulations affect medical waste handling and disposal. It is strongly recommended that landfill owners and operators contact their state regulators regarding disposal requirements and restrictions if medical wastes are delivered to the facility.

Human tissues generally cannot be disposed of as medical waste and require special treatment, such as incineration. Because medical waste regulations vary from state to state, the degree to which different waste types require sterilization before disposal also varies. Most waste materials that have come in contact with human fluids are required to have been treated for pathogens by either high temperature steam, autoclave, or microwave sterilization procedures. Before medical wastes are transported from a hospital, they must be clearly marked, packaged, labeled, and contained within special medical waste disposal bags. Sharps must be contained within crush-proof plastic containers to protect workers from incidental contact. The greatest concern in handling medical wastes after they arrive at a landfill is incidental infection, thus operators must be careful when handling these wastes.

Segregation of medical wastes in dedicated disposal areas is usually appropriate, because most people perceive these wastes as health risks, even if they have been disinfected and treated. Protection of public health and worker safety is paramount. Operators should not drive over bags of medical wastes with landfill equipment, which can tear the bags apart and scatter the contents over the landfill. Medical wastes should be covered carefully and immediately after disposal. Disposal areas should be recorded in the facility's operation records so these areas can be located later, especially if work, such as large-scale removal of wastes, will be occurring.

The owner/operator should contact all local waste hauling firms involved in medical waste transportation, as well as hospitals and the state, to develop sound contractual and operational procedures to ensure proper management of these wastes.

4.7.2 Sewage Sludge and Industrial Sludge

Sewage sludge comes from two primary sources—publicly owned treatment works and other wastewater treatment facilities. This byproduct of wastewater treatment is composed of organic and inorganic solids and water. Usually water and organic material constitute 90 percent, and inorganic material 10 percent, of sewage sludge. The sludge is very high in nutrients and can be biologically active and odorous if not stabilized. Sewage sludge can have an industrial waste component if the treatment plant services industrial facilities.

Sewage sludge cannot be disposed at a MSWLF until it passes the paint filter liquids test (PFLT). Generally, it must be mixed with soil or in some way dewatered to approximately 20 percent solids content to be considered a solid for disposal at a MSWLF. Stabilized sewage sludge, such as compost, which has been treated to kill pathogens, might be used in a landfill as a cover material. Composted sewage sludge also might be used as a soil conditioner to promote grass growth on the landfill if the sludge has been properly treated to destroy pathogens according to 40 CFR Part 503 regulations. Domestic septage—material from septic tanks—is a similar type of material that generally is very wet. Therefore, domestic septage will not readily pass the paint filter liquids test and cannot be disposed at a MSWLF until it has a sufficient solids content to pass the test.

Disposal of sewage sludge can be problematic for two reasons. First, unstabilized sewage sludge can create odor problems. Second, sewage sludge lacks good compaction characteristics. Large volumes of sewage sludge with poor compaction and strength characteristics should not be concentrated near the sideslope of most landfills because of potential for waste slope stability problems. Sludge with pronounced odor problems might require additional daily cover to control odors or the use of a different cover material that more completely contains the migration of odors (e.g., a silty or clay-rich cover soil). In most cases, sewage sludge disposal in a landfill can be accommodated readily with minor modifications to operating procedures.

Industrial sludges can be disposed in landfills provided they are determined to be neither characteristic nor listed hazardous wastes. Some industrial sludges are relatively inert, can be dewatered to a large extent, and potentially can be used as interim or daily cover material, which saves the expense of using soil materials. For example, paper mill primary sludges, which are high in fiber content and clays, can be dewatered to 40 to 50 percent solids, possess good material handling properties, and have been used as daily cover.

4.7.3 Incinerator Ash

Municipal solid waste incinerator ash is the residual product of a variety of incinerator types, including modern waste-to-energy conversion plants, such as large mass burn facilities, and older incinerators, such as small, modular incinerators. In the last half decade, waste-to-energy technology has reemerged as a practical, although at times socially unpopular, means of managing MSW. During incineration, metals contained in the waste ash are partitioned between the bottom and fly ash and the flue gas. (Flue gas treatment residues also might be present in incinerator ash.)

Concerns over ash management at landfills has focused on leachate quality at ash monofills and the potential effects of MSW leachates on the environmental mobility of certain components, such as heavy metals and dioxin and furan isomers potentially formed during the combustion process and contained in the ash. The U.S. Supreme Court ruled on May 2, 1994, that municipal waste combustion ash must be managed under federal hazardous waste rules. This ruling will result in municipal solid waste incinerators and waste-to-energy facilities being required to conduct regular Toxicity Characteristic Leaching Procedure (TCLP) testing on their combustion ash. Ash that exhibits toxicity characteristics must then be managed as a hazardous waste in compliance with RCRA Subtitle C.

From the perspective of the landfill operator, ash management issues can be separated into two areas: potential hot loads and blowing ash. In most incinerators, the fly ash is mixed with the quenched bottom ash and delivered to the landfill as a wet mixture with limited free liquid. This material, if the ash was created during proper combustion conditions, has a consistency of semiwet concrete with large fragments of metallic objects. If the fly ash has been treated with calcium-based flue gas scrubbing agents (lime, CaO), the ash probably will have moderate to high pozzuolanic characteristics; that is, under proper moisture and compaction control, the ash will harden into a low-strength concrete-like material. Therefore, dedicated disposal of the ash might be warranted if water is added as appropriate and the ash is compacted. Under these conditions of proper moisture and compaction, the ash solidifies within several weeks of disposal.

By controlling water content, either at the source or at the landfill, the operator can avoid problems associated with blowing ash and fires. MSW incinerator ash can be a desirable material in landfills because of its mechanical properties, such as strength, compactability, etc. Ash leachates do not appear to present difficulties for modern Subtitle D facilities because of the long-term leachate quality of the ash and stringent waste containment and leachate collection systems required for modern landfills.

Chapter 5
Ground-Water Monitoring

5.1 Introduction to Subtitle D Ground-Water Monitoring Requirements

Subtitle D ground-water monitoring requirements apply to new and existing MSWLF units, as well as to lateral expansions of units. Subtitle D includes limited waivers if a MSWLF owner/operator can demonstrate that the landfill is located in a hydrologic setting that will prevent hazardous constituents from migrating into ground water. This demonstration must be certified by a qualified ground-water scientist and approved by the director of an approved state program. Limited waivers require that no ground-water contamination occur during the active life of the unit, at facility closure, and during post-closure. For all other MSWLF units, ground-water monitoring must be performed.

The time frame for implementing the ground-water monitoring requirements varies depending on the type of landfill unit. New units must have an adequate ground-water monitoring system in place at the time the new unit begins accepting waste. The compliance date for lateral expansions and for existing units depends on their location relative to municipal drinking water intakes. The regulation specifies a phased approach, dependent on the relative location of the units, that requires compliance by the dates listed in the regulation or according to an alternative schedule set by the director of an approved state program. All existing or laterally expanding MSWLFs must have a ground-water monitoring system in place by October 9, 1996, at the latest.

The regulation also states that a MSWLF must have a sufficient number of appropriately located ground-water monitoring wells. This seemingly vague wording has a very exacting purpose—to account for site-specificity. Well locations and sampling must be based on the distinctive hydrologic circumstances at each site. A "spandex hydrology" approach, that is, a one-size-fits-all strategy, which assumes that monitoring systems at different landfills will be the same, is unacceptable. Ground-water flow and hydrogeologic conditions might be similar at some sites, but the variety of circumstances that affect the potential movement of pollutants from a MSWLF must be assessed individually. Unsupported assumptions, such as presupposing that ground-water flow at a site is parallel to the topographic gradient, can be erroneous and costly.

Ground-water monitoring systems must be capable of yielding samples from the uppermost aquifer, that is, the highest water-bearing strata that can release water in usable amounts (usually, to the water-table aquifer). Samples must be representative of ground-water quality, particularly at the *point of compliance*, which is usually a hydrologically downgradient point that any potential pollutant plume is expected to intersect. Determination of the point of compliance can be particularly important depending on site conditions (see Sections 5.3 and 5.3.2) and is specified by the director of an approved state program. In addition, representative background water quality must be able to be ascertained from the wells in the monitoring system. The effort to delineate the naturally occurring, ambient ground water has potential benefits for the landfill owner/operator, particularly in instances where naturally high background concentrations of chemical pollutants can be identified.

Subtitle D states that the appropriate number, location, and depth of monitoring wells should be based on site-specific data, including ground-water elevation measurements, stratigraphy, and measurements of aquifer parameters (such as hydraulic conductivity, transmissivity, and storage capacity). The regulation also states that each landfill unit should have a separate ground-water monitoring system, although multiunit systems may be used instead of separate monitoring systems at each MSWLF unit if approved by the director of an approved state program. Each monitoring system must be certified by either a qualified ground-water scientist or the director of an approved state program.

Sections 5.2 and 5.3 discuss Subtitle D ground-water monitoring requirements in the context of ground-water movement, the types of pollutants commonly found at landfills, and potential pollutant transport. These factors determine to a large degree where ground-water monitoring wells should be located.

Construction of ground-water monitoring wells, including selection of well locations (Section 5.4), installation of wells (Section 5.5), well development and maintenance

(Section 5.6), and abandonment of wells (Section 5.7), is then described. Section 5.8 discusses documentation requirements for ground-water monitoring. Section 5.9 presents ground-water sampling techniques, as well as monitoring of the vadose zone, which is the predominantly unsaturated zone between the ground surface and the ground-water zone. Also included in this section are methods for ground-water elevation and aquifer parameter measurements. Section 5.11 provides an overview of sample analysis, with an emphasis on statistical significance. Finally, Sections 5.10 and 5.12 discuss detection and assessment monitoring, two types of monitoring specified in Subtitle D. For more information on ground-water monitoring methods, see U.S. EPA (1993c.)

5.2 Overview of Ground-Water Movement

The following discussion covers selected concepts concerning ground-water flow, focusing on the relationship between ground-water movement and the design of MSWLF ground-water monitoring systems. Ground-water flow concepts underlie the fundamental principles of contaminant plume migration, the location of the point of compliance, and release characterization and remediation. For more comprehensive reviews of the principles of ground-water hydrology, refer to Freeze and Cherry (1979).

Historically, ground-water flow has been not well understood, as evidenced by early environmental laws, which described all ground-water flow in terms of underground rivers and streams. In reality, there are few underground rivers and streams where ground water moves through channels or conduits. (Such constrained flow paths do exist, such as fractured rock or cave systems in karst regions, but these ground-water environments are not prevalent at most landfills near the ground surface.) More commonly, ground-water movement is laminar (occurs through small, interstitial spaces [interconnected voids] between solid, granular particles) and is of low velocity. Turbulent, high-velocity ground-water movement can exist in fractured rock, karst terrain, or certain gravel systems, or near pumping wells. More often, however, ground-water flux is nonturbulent.

5.2.1 *Hydraulic Head, Hydraulic Gradient, and the Water Table*

Ground water flows from regions of high hydraulic head to low hydraulic head. Total hydraulic head is the sum of elevation head (potential energy expressed as a distance above a reference plane) and pressure head (expressed as a depth below a free-water surface). In regions with little vertical ground-water movement, the slope of a water table, which is the interface between the vadose zone and the ground-water zone, is a measure of the change in total hydraulic head with distance. This change in hydraulic head with distance is also called the hydraulic gradient. The hydraulic gradient can be thought of as the driving force for ground-water flow. Therefore, in the absence of vertical ground-water flow, water will move horizontally from regions of high water-table (or piezometric) elevations to low elevations. With respect to landfills, the uppermost aquifer is of primary concern; thus the slope of a water table will provide a first approximation of the direction of ground-water flow. Because the slope of the water table may change with time, temporal considerations can be of particular consequence to the final spatial design of a ground-water monitoring system at a MSWLF. If vertical ground-water flow also is present at a site, both horizontal and vertical hydraulic gradients are crucial for interpreting ground-water flow under a landfill.

In the aqueous phase, the water-soluble components of leachate from a landfill move similarly to any infiltrating water. The leachate will percolate down to the ground-water zone and be transported according to the hydraulic gradient. As the leachate plume moves with the ground water, mechanical dispersion will occur, spreading the plume longitudinally (in the direction the plume is moving) and transversely (perpendicular to the plume movement). Typically, longitudinal dispersion is greater than transverse dispersion; this difference is normally accentuated in highly permeable zones.

5.2.2 *The Ground-Water/Surface-Water Link*

Ground-water flow and surface-water drainage surrounding landfills are closely linked. The ground-water monitoring system designer needs to understand the links between surface water and ground water to design a sensible ground-water monitoring system. Key to this understanding is a knowledge of gaining and losing streams. In gaining streams or perennial streams, the stream gains water from the adjoining aquifer because the water table in the aquifer is higher than the water level in the stream itself. Ephemeral streams, or losing streams, exist where the water table is lower than the water level in a stream (or bottom of the streambed if the channel is dry). Water can infiltrate from a surface-water channel to the ground water or can be supplied from the subsurface to a gaining stream. Consequently, pollution from a surface discharge can become a ground-water problem or vice versa. For example, any water in surface channels under losing-stream conditions will tend to move downward. Surface discharge of liquid pollutants adjacent to landfills with deep water tables will create downward migration of contaminants to ground water, and the resultant pollutant plume could be mistaken for leachate originating from the landfill.

Figure 5-1 shows a gaining stream with adjacent ground water flowing from high hydraulic head to lower hydraulic head in the stream. Note that water is also flowing upward under the stream; although topographically upward, the flow is moving hydraulically from a higher hydraulic head to a lower hydraulic head. Piezometers, which are tubes or small-diameter wells used to measure pressure, can be placed at different depths to ascertain vertical head differences and vertical direction of flow. Head differences between two vertically displaced piezometers could indicate upwelling water or downward-moving water. Knowledge of these types of movements near landfill sites is profoundly important.

Siting landfills near losing streams can result in several problems. For example, many regions' landfills often have been sited in the cavities left by sand and gravel operations or other excavation activities. In arid regions of the United States, sand and gravel operations often are conducted in dry, ephemeral streambeds. Streambeds typically have potentially high infiltration rates and serve as ground-water recharge areas when stormwater flow occurs. In addition to the obvious drawback of possible intermittent flooding of a landfill near the streambed, the water tables in recharging areas become elevated, or mounded, during storms. When the water table mounds, the distance from the ground water to the bottom of the landfill decreases, and ground water can even flood a landfill from below. In addition, in regions of the United States where glaciation has occurred, sand and gravel companies have often mined in eskers, which are remnant fluvial features possessing high hydraulic conductivity. These mined areas, when abandoned, often have been used as landfills. Because eskers are primary aquifers in glaciated terrain, landfills, with their potential pollutants, and aquifer systems might be in close contact.

5.2.3 *Factors Affecting Point-of-Compliance Selection*

Subtitle D requires that MSWLFs be designed in one of two ways. Either (1) specifications detailed in the regulation for a particular type of liner and leachate collection system must be met, or (2) the design must ensure that the concentrations of certain chemicals listed in the regulation do not exceed specified maximum contaminant levels at the relevant point of compliance. (The second design option may be used in states with approved programs or by petition in states without approved programs.) Design criteria are discussed in more detail in Chapter 3. The point of compliance for a MSWLF, specified by the director of an approved state program or set at the waste management unit boundary in states without an approved program, is based on hydrogeological characteristics of the area, physical and chemical characteristics of the landfill leachate, ground-water quality and use, and other relevant factors specified in the regulation.

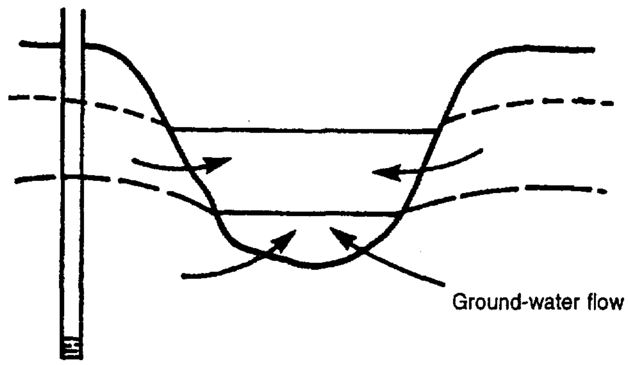


Figure 5-1. Example of a gaining stream (U.S. EPA, 1987a).

The purpose of establishing a point of compliance is to locate a measurement point where any ground-water pollutant from the landfill will be sure to pass, and where a representative sample can be obtained. Although determining a point that is hydraulically downgradient seems to be straightforward, many complicating factors can make selection of a point of compliance difficult. For example, if an area is located near a losing stream or recharge area, the hydraulic gradient and direction of flow could vary over time.

Other factors that can affect the direction, velocity, and water level of ground water include well use and tidal cycles. For example, seasonal fluctuations in ground-water pumping, such as those associated with agricultural water use, can alter and even reverse the direction of flow. Ground-water and landfill leachate flow can be slowed, stopped, diverted, or sped up.

Thus, ground water near a landfill cannot be assumed to be a static system that is only affected by leachate or water moving through the landfill. If head conditions vary over time, the optimal point of compliance also will vary. Therefore, in situations where temporal changes in hydraulic head occur, a greater density of monitoring wells will be needed at and around the landfill facility to account for ground-water movement in several directions.

5.2.4 *Subsurface Heterogeneity*

So far, this discussion has assumed that a homogeneous, isotropic aquifer surrounds a landfill site—one in which hydraulic conductivity at any point is of the same magnitude in any direction, and hydraulic properties are uniform at different points in the subsurface. Actual landfill sites can be quite heterogeneous in the subsurface environment and may include clay lenses and other barriers to ground-water flow. Faults, fractures, and secondary porosities, such as animal burrows, worm holes, or plant root perforations, can redirect leachate movement and change the rate of vertical migration.

Heterogeneous hydraulic properties in an aquifer can be the result of spatial variation in geologic structure and materials. This variability can include aquifers on top of other aquifers, as shown in Figure 5-2. The top, unconfined water-table aquifer must be monitored according to the Subtitle D regulations. An underlying confined aquifer also is shown in the figure, sandwiched between confining layers of soil or other geologic materials.

A confined aquifer is also known as an artesian aquifer, and a well placed in this type of aquifer is referred to as an artesian well, named after a town in France where this type of well was first used. If the pressure is high enough in an artesian aquifer, the water will flow out freely at the top of the well. Artesian aquifers are rarely uppermost aquifers because they are sandwiched between confining layers (aquicludes) or semiconfining layers (aquitards). Although the Subtitle D regulation states that monitoring is required in the uppermost aquifer (typically an unconfined or water-table aquifer), an underlying, confined aquifer also can become contaminated.

A confined aquifer, bounded by aquitards that can transmit water from overlying or underlying aquifers, is termed a leaky aquifer. If municipal water supply wells were drawing water from a leaky confined aquifer, the reduction in hydraulic head would encourage flow into the leaky aquifer from overlying and underlying water-bearing strata. Any landfill leachate present in a nearby shallow, unconfined aquifer would be influenced to move vertically downward at these types of sites. In this situation, monitoring may be required in an underlying aquifer as well as in an uppermost aquifer.

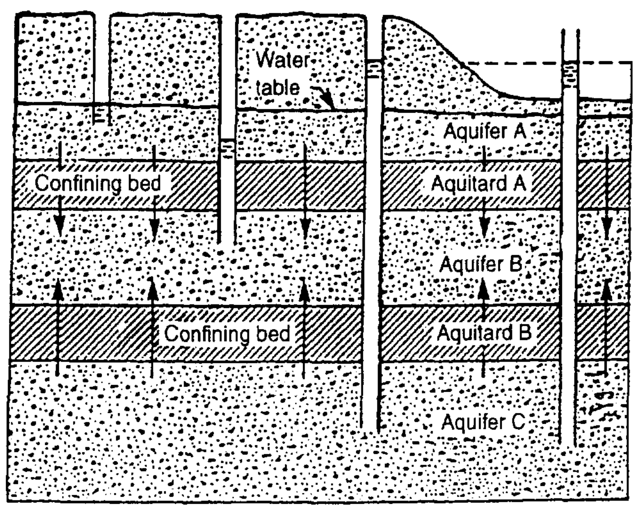


Figure 5-2. Example of geologic heterogeneity, with one aquifer above another (U.S. EPA, 1987a).

5.3 Pollutants at Landfills

5.3.1 *Overview of Types of Pollutants*

Pollutant migration depends not only on the complexities of ground-water movement, but also on the physical and chemical characteristics of the pollutants themselves. These characteristics can determine pollutant transport to a large extent. Historically, many different pollutants have been dumped into landfills (e.g., liquids, caustic materials, pesticides, and sludges, many of which are hazardous). In new and future landfill units, hazardous pollutants probably will be less of a problem because of better landfill construction and control of the types of wastes disposed at landfill sites.

Several classes of chemicals typically found in landfill leachate might be detected in a monitoring well located on the leading edge of a contaminant plume. One important chemical parameter that might be an early warning of the potential migration of other landfill pollutants is nitrate, which is found at high levels in the breakdown products of organic material. Nitrates (NO_3) typically are very mobile in the subsurface system and often are generated readily; thus, the presence of nitrates might be a good indicator of landfill leachate pollution at some sites if other nitrate sources, such as fertilizers, are not located nearby. Increased total dissolved solids (TDS) in ground water can be another indicator of impending leachate movement from landfills. In older landfills, a variety of wastes often can be found in the subsurface. Many of these wastes are soluble in ground water and can contribute to increased TDS levels. Such wastes found in landfills might include pesticides, solvents, petroleum products, and metals.

5.3.1.1 Aqueous-Phase Pollutants

Aqueous-phase pollutants, which are dissolved contaminants that can move in ground water, are important considerations at all landfill sites. These dissolved chemical compounds generally move according to the same principles as water (see Section 5.2): from high to low hydraulic head and in a laminar fashion, unless the flow is altered by pumping, fractured rock media, confining layers, or other factors. Their movement, however, can be retarded by their sorption onto soil particles.

5.3.1.2 Nonaqueous-Phase Pollutants

Some liquid landfill pollutants generally do not dissolve in water. These nonaqueous-phase liquids (known as NAPLs) exist in a separate liquid phase that is immiscible with water; that is, NAPLs do not mix freely with water. NAPLs include petroleum products, such as oils, diesel fuel, and gasoline; industrial solvents, such as degreasing agents; PCBs; and other related compounds. Historically, NAPLs have been disposed at many municipal landfills, creating a legacy of tainted soils and contaminated ground water.

In spite of the inability of these liquids to mix with water, the compounds that constitute NAPLs can dissolve slowly in water. Many NAPLs are hydrocarbon mixtures, which contain hundreds of component compounds; for example, gasoline contains 200 to 300 compounds. These individual compounds have varying aqueous solubilities. Compounds that dissolve readily in water can be swept from a subsurface spill, for example, leaving a residual of less-soluble products in the soil. The movement of NAPLs, which differs from general ground-water flow, is described in Section 5.3.2.2.

5.3.2 *Pollutant Transport*

5.3.2.1 General Principles

Fortunately, many pollutants in landfill leachate do not migrate rapidly. Many chemicals bind to soil and other geologic material, which inhibits their movement. For example, many metals and pesticides have a tendency to adsorb onto soil and can be retained in one area for long periods. But chemicals that tend to mobilize pollutants also can exist in landfill wastes. Mobilizing pollutants include chelating agents (e.g., soaps), complexation agents, or solvating agents. These agents restrict the ability of certain pollutants to sorb onto porous material by wrapping themselves around a chemical, thus inhibiting adsorption, allowing mobility, and possibly increasing migration of landfill contaminants.

An important factor in the mobility of metals is speciation. Speciation is the ability of an element to assume a certain chemical configuration similar to that of closely related compounds. Metals can exist in more than one form in subsurface environments. Different species of metals have different mobilities, sorption coefficients (which describe the ability of a compound to adsorb onto soils), and partitioning coefficients (which describe the ability of a compound to volatilize, dissolve, or otherwise change phase). Chromium, for example, can take the form of hexavalent chromium (including chromate, bichromate, and dichromate) and trivalent chromium. The hexavalent chromium species are very mobile in the subsurface, whereas the trivalent species are relatively immobile and will not readily move in the subsurface.

Speciation is determined by subsurface oxygen and pH conditions. Basic solutions are represented by pH greater than 7, and acidic solutions by pH less than 7. The term eH is used to represent oxygen conditions. Zero eH represents a neutral oxygen condition, high eH represents high oxygen conditions, and low eH represents lower oxygen (or reducing) conditions. Shifts in eH or pH can change the species of chromium and therefore its mobility because each metal in the landfill will move according to its speciation. Other ambient conditions can affect the pH or eH and therefore speciation; for example, microbiological conditions in the geologic environment surrounding a landfill can affect oxygen concentrations and, thus, transport.

In addition to the chemical characteristics of pollutants, other processes also are important to the transport of pollutants from landfills. These processes are discussed below.

Advection

Advection involves the mass flux of a fluid or gas from one region to another according to pressure or head gradients. Movement by advection in ground water reflects pressure/elevation potential (e.g., from high hydraulic head to low hydraulic head). For gaseous migration, advection involves vapor flux from high gaseous pressure to low gaseous pressure.

Diffusion

Diffusion is the process by which elements equilibrate. It results from the Brownian (random) motion of energetic molecules in a fluid undergoing constant collision with other particles. Diffusive processes are driven by concentration gradients rather than pressure or head gradients (as in advection). Diffusion does not result in the large-scale lateral movement of a fluid body, as does advection. Rather, diffusive processes are typically slower than advective processes and generally proceed four or five orders of magnitude slower in a liquid than in a vapor. Diffusive processes dominate in media with low permeability, such as clay landfill liners.

Dispersion

Gas or liquid cannot move in a straight line in geologic media. Solid particles block flow paths, and the migrating fluid moves around these particles and spreads out. This spreading process is called mechanical dispersion. Spreading occurs transversely (perpendicular to the flow direction) and also longitudinally (in the direction of flow) because pore space size varies. Flow velocity will vary as well. Longitudinal dispersion typically is several times greater than transverse dispersion.

Other Transport Considerations

Advection, diffusion, and dispersion are the basic mass transport mechanisms, but other processes also allow mass transfer, partitioning, and transformation. These processes include secondary porosity, cosolvent effects, and particle transport, which are discussed below. Additional transport mechanisms include sorption, complexation, acid-base reactions, dissolution, and biological transformation. Discussion of these latter mechanisms is beyond the scope of this document.

Secondary porosity can be created by naturally occurring phenomena, such as animal burrows, root holes, worm holes, and shrinking clays, which enhance downward movement of liquids. A cosolvent effect is the change in aqueous solubility of a compound caused by the introduction of another compound. This effect can create significant changes in the rate of a pollutant's migration. Because a landfill can contain many solvent mixtures, it is possible that cosolvent effects could occur in MSWLFs.

Particle transport is associated with ground water flowing through fractured rock. Normally, metals or pesticides in a fractured rock media will adsorb onto the sides of the walls and not move (with some exceptions). If colloidal material is carried with the ground water, however, a pollutant may sorb onto the suspended particles that are flowing with the water and become mobile. Particles that can serve as vehicles for pollutants include clay material, asbestos, bacteria, viruses, and yeast particles.

5.3.2.2 A Special Case—Transport of NAPLs

NAPLs, which are characterized by their inability to dissolve in water, were introduced in Section 5.3.1.2. These compounds pose environmental problems not only because of their individual toxicity, carcinogenicity, or teratogenicity, but also because they can serve as preferred solvents for other pollutants. Many pesticides, for example, have low aqueous solubility but will readily dissolve in an organic liquid. The preferential partitioning of some pollutants into any existing fuel, solvent, or oil near a landfill can dramatically affect the ability of the pollutants to migrate. Movement of certain landfill pollutants is dictated primarily by whether NAPLs exist in or near the facility, such as from a service station or other potential source.

Aromatic hydrocarbons, such as benzene, toluene, ethyl benzene, the xylene compounds, and naphthalene, are the most water-soluble components of NAPLs and often will undergo dissolution from a landfill environment. Appearance of these compounds in ground water could be a precursor to more widespread petroleum contamination at a site.

Liquid movement in the vadose zone is dominated by competing gravity and capillary forces. In regions where only a small amount of liquid is present, or in fine-grained material, liquids are held in tension (under negative-gage pressure) and flow occurs because of capillary forces. If that same liquid is allowed to build up and the liquid assumes a positive gage pressure, gravity flow can begin. The two types of flow are notably different—under capillary flow conditions, a liquid will remain in small pore spaces; under gravity flow conditions, liquids will flow readily into large pore spaces.

Aqueous-phase and nonaqueous-phase liquids compete for pore space in strikingly different ways. Many soils and other porous geologic materials are hydrophilic; that is, they have greater adhesive forces with water than with NAPLs. Because of the hydrophilic environment and because water has over twice the cohesive force between its molecules than that of most other liquids, water will often "win the battle" for small pore spaces in a NAPL-soaked vadose zone or NAPL-contaminated aquifer.

As a result of these physical properties, wet, porous clay layers can block downward-moving NAPLs by occluding the pore space with water. The blocking action in these fine pore spaces, often referred to as a capillary barrier, can deflect NAPLs in seemingly unexpected directions. For example, if a NAPL is allowed to accumulate above a capillary boundary, it will build up its own fluid pressure and eventually will be able to penetrate and move through the underlying barrier. Such penetration is normally along narrow bands or fingers that represent paths of least resistance for the NAPL. If the source of a NAPL is discontinuous over time and if a leak slows down, water could reinvade regions previously saturated with NAPL, leaving isolated NAPL globules in the larger pore spaces. Generally, movement of these globules would be inhibited by buoyant or gravity forces because of the water-NAPL interfacial tension that holds them in place. Soaps or surfactants, however, can break down interfacial tension and mobilize NAPL globules.

When NAPLs are present at a landfill site, their individual compounds can volatilize to gases in the vadose zone, dissolve in water, or adsorb onto solids. The ability of these compounds to partition in these different ways underlines the importance of calculating a mass balance at landfill sites. For example, if a pollutant has a high volatility, it may direct remedial efforts toward the gaseous phase rather than the liquid phases. Mass balance estimates can be useful in quantifying and more accurately representing the distribution of contaminant concentrations (i.e., aqueous or nonaqueous), validating sampling results, and designing remedial alternatives.

Light Nonaqueous-Phase Liquids

An important consideration in understanding the movement of NAPLs at a landfill site is whether they are light (i.e., lighter than water) or dense (i.e., heavier than water). The movement of light nonaqueous-phase liquids (LNAPLs) differs significantly from dense nonaqueous-phase liquids (DNAPLs) in subsurface environments. LNAPLs have a specific gravity of less than one, and thus will float on top of a free surface of water and on top of a water table. Conversely, DNAPLs, such as solvents, PCBs, or creosote, will move downward relative to the ground water around them.

Figure 5-3 illustrates the different ways that light nonaqueous-phase liquids can exist in the subsurface. LNAPLs can float on top of the water table if a sufficient quantity has leaked into the subsurface. In many landfill environments, however, where relatively little NAPL has been spilled, a pure product will not reach the water table. Instead, as LNAPLs leak through the vadose zone, residual globules will be left and held in this predominantly unsaturated medium.

A dissolved or aqueous phase also can occur either when percolating rainwater contacts residual LNAPL in the vadose zone or, as illustrated in Figure 5-3, when ground water contacts a floating LNAPL pool in the saturated zone. In addition, when a water table overlaid with floating LNAPL rises or lowers, LNAPL globules can be smeared. This smearing can increase the contact area between the water and the LNAPL globules, leading to increased dissolution rates.

Dense Nonaqueous-Phase Liquids

DNAPLs have a propensity to move downward relative to the surrounding water. For example, trichloroethylene (TCE) has a specific gravity of 1.46 at room temperature, which is about one and a half times the density of water. Downward-moving DNAPLs that reach the water table will tend to move toward the bottom of an aquifer. Figure 5-4 illustrates this downward migration pattern.

The migration of DNAPLs is a function of the physical and chemical properties of the liquid, the site geology, and the size of the release. The important physical and chemical properties affecting migration include the liquid's density, viscosity, solubility, ability to partition into an organic liquid, volatility, interfacial tension, wetability to solid surfaces, and ability to have its chemical components absorbed. Perhaps the most important geologic site factor at landfills (aside from clay liners) affecting the downward gravity movement of DNAPLs is the site stratigraphy, particularly the presence of any capillary barriers where small, water-filled pore spaces block migration. The size of the liquid leak is also important. A larger leak will have more potential to retain positive fluid pressure and move downward. Figure 5-5 shows a schematic in which enough DNAPL has leaked to cause full vertical penetration through an aquifer. Note that geologic barriers can cause downward-moving DNAPLs to deflect in unusual directions; in the schematic, DNAPLs deflecting off a bedrock surface are moving opposite from the direction of ground-water flow. Such unusual movement profoundly changes the way that point of compliance is defined at a site.

5.4 Selecting Monitoring Well Locations

Two major considerations in siting a ground-water monitoring system around a landfill are (1) the number of wells appropriate to the particular site and (2) geologic and stratigraphic conditions that might affect choice of locations.

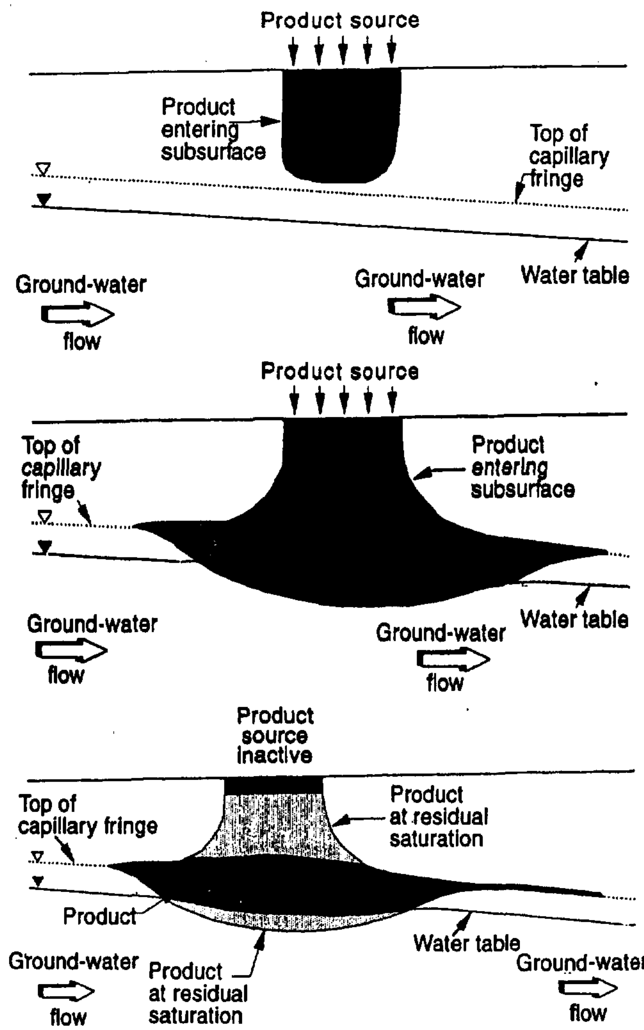


Figure 5-3. Movement of LNAPLs in the subsurface (Palmer and Johnson, 1989).

5.4.1 Number of Monitoring Wells

An appropriate question to ask at all landfill sites is, "How many monitoring wells should be put in, and where?" The spacing and depth of monitoring wells are crucial design factors and should be based on site-specific characteristics. The geology at different landfills is often profoundly different, and the optimal point of compliance at even a single landfill can vary with time and water movement. Therefore, no one rule for the number and configuration of monitoring wells is appropriate at all landfills at all times. Likewise, there is no predetermined number of wells at a site that is appropriate for all monitoring needs.

Monitoring wells have several purposes. They are used primarily to extract samples for water quality purposes, but also can be used to ascertain hydraulic conductivity of the porous medium and to measure hydraulic head,

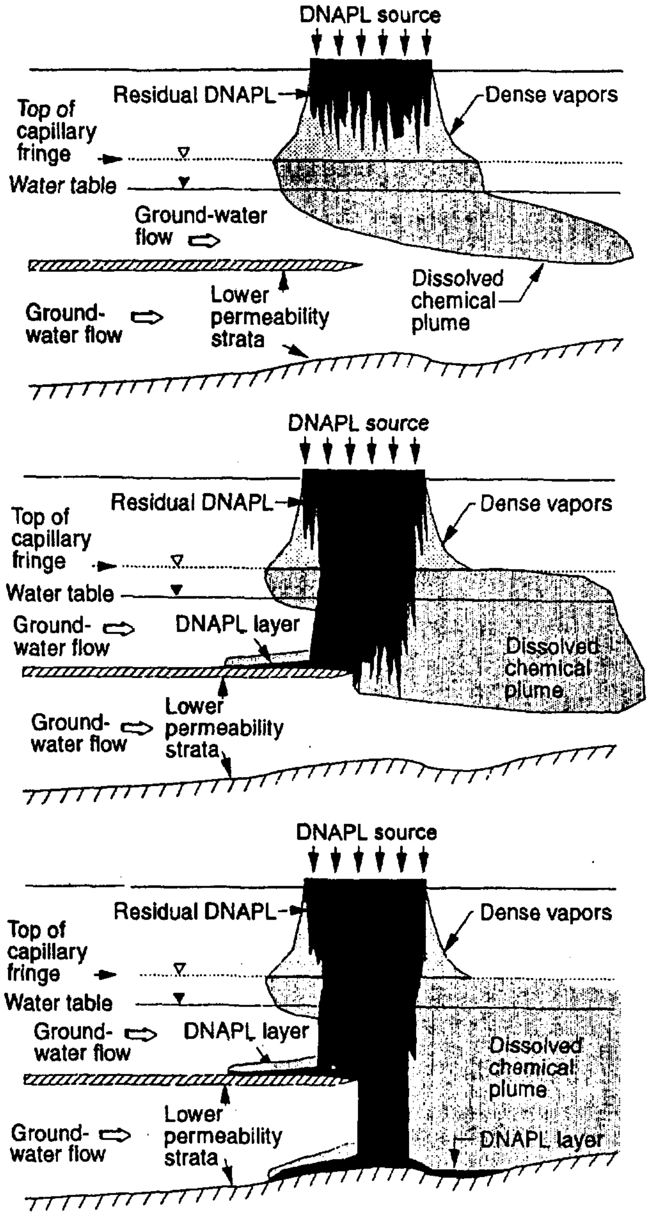


Figure 5-4. Movement of DNAPLs in the subsurface (Palmer and Johnson, 1989).

which is an indicator of ground-water direction. If, for example, nearby production wells are being turned on and off, or if local river stages are changing with time, the fluctuations in hydraulic head can be measured to indicate the directional variation of ground-water flow.

A minimum of three head measurements at three wells, in theory, could delineate the direction of ground-water flow at any one time if the porous medium surrounding the landfill was perfectly homogeneous and isotropic, if the water table was a perfect plane, and if all flow was horizontal only. The potentiometric surface (or water table) would, in this circumstance, be defined in much the same way as any three points would define a plane.

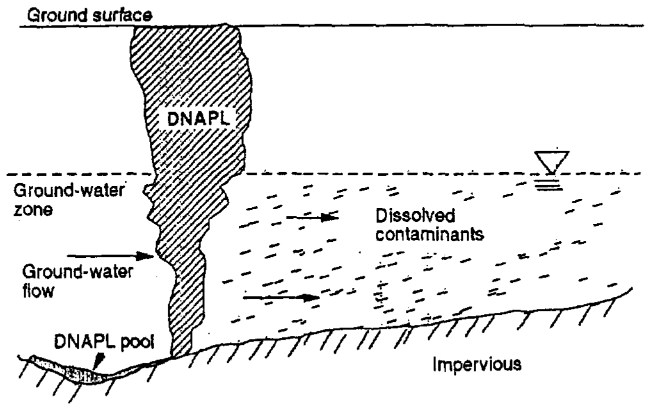


Figure 5-5. Full vertical penetration of DNAPL through an aquifer (U.S. EPA, 1992c).

Unfortunately, such perfect, uniform conditions rarely if ever exist at sites, and consequently several more wells are usually necessary to define flow direction. Observing any changes in head conditions with time then would help define temporal changes in ground-water flow. When the direction (both horizontal and vertical) and the magnitude of ground-water flow is understood, then the point of compliance (hydraulically downgradient monitoring locations) can be established and background monitoring wells can be positioned to measure ambient water quality.

As a general rule, the more complicated the geology and hydrology at a site, the greater the number of monitoring wells needed to define flow. Similarly, the more production wells present or the more tidal or river stage fluctuations occurring in the area, the greater the number of monitoring wells needed to accurately interpret ground-water movement. Any vertical movement of ground water should be accounted for by measurements from depth-specific wells.

5.4.2 Stratigraphic and Other Well Location Considerations

A number of well location and design issues should be considered when a monitoring system is installed around a landfill. If the site is associated with a perched water table (water held above the main water table), if the presence of DNAPLs is suspected, or if vadose-zone monitoring is appropriate, special considerations might be necessary, as discussed below.

5.4.2.1 Perched Layers

Perched water is held above the main water table of an unconfined aquifer by a lens of low-permeability material. Subtitle D regulations require the monitoring of an uppermost aquifer at a site; at some sites, this aquifer can be difficult to distinguish from an overlying perched zone, particularly if that zone is thick and horizontally extensive. Distinctions between an upper water-bearing aquifer and perched water are made on a site-by-site basis, usually with the assistance of and/or agreement with the state.

Perched layers in the vadose zone are important for other reasons as well. Landfill leachate moving downward can be held in perched layers under a landfill. Leachate pollutants can build up on this subsurface impoundment, and horizontal movement of these pollutants will probably increase. As liquid builds up on top of a perched layer, positive fluid pressure also will build up. A poorly constructed well that is drilled through this perched layer can allow leachate and contaminants to cascade down the bore hole. Years of benign contamination can be exacerbated rapidly when a perched layer is pierced.

Application of proper well construction techniques can prevent downward flow when a monitoring well penetrates a perched water layer. If the local stratigraphy is known, for example, a well telescoping method can be used. In this method, a well is drilled in steps. First, a bore hole is drilled to the low-permeability unit, casing is installed, and then grout is added between the casing and the bore-hole wall. Downward drilling is then continued with a smaller-diameter drill; the upper grout seal prevents downward leakage from the perched system. Alternatively, horizontal drilling or slant drilling techniques, discussed in Section 5.5.2, can be used.

5.4.2.2 Presence of DNAPLs

In the vadose zone, NAPLs, if present in sufficient quantities to move downward, can build up on or deflect off of low-permeability units. Because DNAPLs can, and almost certainly will, continue their downward movement below the water table, they also can pool up on low-permeability units in the ground-water zone, such as a bedrock surface or a clay lens. As with perched systems, improperly constructed wells that penetrate through DNAPL pools can allow DNAPL movement down the bore hole. If enough DNAPL exists to provide sufficiently positive fluid pressure, DNAPLs will flow down an open bore hole and can be found at the deepest parts of a well.

At many landfill sites, environmental professionals often are pressured to drill immediately in the "hot spot" of known pollution leakage. As discussed above, however, drilling in zones of extensive contamination without clear knowledge of the site stratigraphy can be very risky. When contamination, particularly DNAPL contamination, is known to exist at a site where the geology is not well characterized, drilling operations might be more safely begun near the suspected outer limits of a plume. Drilling operations can then be moved toward the region where higher contamination is suspected.

5.4.2.3 Vadose-Zone Monitoring

As already indicated, the vadose-zone (or zone of aeration) is the mostly unsaturated region between the ground surface and the water table. Although vadose-zone monitoring is not required by Subtitle D, it is often extremely useful and is certainly not restricted by the regulation. In a basic monitoring system located only in the aquifer, downgradient monitoring wells are placed in the uppermost aquifer around landfills to identify a leaking landfill. By the time pollution is identified in a monitoring well, however, the ground water will have already been contaminated and remedial costs will be very high. Vadose-zone monitoring can allow early detection of landfill leaks, before ground water becomes contaminated, thus allowing much more cost-effective remediation.

Vadose-zone monitoring is particularly useful where the water table is deep and extensive subsurface contamination could occur before a ground-water monitoring well could indicate a problem. In regions with a very shallow water table, vadose-zone monitoring might not be as effective because ground-water contamination might quickly follow leak detection in the vadose zone.

5.5 Installation of Monitoring Wells

Several handbooks provide detailed information on the design and installation of ground-water monitoring wells, including U.S. EPA, 1989a, and the Illinois State Water Survey (1983.) The following sections provide a brief description of monitoring wells and their installation.

5.5.1 Basic Components of Monitoring Wells

Subtitle D requires that a rendering of the design and installation of monitoring wells be placed in the operating record and that the state director be notified. A typical monitoring well is shown in Figure 5-6. The well casing is a pipe with openings, known as screened intervals, located near the bottom of the well that allow water to enter. The screened intervals are either slots in the casing itself or commercially available, perforated attachments. The well casing includes a plug at the bottom to prevent sediment from entering the well. Between the screened area of the well and the bore-hole wall, sand or pea-gravel, known as filter pack, is added to prevent fine material from being drawn into the well while permitting water to pass easily into the well. The filter pack increases the effective radius of a well. Above the filter pack, in the space between the unperforated casing and the bore-hole wall, an annular seal of grout is placed to prevent vertical movement of water (and any potential pollutants). The grout material is usually either cement or bentonite clay.

The upper portion of a monitoring well is designed to prevent liquid from entering and contaminating, diluting, or changing the nature of the water in the well. A surface

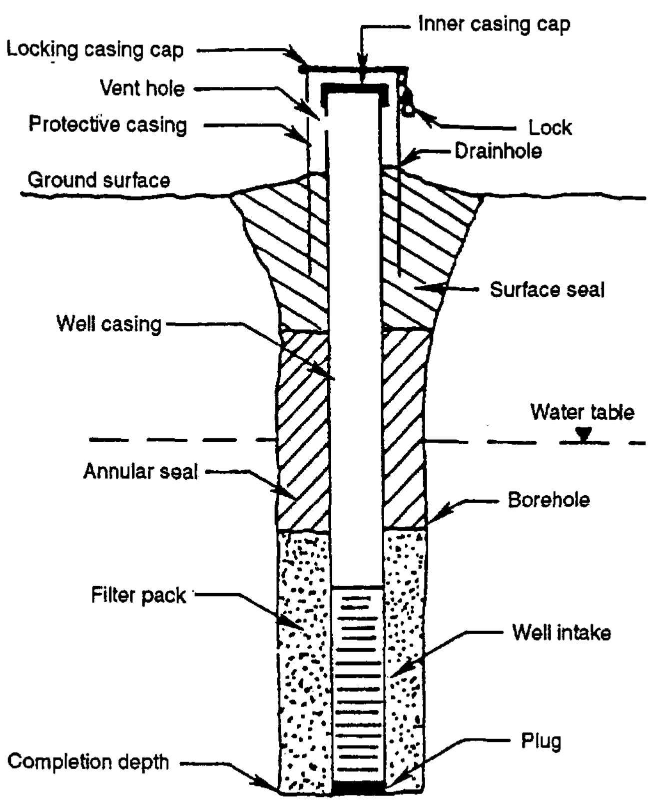


Figure 5-6. Components of a typical ground-water monitoring well (U.S. EPA, 1989a).

capping system is crucial, not only where water otherwise would penetrate into a well from above but also in artesian systems, in which water in the well is under pressure and could escape. The surface construction of a monitoring well includes inner and outer casing and caps, surface grout, and installation security measures.

The inner casing that appears at the surface is an extension of the same casing that runs the length of the well. Locking, watertight caps for the inner casing are commercially available. Surrounding the inner casing is an outer or protective casing, often of anodized steel, for which locking caps also are available. To prevent accumulation of water between the inner and outer casing (and subsequent freeze-thaw problems), some installers drill a vent hole in the outer casing. A surface grout or seal prevents surface water from flowing down the well and holds surface casings in place. In heavily trafficked areas, monitoring wells must be built at or below grade.

5.5.2 Drilling

Many well drilling methods are used for installing ground-water monitoring wells. These methods include traditional vertical drilling, slant drilling, horizontal drilling, and innovative techniques. This discussion focuses primarily on vertical drilling. The three basic types of vertical drilling techniques—hollow-stem auger, direct rotary, and cable-tool—are discussed below and are shown in Figure 5-7.

5.5.2.1 Hollow-Stem Auger Drilling

Hollow-stem auger drilling is a reliable method for drilling monitoring wells down to 150 feet deep in many types of unconsolidated material. Indeed, the most appropriate auger method for environmental work is usually a hollow-stem auger, which generally is attached in a series of 5-foot sections. A hollow-stem auger has a bit at the bottom that rotates and brings cuttings up to the ground surface on the auger flighting (helical metal strips). The hollow auger allows coring tools to be lowered inside the auger flights so that soil core samples can be taken in advance of the drill bit. Such samples can be taken through the center of a hollow-stem auger using devices known as split-spoon samplers, shelby tubes, or thin-walled samplers.

Typically, the 5-foot sections of hollow auger drills are connected with bolts. In the past, threaded bolt connections were heavily greased throughout the system for lubrication. This practice produced oil and petroleum residuals in the hole. In current practice, modern commercial lubricants that contain no metals and no petroleum products are used to ensure clean drill-rig operation.

5.5.2.2 Direct Rotary Drilling

In rotary drilling, a fluid is circulated in the subsurface. Traditionally, in water production wells, the circulating fluid was typically a mixture of water and bentonite clay, known as mud. Mud was used because it could cool and lubricate the bit, hold up the cuttings, coat the bore-hole walls, and prevent fluid loss from the bore hole. But mud can contaminate bore holes and generally is not used for monitoring wells. Other circulating agents can be used, including water, foam, and, more commonly in the monitoring well industry, air. Rotary drills include a tricone bit that grinds the rock; the cuttings are then pulled up the bore hole by entrainment in the upflowing fluid. In reverse rotary drilling, fluids circulate down the annular space and up the central tube of a drilling system, which is the opposite of straight rotary methods. Higher upward velocities can be achieved with reverse circulation, allowing heavier, larger cuttings to be brought to the surface.

As mentioned above, air is a common circulating agent used for environmental work. The air must be well filtered before it is circulated downhole, so that oil and petroleum products do not contaminate the inside of the well bore. Because circulating air can readily escape into a geologic formation, an outside casing typically is driven down the bore-hole wall to reduce the amount of escaping air into the subsurface. Even in a well-designed system, however, approximately one-third of the circulating air

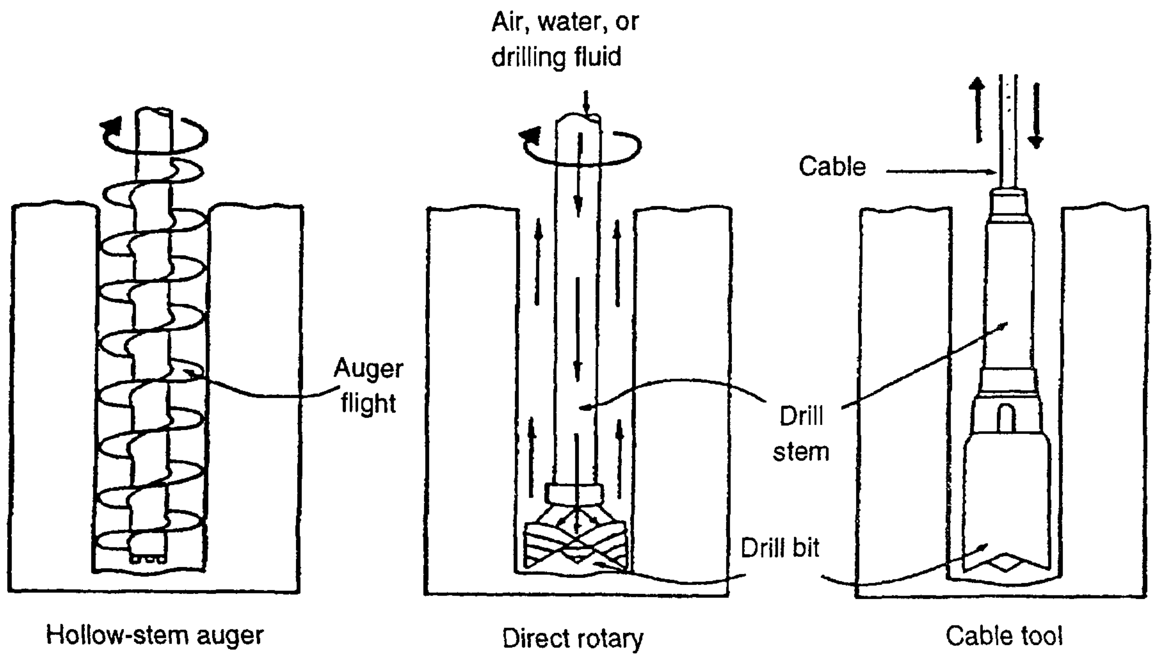


Figure 5-7. Schematics of the three basic types of vertical well drilling methods (U.S. EPA, 1992c).

can be lost into the subsurface. Air is circulated usually at a rate of about 750 cubic feet per minute. If one-third of that is lost on average into the subsurface system, 250 cubic feet of air per minute is blown into the subsurface. Soil gas surveys, which are run concurrently with air-rotary drilling, will be strongly affected by this disturbance in the natural gaseous system.

5.5.2.3 Cable-Tool Drilling

In cable-tool drilling, a cable on a rig alternately raises and drops a heavy bit. As the bit is lifted and dropped, it rotates, chopping material at the bottom of the hole and creating cuttings. The driller concurrently drives a casing down the hole, preventing loose material on the bore-hole walls from collapsing. To remove cuttings, the driller stops the drilling, pulls the bit out of the hole, and lowers a bucket called a bailer to collect the cuttings. Cable-tool drilling is a laborious process, particularly as a hole becomes deeper. This technique, therefore, is more useful for shallow bore holes drilled in soft, unconsolidated materials.

5.5.3 Casings and Screens

Monitoring wells must be cased to maintain bore-hole integrity and meet design specifications. Just as there is no one perfect well design, there is no single, perfect well material for all sites. Screens and casings can be made of many different materials, with PVC being the most commonly used at landfill sites. Stainless steel often is used, although in many corrosive environments (e.g., acidic, clayey soils) even stainless steel will disintegrate. Another popular type of well casing material is polytetrafluoroethylene (PTFE), often referred to by the brand name, Teflon. Although Teflon is thought to be relatively chemically inert, it is porous and will flow under compressive pressures. Consequently, slots in Teflon casing can close under compressive forces, restricting water movement into older well installations.

Two or three primary monitoring well screen designs typically are used at landfills. The most prevalent type used in PVC casings is constructed with a series of horizontal slots that are directly cut into the casing. Various aperture widths are available for slotted casings. Examples of common slot aperture widths include 10-slot, 28-slot, or 64-slot designs. These designations refer to the thousands-of-an-inch spacing in the slot. The slotting typically is cut with a circular saw, which means that the outside slot is longer than the inside slot. Slot size is usually dependent on the grain size of the surrounding filter-pack material or the naturally occurring grain sizes in the geologic formation. With finer material, such as clays, a smaller slot size is used; with sand or gravel filter-pack material (which can filter out fine material), a larger slot size can be used. Slot size is often just smaller than the grain size of the filter pack. This sizing allows bulk purchases of slotted screen and filter-pack material. Other slot configurations are available. Slots also can be vertical, although this configuration is less common than horizontal slotting. Another perforation type is a louvered or shutter-type screen, schematically presented in Figure 5-8a.

A popular type of monitoring well screen is a continuous slot, wire-wound design shown in Figure 5-8b. Continuous wire-wound well screen consists of a bevelled wire

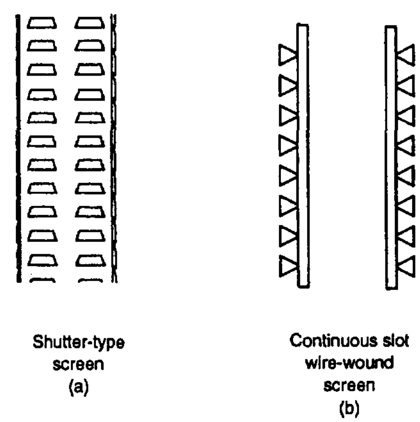


Figure 5-8. Examples of a shutter-type screen and a wire-wound screen (U.S. EPA, 1989a).

that is helically wrapped around small vertical rods. Designs such as continuous wire-wrapped screen have a large perforated or open area relative to screen length. The advantage of this design is that the added opening per screen length allows lower ground-water entrance velocities. At lower velocities, sediment is less likely to be carried into the well, and the dissolved gaseous content and aquatic chemistry of a sample taken during ground-water withdrawal will be more representative of the ground water from which it was removed.

5.5.4 Joints

Casings or well screens usually are available in 5-foot sections that must be connected through threaded or glued joints. These connections come in several configurations, shown in Figure 5-9. Several nonthreaded joint types are less appropriate for environmental monitoring-well applications because they involve cementing agents that have the potential to contaminate water samples. Nonflush joints, which extend radially outward from the casing, are not recommended for monitoring wells because they restrict the available annular space for filter-pack material, grout, and/or tremie tubing (pipe used to direct materials such as filter pack down the bore hole). With a nonflush joint, the joint sleeve, which extends into the annular space, could potentially intercept falling filter-pack material or grout and cause bridging during emplacement. Bridging occurs when falling material forms a span between the casing and the bore-hole wall, leaving an underlying cavity.

Threaded joints are now fairly standard for casing connections and are available in PVC or metal with a small O-ring for better sealing. A threaded joint is the preferred way to join casing and screen together, but different size threads are available; mismatching thread size must be avoided. A standard-size thread meeting American Society for Testing and Materials (ASTM) criteria is now available for well casing and screen joints.

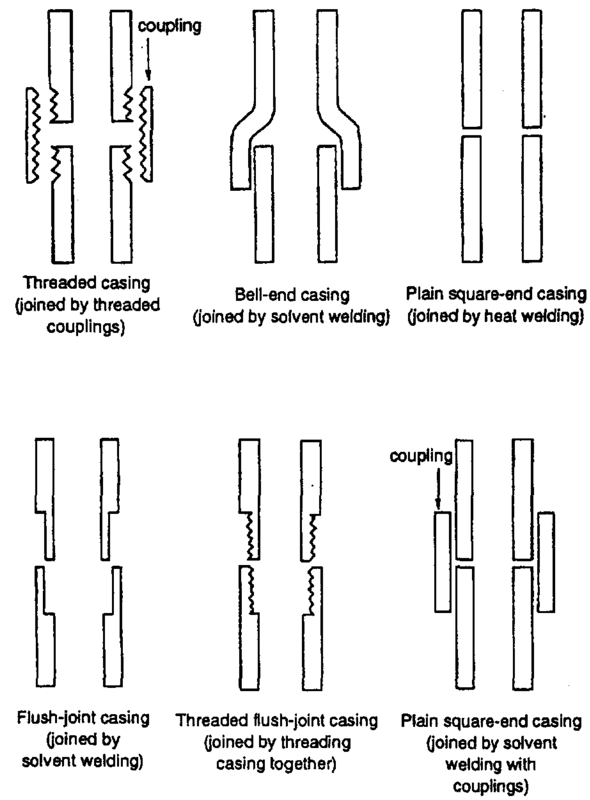


Figure 5-9. Various types of casing joints (U.S. EPA, 1989a).

5.5.5 Filter Packs

The particle size of filter-pack material depends on the aperture size of the slots or perforations in the screen. Typically, clean graded, kiln-dried sand is used as filter-pack material to avoid introducing contaminated material into the well bore. Sand should be added to the bore hole through a tremie tube, which directs the material to a proper depth, inhibits the gravity separation of granular material according to particle size, and reduces bridging of the material. Filter-pack material can be prepackaged and enclosed between an inner and outer well screen. Prepack filters/screens that are configured in this way are attached to the bottom of the casing and lowered down the bore hole in the same way as a normal well screen. During installation, the bore-hole environment must not be contaminated; any prepack, screen, or casing must be clean before placement and handled with clean gloves during placement.

5.5.6 Grouting

Grouting in the annular space outside the casing is necessary to prevent vertical movement of water or other fluids along the bore-hole wall. Two generic types of grout are available: bentonite clay or cement grout. Pelletized bentonite grout is used to seal annular space below the water table, whereas a bentonite clay slurry is used to seal regions in the vadose zone. Adequate time must be allowed for clay hydration, and pellets or slurry should be tremied down the hole when possible. Cement grout can be used as an alternative to clay grout. A cement-grout mixture should not be too lean or too rich; otherwise, fractures, cavities, or other void spaces might be produced. Figure 5-10 shows cavities, cracks, and fractures in improperly installed annular seals. Grout shrinkage or improperly prepared grout also will create cavities through which liquids can flow vertically along the well bore. In addition, because the hydration of clay or cement can produce heat, caution should be exercised if any of the well material is thermally sensitive.

5.5.7 Well Surface Considerations

5.5.7.1 Surface Cap and Protective Covering

The top of a monitoring well must be clearly marked and accessible, must protect the well from impact and vandalism, and must prevent surface water from draining down the well bore. The components of the surface protection system include surface protective grout, inner casing and an inner casing cap, outer protective casing with a locking cap, and bumper guards or other forms of protection from vehicular traffic.

Surface grout, typically cement, is mounded slightly above grade to discourage ponding of surface water at the wellhead. In a cross-sectional view, Figure 5-11 shows that the surface grout is slightly wedge-shaped (although slanted sides should not be pronounced) to avoid frost heaving in colder climates. The cement surface grout is typically 8 inches to 1 foot deep and approximately 1-1/2 to 2 feet in diameter around the inner casing.

The inner surface casing is an extension of the casing that runs to the bottom of the well and must be capped at the top with a watertight seal. Commercially available caps have gaskets that expand to block and seal the top of the inner casing when a butterfly nut is tightened on the top of the cap. When the well can be built above grade, an outer surface casing that surrounds and protects the inner casing is built. This outer protective covering is usually a short, wide, anodized pipe with a cover that can be locked to restrict access. Some wells must be built to allow traffic to pass over the well. In this case, the well is constructed below grade, with the inner casing protected by a flush-mount outer well casing (a small watertight manhole) or a heavy-duty utility box. Optimally, the area immediately surrounding the well installation should be mounded to discourage ponding of surface water near the well. The cover of the manhole, box, or outer casing should be watertight, as should the cap of the inner well casing.

In a landfill environment, potential subsidence problems can destroy the integrity of a monitoring well. Wells should not be located in areas susceptible to subsidence. Otherwise, cracks and fissures can form along a well casing, allowing pollutants to enter in or near the well. Pollutants entering the well environment in this way not only defeat the purpose of monitoring, but also exacerbate pollution.

Tampering also can be a problem. Locking covers can prevent tampering, but locks can corrode. Plastic materials that cover locks are available commercially. The outer casing can be anodized metal, which also prevents corrosion. It is usually a good idea to purchase a set of locks that all use the same key.

Proper labeling of monitoring wells is important for several reasons. Monitoring wells must be distinguished from underground storage tank fill lines, for example.

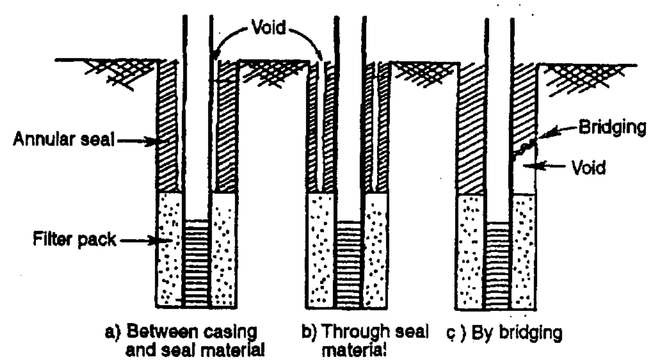


Figure 5-10. Void spaces produced by improperly installed annular seals (U.S. EPA, 1989a).

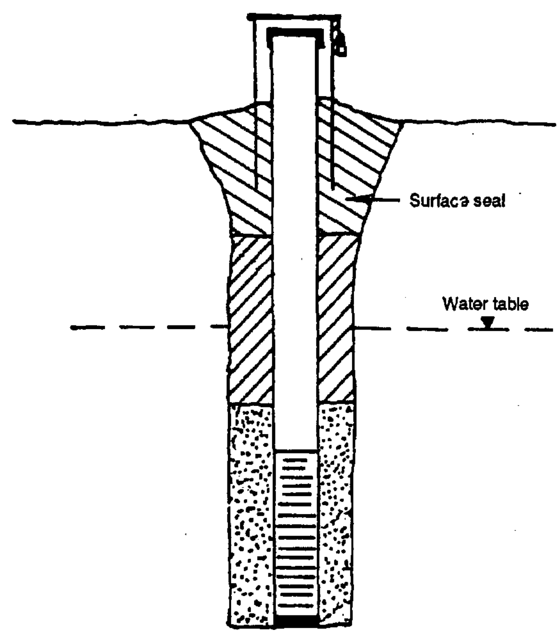


Figure 5-11. Correct wedge shape for surface grouting (U.S. EPA, 1989a).

Also, different monitoring wells must be distinguished from each other; therefore, labeling only the cap can create problems if the well caps are shuffled. Monitoring wells should be labeled on immovable parts of the well. Documentation also is important for surveying and locating the well, particularly for vertical elevation of a well. A key element in assessing ground-water flow and direction is the relative water-level difference in several wells at a site. Because ground-water gradients can be somewhat flat under many landfills, relative water levels must be measured correctly to within at least a tenth of an inch, necessitating accurate vertical surveys.

5.5.7.2 Well Construction and Site Selection Safety

In traffic areas, bumper guards around monitoring wells will help protect aboveground installations from damage. Bumper guards come in various sizes and strengths and are typically constructed for high visibility and trimmed with reflective tape or highly visible paint containing reflective material.

Drilling operations should give overhead powerlines wide berth, and, to prevent electrocution, rigs should move only when the mast has been lowered. Precautions also must be taken when drilling near subsurface utilities, such as water, power, and sewer lines.

Special dangers are associated with drilling in the middle of landfills. Because many drill rigs are very heavy, caution is required at certain sites to avoid subsidence. Also, drilling through material in an old landfill can be dangerous; some municipal landfills historically had hazardous material deposited, and serious drilling risks are possible. If it is necessary to drill under a landfill, slant or horizontal drilling techniques often are warranted to avoid drilling through old refuse. Occasionally explosive material has been deposited in landfills. If explosive material is suspected of being mixed with soils at a site, special techniques should be used to test the soils to determine whether an explosion is likely to occur. During all types of drilling activities, material brought out of the ground might be contaminated and therefore might require special handling and disposal.

5.6 Well Development and Maintenance

After a well is installed, well development and maintenance activities ensue. Plans for well development must, under Subtitle D regulations, be placed in the operating record, and the state director must be notified. Several types of development and maintenance activities are likely to be required. Residuals from the drilling process, such as fine, suspended particles, can be present in bore-hole water and eventually inhibit water movement into the well. The well development process is designed to remove these particles. Particles are removed by creating a surging action of water in and out of the well screen and filter pack. Also, over time, encrustation can build up in some wells; for example, calcium carbonate can be deposited from "hard" water systems. Biological clogging also can occur in the form of algal or microbial mats in well screens or well bores. Physical scraping or swabbing can remove encrustation or biological clogging. Another well maintenance problem, particularly significant at landfills because of the potential for ground subsidence and settling, is casing failure and collapse. The following sections describe in detail these and other development and maintenance activities.

5.6.1 Techniques To Clean Wells and Control Problems

The purpose of withdrawing water from a monitoring well is to obtain a *representative* sample. Water that is representative of an aquifer is never assured, but definite steps can be taken to secure the best sample possible. Before a water sample is withdrawn from a well, any stagnant water must be purged. Fine material in the well also can lead to unrepresentative water samples. Likewise, encrustation or clogging that occludes portions of the well screen can cause incoming water to have greater velocity and thus a greater potential to change pH, carbon dioxide levels, and chemical concentrations. Therefore, well development and maintenance goes beyond aesthetic considerations; procedures are designed to enhance the chances of gathering samples that are truly representative of ground water near the well.

5.6.1.1 Physical Methods

Surging is mentioned above as a technique to remove fine sediments during the well development process. Often, wells are cleaned using a surge block, which is a metal disk that acts somewhat like a plunger. Surge blocks for production wells historically were constructed of wood; for monitoring wells, however, wooden surge blocks are not used because porous material can trap and hold contaminants.

The surge block is alternately pulled up and pushed down the well. When pushed down, it propels water out of the well through the screen; when pulled up, it conveys water in. The in-and-out motion of water caused by surging dislodges fine material. This method of well development also can break up encrustation.

Another well development method is jetting, in which water is shot at high velocity through well perforations. Commercially available jetting tools discharge an outward stream of water through a well screen; return flows come back into the well above and below the outward jet. The tool is lowered and raised in the well bore, with nozzles on the jetting tool typically pointing outward in several directions. The outward and inward flow create the necessary in-and-out surge to break up and extricate clogging particles.

Sonar jetting also can be used to reduce encrustation and particulate buildup problems by cleaning out perforations in the well. Sonar jetting uses very small explosive charges to set up shock waves in the water. The shock waves find weaknesses in the casing; because the encrusted perforations are weaker than steel pipe casing and many other casing materials, the shock waves pass through them and knock the buildup out of the perforations. The sonar jet charges can be accurately positioned to clean only the portion of the well that needs to have perforations opened.

Another technique is air development or air eduction, which is a two-step process. In step one, air is blown down a pipe (eductor pipe) placed in the well. The bubbles flow back up and entrain water, producing a slight pumping effect and drawing water out of the formation. Step two involves shutting off the air flow, allowing air pressure to build up, and lowering the eductor pipe down the well. The air is then suddenly turned back on, and a large slug of pressurized air forces water from the well bore into the formation, creating a surging action. As the air pressure decreases, the eductor pipe is raised and the process is repeated.

For encrustation problems, swabbing techniques, such as brushing and scraping, often are used as a quick technique for breaking up material that clogs a well.

5.6.1.2 Chemical Methods

Certain chemicals also can be used to control encrustation and other problems. Yet some of the chemicals used to control these problems in production wells should not be used for monitoring wells because if these particular chemicals enter a monitoring well, they can change the acidity or the chemical constituents in the well water or introduce pollutants.

Chelating agents (such as soaps), wetting agents, surfactants, or inhibitors have been used to unblock obstructed well screens. Acids could be used to degrade calcium carbonate encrustation, but the change in pH caused by acids might mobilize some contaminants in the subsurface.

5.6.2 Decontamination

When a well is drilled, a pathway is opened in the earth. While samples of subsurface fluids can be extracted through a well and remedial substances such as nutrients can be introduced, unfortunately, contamination can be released into the subsurface from an unclean well. Pollution problems must not be exacerbated by improper decontamination of drilling and sampling equipment.

Wherever possible, drilling or sampling operations should begin outside of the hot spot of recognized pollution and proceed toward the hot spot; equipment should be decontaminated after each hole is drilled or each sample taken. If the regions of highest pollution are left until last, contamination is less likely to be carried outward from the hot spot.

Decontamination involves specific procedures. The process of washing materials can generate contaminated rinsate, which becomes a pollutant. Minimizing the rinsate generated usually is a cost-effective measure during the cleaning of drilling and sampling equipment. A decontamination area usually is established at a drilling or sampling site, which often is fenced or gated and locked, or otherwise secured. An impermeable ground cover such as plastic should be spread on the ground to catch any run-off at these areas. A three-bucket method of washing and rinsing often is used to minimize the water generated from the cleaning process.

Anything put into a well or bore hole, such as bits, auger flights, bailers, pumps, samplers, clamps, or tremie pipes, should be decontaminated. Heavy equipment, such as drill rigs, also should be decontaminated. Workers should use clean, protective gloves during drilling and sampling operations. Porous gloves and ropes and other porous materials cannot be reused; they should be thrown away after use. Drilling equipment normally is decontaminated after each hole is drilled, although equipment can be washed more often as needed. Every time a new hole is drilled, everything used in the drilling process must be washed. For sampling equipment, every time a new sample is taken, the sampling implements must be washed. A dedicated pump that remains in a well is particularly advantageous for sampling because repetitive cleaning is avoided. Disposable bailers are also available that should be discarded after a single use.

Quality assurance procedures for decontamination involve checks to ensure complete cleaning. To check the effectiveness of decontamination, the final rinse water can be tested periodically. In this procedure, a sample of the final rinse water is collected and sent to an analytical laboratory to determine its cleanliness and chemical composition. This procedure is an "after-the-fact" determination, however, because there often is a lag time between sampling and receipt of analytical results. Another type of decontamination testing is wipe testing, in which a piece of gauze or a cotton ball is used to wipe the equipment. The cloth is then put in a container and sent to a laboratory for analysis. An emergency shower for human use also is requisite at sites where the presence of hazardous material is suspected.

5.7 Well Abandonment

The design for decommissioning any monitoring wells must, under Subtitle D regulations, be placed in the operating record, and the state director must be notified. If a well must be abandoned, certain procedures are necessary to ensure that the well does not become a conduit for the downward flow of pollutants. Most importantly, the well must be sealed throughout its length to prevent vertical migration of water. The decision to either perform maintenance on a failing well or abandon it entirely often is difficult.

The procedures for sealing a well to prevent vertical flow sometimes are dictated by individual states, but all involve grouting the well bore. In some states the entire well length must be grouted, whereas in others, selected layers in the well can be sealed. Because both the outside and inside of a well casing are potential conduits for flow, both areas must be grouted. Grouting of both areas can be achieved by removing the well casing, if bore-hole collapse is not anticipated. Casing removal can be difficult, but for shallow wells with bentonite clay grout, a large-diameter hollow-stem auger might be able to over-drill the entire monitoring well, simplifying removal. Grout must be placed while the casing is being removed to help prevent bore-hole collapse.

If the casing is not removed, grout must be injected into both the well and the annular space between the casing and bore-hole wall. To inject grout between the casing and the bore-hole wall, the casing might need to be perforated. Perforating tools cut the casing by either shooting pellets or burning holes sideways through the well and into the formation. Cement grout is then pumped into the annular space.

5.8 Documentation

Careful documentation is required by Subtitle D during all stages of well drilling, completion, operation, and abandonment. Procedures and information important to record include: drill-hole logging and core sampling, which indicate lithology and the stratigraphy of a site; geophysical testing and data; soil sampling methodology; water sampling methodology; sampling results; and well design details. Chain-of-custody procedures for samples are required to ensure that the source of information gathered is verifiable. It is important to regulatory agencies that the locations of abandoned wells be known. Abandonment notification should be considered and may be required in some states.

5.9 Ground-Water and Vadose-Zone Sampling

Subtitle D requires that ground-water samples be taken from the saturated zone, specifically from "the uppermost aquifer," and describes appropriate procedures for sampling monitoring wells for specific hazardous constituents. The rule includes requirements for determining background ground-water quality, ground-water elevations, and number of samples to be collected. Methods for sampling these parameters in the saturated zone are presented in Section 5.9.2, along with specific issues that should be considered when monitoring in the saturated zone. Samples also can be taken from the vadose, or unsaturated, zone, as discussed in Section 5.9.1. Screening techniques, designed to optimize sampling, are beneficial at most sites.

5.9.1 Vadose-Zone Sampling Techniques

Vadose-zone sampling is associated with three phases: a solid phase (soil), a liquid phase, and a gaseous or vapor phase. Samples from all three phases can be taken, as discussed below. The basic advantage of vadose-zone sampling is that it can provide advance warning of ground-water pollution, and thus may reduce or eliminate the need for remediating ground water.

5.9.1.1 Soil Samples in the Vadose Zone

Soil samples can be taken from a range of locations in the soil profile. Shallow sampling methods are available for soil material, and deeper methods for aquifer solids, which are usually carried out with drill rigs. Shallow samples can be taken with hand augers, a brace and bit, a post hole digger, or coring devices. For deeper samples, split-spoon samplers, thin-walled samplers (sometimes referred to as shelby tubes), California ring samplers, and other coring-type devices that can be driven down the center of a hollow-stem auger can be used.

5.9.1.2 Liquid Samples in the Vadose Zone

Liquid samples in the vadose zone typically are withdrawn through a ceramic cup lysimeter, which draws pore water into a porous cup under negative gage pressure and collects the water. Extracting water samples from the vadose zone is very difficult because volatile constituent concentrations are perturbed by the partial vacuum exerted on the water, leading to nonrepresentative samples.

There are PTFE (Teflon) cup lysimeters available, but these cups have a larger pore size and maintain lower vacuum pressures than ceramic cups; thus, Teflon cups are less effective than ceramic cups in very dry conditions. Typically the lysimeter is placed in a hole surrounded with fine silica flour so that any water in the soil is drawn into the flour. When negative pressure is created inside the lysimeter with a pump, water is pulled out of the ground into the cup.

Another type of lysimeter is the pan or glass-block lysimeter, which uses the downward, free gravity flow of water to fill a flat container or collection pan. Because free drainage is required for the successful operation of pan lysimeters, these devices are used only in extremely wet vadose-zone environments. At some landfills natural geologic or landfill design features can aid in collecting escaping leachate.

The same type of ceramic cup used in a lysimeter can be used in a tensiometer to measure the matrix potential (negative water pressure) in the vadose zone. The matrix potential is an indicator of moisture content. The tensiometer is a water-filled tube with a ceramic cup on one end hooked to a pressure gage. The instrument is placed in the ground, and water in the tube is drawn out of the ceramic cup into the surrounding soil. As soil moisture and material size decrease, the water volume and negative gage pressure in the tube increase. The negative pressure in the tube essentially equilibrates with the negative pressure of water held in the soil. A tensiometer can therefore give a quick estimate of soil moisture variation at a site.

5.9.1.3 Soil Vapor Samples

Analysis of soil vapor is a quick screening method that can help identify onsite and offsite contaminant plumes in the landfill environment. Vapor samples can be collected with a probe driven into the ground and hooked up to a pump or with a passive device containing material to adsorb target vapors. In the former method, the inside of the driven probe is purged of vapor and a syringe or evacuated container is used to collect a gaseous sample. Typically, this vapor sample then is injected into a gas chromatograph and analyzed. Elevated concentrations of contaminant vapors or reduction in oxygen conditions can be indicators of pollution. Passive samplers usually are buried in the soil to adsorb vapors. The adsorbent is then exhumed and taken to a laboratory where adsorbed vapors are released (normally by heating) and analyzed.

Soil vapor sampling can be a quick, relatively inexpensive method to screen a site. Because natural biodegradation of some contaminants can occur, carbon dioxide (CO_2) vapor can be used as an indicator of pollution even for nonvolatile contaminants. The CO_2 method is more effective farther away from a landfill, where offsite vapors will not be influenced by landfill gas generation.

Some vapor monitoring system designs contain slotted collection pipes beneath a new landfill. An advantage of this strategy is that a liquid leak could be dried by air circulation (evaporation) beneath a landfill, reducing fluid potential, downward gravity movement, and, consequently, remediation costs. This design is in an experimental stage. The prospects of promoting landfill fires with the introduction of oxygen or introducing a conduit for surface-water flow downward if the top of a slotted pipe were to become damaged are important problems to be resolved in the development of this technology.

Another gaseous monitoring technique that is very useful in landfills, particularly to identify methane migration, is a flux chamber, which measures the flux of gases across the ground surface. If a site has methane problems, flux chambers can help determine the potential for migration into structures and the potential for explosion. The device, with a small, closed dome driven into the ground, periodically samples the air space under the dome. To keep the fluxing gases from building up under the dome, which would inhibit upward movement of gases, air is constantly circulated under the dome.

5.9.2 Saturated-Zone Sampling Techniques

Sampling in the saturated zone, as required by Subtitle D, involves measuring water quality, ground-water elevation, and the aquifer parameters of transmissivity and storage coefficients, as discussed below. These ground-water measurements are critical to site investigations and should be considered in the construction of monitoring wells. Other sampling considerations, also discussed below, include sample filtering, sampling at different depths, and frequency of sampling.

5.9.2.1 Sample Collection Methods for Water Quality Measurements

Devices for withdrawing water from a well for the purpose of water quality measurements include bailers, submersible pumps, bladder pumps, and driven wells. Bailers are similar to buckets or ampules with either double- or single-ball check valves. As the bailer is lowered down a well, water is propelled upward through a valved cylinder. When the bailer is hauled upward, the ball valve at the bottom of the bailer moves down, sealing the bottom and permitting a sample to be raised to the surface. Another type of bailer consists of an open cylinder with spring-loaded closures on either end. After this sampler is lowered to the desired sampling depth, a weighted messenger slides down the haul line, strikes the trigger for the spring-loaded closure, and closes up the sampling tube. Bailers are inexpensive, can be made of a variety of material, and are easy to repair in the field. Bailers, however, cannot quickly purge a well (particularly a large well), and they require time-consuming decontamination between samples.

Submersible pumps are particularly useful for purging stagnant water from a well bore because of their high pumping rates. They generally are made of stainless steel and have low operating costs if one pump is dedicated to each well. Submersible pumps are very effective, are sized to fit small-diameter wells, and can operate at variable speeds. In addition, some models can operate at low pumping rates, making them appropriate for sampling volatile compounds. Submersible pumps, although probably more versatile, are more expensive than bailers.

The bladder pump is a diaphragm pump. Bladder pumps operate by injecting and releasing air in and out of a flexible diaphragm, gently squeezing water to the surface. This method is probably one of the most accurate for sampling volatile organic chemicals because of its ability to retain sample integrity. Bladder pumps can be operated at variable speeds, can be made of different materials, and are easy to repair in the field. Although bladder pumps can be effective, they can be expensive if a source of compressed gas is not readily available.

Driven samplers are specialized, removable drive points that act as temporary wells. Driven samplers, such as the cone penetrometer, can allow rapid samples of shallow ground water to be extracted (in areas with shallow water tables and loose, unconsolidated geologic material). Driven samplers are particularly useful because they can take preliminary ground-water samples. These preliminary samples can serve as a guide to placing more expensive monitoring wells. Driven samplers are not acceptable as permanent ground-water monitoring wells because they are not grouted, and surface water can move down the side of the probe. This short-circuiting precludes the long-term effectiveness of driven samplers.

5.9.2.2 Sampling Methods for Ground-Water Elevation Measurements

Subtitle D requires ground-water elevation monitoring to facilitate accurate ground-water flow and direction determination. Ground-water elevation measurements must be made every time a well is sampled, immediately before well purging. If a sufficient density of water-level elevations is known, a series of water-level contour lines, called equipotential lines, can be mapped. Flow lines can then be drawn perpendicular to these equipotential lines. These two sets of lines are commonly referred to as a flow net. Water-level contour maps, which show the elevations of either a water table or a piezometric surface, indicate the pathways of ground-water flow at any point in time. The direction of ground-water flow can change with time at a landfill site; nonetheless, water contour maps are useful tools. Additionally, water levels in two adjacent wells screened at different depths can indicate vertical ground-water flow, which is crucial information at many sites.

Several monitoring devices are available to measure ground-water elevations in wells. One of the simplest methods is an incremented steel tape chalked on its downhole end. When the lowered tape strikes the water in the well, the chalk at that particular depth is rinsed off. When withdrawn, the demarcation of the water level is visible, and the depth to water can be measured. The water-level elevation from the top of the well then can be calculated.

Other devices to measure water level include electric probes, bubble tubes, and pressure transducers. Electric probes set off an alarm when water comes in contact with the probe. The probe is lowered into a well at the end of an incremented cable, which usually is unwound from a reel. The water acts as an electrical conductor, completing a circuit on the probe. Bubble tubes and transducers measure the pressure at a known distance below the top of a well. The pressure measurement then can be used to calculate the depth below a water surface and infer the water-level elevation.

5.9.2.3 Sampling Methods for Aquifer Parameters

To predict ground-water velocity, an estimate of subsurface hydraulic conductivity must be made. Standard hydrologic field tests for hydraulic conductivity and other hydrologic parameters include slug (rate-of-rise) techniques and aquifer (pumping) tests. A common laboratory procedure to determine hydraulic conductivity is a permeameter test; this test, however, is rarely used because it requires an undisturbed sample of soil or aquifer material, which is very difficult to obtain.

A slug test allows the hydraulic conductivity in the area of the well to be estimated. With this type of test many wells can be analyzed quickly for differences in hydraulic conductivity at a site. This localized test is performed by raising or lowering the water level in a well or piezometer and noting the rate at which the water level recovers to its previous level. If the screen in the well being tested extends through and above the water table, the water level should be lowered, not raised. To avoid physically removing or adding water during a slug test, a solid, heavy cylinder can be placed in the well below the water level and, after equilibration, removed. The water-level recovery is then measured. This method eliminates the need for removing and disposing contaminated water.

A pumping or aquifer test examines the properties of a bigger area than a slug test. Typical pumping tests measure hydraulic conductivity and coefficient of storage over areas from approximately 5 to 200 meters in diameter. A well is pumped, and the drawdown of the water level in nearby wells is observed. Standard equations for unconfined aquifers are used to determine transmissivity and storage coefficients, such as Bolton's equation. The storage coefficient is a measure of the amount of water stored in the aquifer, and the transmissivity is the hydraulic conductivity times the aquifer thickness.

5.9.2.4 Filtering Water Quality Samples

Subtitle D requires that samples must not be filtered prior to chemical analyses. Colloidal material (e.g., clay, asbestos fibers) might be present in some ground water; if the ground water is moving through fractured rock, these fine, suspended particles can facilitate the transport of adsorbed pollutants. Nonfiltered sampling provides information on the presence of these types of materials.

Some states might interpret the need for filtering differently. In individual cases, there can be strong scientific arguments for why one might or might not want to filter a sample. Subtitle D regulations do not preclude doing both. Analyzing both filtered and nonfiltered samples is more costly, but having both sets of data available might be important at some sites.

5.9.2.5 Sampling at Different Depths and Distances

Because contaminant plumes can move vertically as well as horizontally, water quality and hydraulic head often should be measured in both directions. Many owners/operators, to save money, equip a site with only a minimum number of shallow wells. In many cases, this supposed cost-saving measure results in higher costs to the owner/operator because an inadequate number of wells could miss a contamination event, particularly one with a strong vertical flow. Remedial costs are always profoundly higher if a contaminant plume is not detected early. One deep well with a long screen that fully penetrates the aquifer is an unsatisfactory solution to the problem of identifying vertical pollution movement, because if water enters the well bore from clean portions of the aquifer, samples will become greatly diluted. The optimal arrangement at many sites is to install wells that allow sampling at different depths.

Two types of systems are available for sampling at different depths, as shown in Figure 5-12. The first is a multiport sampler. The second is a nested sampler, either in a single bore hole or in multiple bore holes. A multiport sampler has a hollow tube that is lowered through the center of a well. This sampler has multiple windows or ports vertically distributed along the well length. An ampule is sent down the center tube, and when it arrives at the desired port, it is stopped. Activation of the port and ampule from the surface opens up the system and permits water to flow and fill the ampule from that particular interval. Thus, a discrete interval sample is obtained and hauled to the surface. Multiport sampling systems are fairly expensive.

When a nested sampler in a single bore hole is used, several wells, screened at different intervals with grout between the layers, are installed. Alternatively, depth-specific wells can be nested in individual bore holes. This latter method is highly recommended at many sites because it captures water quality at different depths as well as vertical water pressures (hydraulic head). If water is moving upward under a landfill, as indicated by greater hydraulic head at different depths, the leachate might not spread quickly. If water is moving downward, however, the leachate probably will be less constrained. Vertical head measurement is a very useful tool for predicting the direction of ground-water flow.

The distance between monitoring wells also is important. Several pollutants released at the same time might move at different rates. This difference in transport speed is important because samples taken from one well might indicate the existence of only a single pollutant. Several pollutants, however, could be present in a plume but be separated because of differences in transport rates. The proper density of monitoring wells is not easily anticipated; adjustments are necessary in most monitoring designs. The number, spacing, and depths of monitoring systems must, under Subtitle D, take into account site-specific geology and be certified by a qualified ground-water scientist, as defined in the regulation, or the director of an approved state program.

5.9.2.6 Frequency of Sampling

The Subtitle D regulations state that ground-water monitoring must be performed "at least semiannually." The object is to understand the subsurface system, the hydrology, and the spatial and temporal distribution of contaminants. If sampling frequency is inadequate, it is possible to sample and not understand the system at all, to not know the best and most cost-effective remediation approach, and to be misled by the periodic data collected. For example, if a cave or limestone system underlies a landfill, it might be better to measure subsurface parameters before it rains, while it rains, and after it rains, rather than just once every 3 or 6 months because significant changes in water quality and hydraulic head often are associated with storm events in these karst areas. Also, periodic sampling undertaken at a different frequency than that of a natural periodic change can make the process appear to be going backwards, and the resulting information can be confusing.

Choosing a frequency for sampling is a crucial decision. It is often best to determine first what frequency is required to understand the system and then examine regulatory requirements. Some types of frequent measurements can be relatively inexpensive; for example, transducer-type water-level measuring devices can be

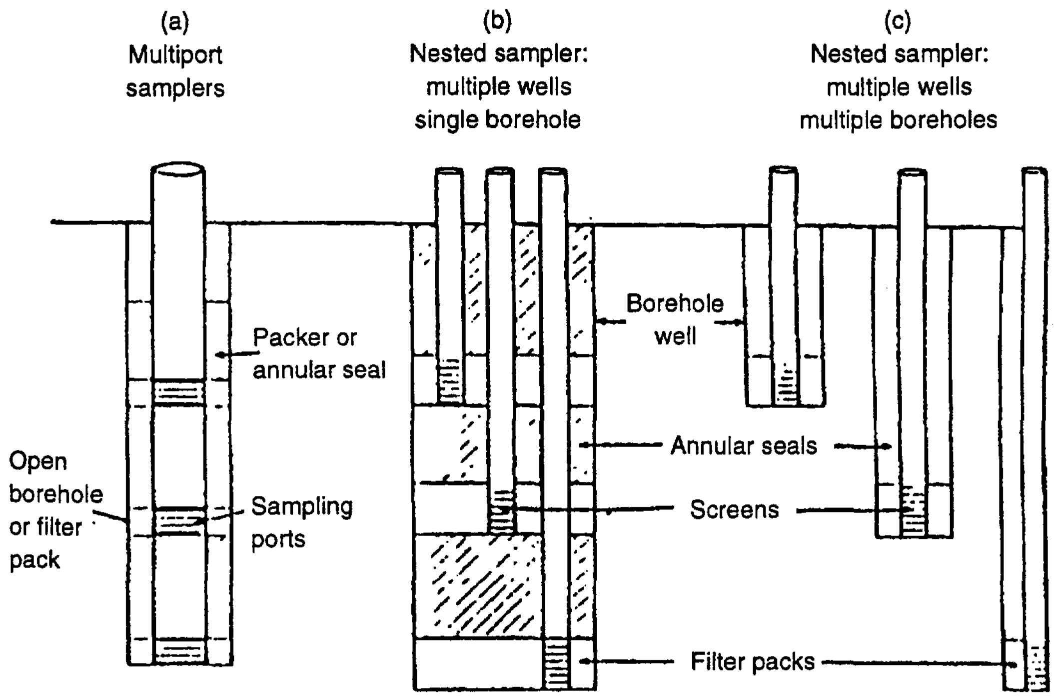


Figure 5-12. Examples of a multiport sampler and two types of nested samplers (Johnson, 1983).

placed in a well and linked to a data logger to assemble essentially continuous records.

5.10 Detection Monitoring

The monitoring requirements for Subtitle D are divided between detection monitoring and assessment monitoring. The flow path for required actions is diagrammed in Figure 5-13, and described below. Detection monitoring is required by Subtitle D to establish initial background levels and potential migration of contaminants. The elements and compounds that must be analyzed include 47 volatile compounds and 15 metals listed in the regulation (see Table 5-1). Detection monitoring must be performed at all MSWLFs at least semiannually. The director of an approved state may: (1) specify an alternate sampling frequency, with a minimum of annual sampling; (2) delete constituents from the list, based on what is reasonably expected from conditions at the site; and (3) establish an alternative list of inorganic constituents that provides a reliable indication of inorganic releases at the site. If a statistically significant increase over background levels is found for one or more of the constituents, the owner/operator must establish an assessment monitoring program (see Section 5.12) and notify the state. Monitoring programs should be continually reviewed and modified, if necessary, based on results obtained.

5.11 Statistical Data Analysis

The owner/operator must specify a statistical method in the operating record, to be chosen from a list of methods in Subtitle D, to evaluate ground-water monitoring data for each contaminant. The statistical test chosen must be conducted separately for each contaminant in each well. The choices of tests to identify statistically significant evidence of contamination are: (1) a parametric analysis of variance, followed by multiple comparisons procedures; (2) an analysis of variance based on ranks, followed by multiple comparisons procedures; (3) a tolerance or prediction interval procedure; (4) a control chart approach that gives control limits for each constituent; or (5) another statistical test that meets performance standards.

What is statistically significant? A whole range of answers to this question exist. Subtitle D allows for flexibility regarding analytical methods if proper justification is given. Steps can be taken to obtain a better understanding of water quality data, such as plotting pollutant concentrations over time. Plots will provide visual information on data distribution and variability and will show outliers from average values.

What sort of distribution does the data have? If there is variance, is there homogeneity in that variance? A normal distribution (i.e., bell curve) can be determined by constructing a simple "box and whisker" diagram or probability plots; if the median of the values is within an intercortile range, then there is relative homogeneity of variance, and the data are normally distributed. A straight line on a probability plot is another indicator of normal data distribution. With scant data, it is best not to assume that the data are normally distributed. A log normal distribution might, for example, be a better assumption in the absence of sufficient data.

EPA has developed a statistical analysis tool designed to facilitate the storage, analysis, and reporting of ground-water data. The Ground Water Information Tracking System with Statistical Analysis Capability (GRITS/STAT) can be used to assist MSWLF owners/operators in evaluating ground-water monitoring results (U.S. EPA, 1992d).

5.12 Assessment Monitoring

If detection monitoring at a MSWLF shows evidence of a statistically significant increase in an Appendix I parameter over background levels, assessment monitoring is required.

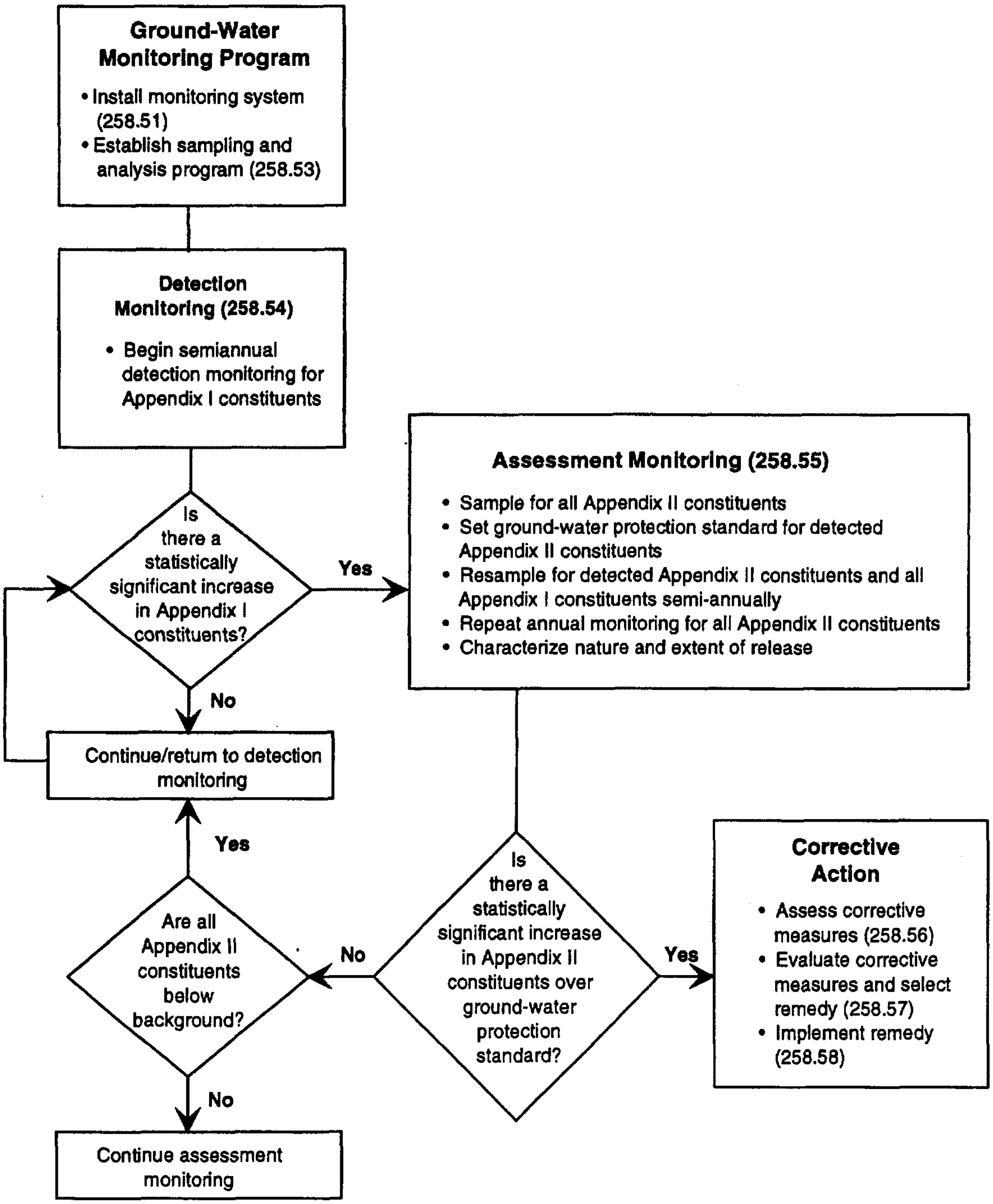


Figure 5-13. Subtitle D ground-water detection and assessment monitoring (40 CFR, Part 258, July 1, 1992).

Table 5-1. Constituents for Detection Monitoring (40 CFR Part 258, Appendix I)[1]

Common Name[2]	CAS RN[3]
Inorganic Constituents	
(1) Antimony	(Total)
(2) Arsenic	(Total)
(3) Barium	(Total)
(4) Beryllium	(Total)
(5) Cadmium	(Total)
(6) Chromium	(Total)
(7) Cobalt	(Total)
(8) Copper	(Total)
(9) Lead	(Total)
(10) Nickel	(Total)
(11) Selenium	(Total)
(12) Silver	(Total)
(13) Thallium	(Total)
(14) Vanadium	(Total)
(15) Zinc	(Total)
Organic Constituents	
(16) Acetone	67-64-1
(17) Acrylonitrile	107-13-1
(18) Benzene	71-43-2
(19) Bromochloromethane	74-97-5
(20) Bromodichloromethane	75-27-4
(21) Bromoform; Tribromomethane	75-25-2
(22) Carbon disulfide	75-15-0
(23) Carbon tetrachloride	56-23-5
(24) Chlorobenzene	108-90-7
(25) Chloroethane; Ethyl chloride	75-00-3
(26) Chloroform; Trichloromethane	67-66-3
(27) Dibromochloromethane; Chlorodibromomethane	124-48-1
(28) 1,2-Dibromo-3-chloropropane; DBCP	96-12-8
(29) 1,2-Dibromoethane; Ethylene dibromide; EDB	106-93-4
(30) o-Dichlorobenzene; 1,2-Dichlorobenzene	95-50-1
(31) p-Dichlorobenzene; 1,4-Dichlorobenzene	106-46-7
(32) trans-1,4-Dichloro-2-butene	110-57-6
Organic Constrituents	
(33) 1,1-Dichloroethane; Ethylidene chloride	75-34-3
(34) 1,2-Dichloroethane; Ethylene dichloride	107-06-2
(35) 1,1-Dichloroethylene; 1,1-Dichloroethene; Vinylidene chloride	75-35-4
(36) cis-1,2-Dichloroethylene; cis-1,2-Dichloroethene	156-59-2
(37) trans-1,2-Dichloroethylene; trans-1,2-Dichloroethene	156-60-5
(38) 1,2-Dichloropropane; Propylene dichloride	78-87-5
(39) cis-1,2-Dichloropropene	10061-01-5
(40) trans-1,3-Dichloropropene	1006-02-6
(41) Ethylbenzene	100-41-4
(42) 2-Hexanone; Methyl butyl ketone	591-78-6
(43) Methyl bromide; Bromomethane	74-83-9
(44) Methyl chloride; chloromethane	74-87-3
(45) Methylene bromide; Dibromomethane	74-95-3
(46) Methylene chloride; Dichloromethane	75-09-2
(47) Methyl ethyl ketone; MEK; 2-Butanone	78-93-3
(48) Methyl iodide; Iodomethane	74-88-4
(49) 4-Methyl-2-pentanone; Methyl isobutyl ketone	108-10-1
(50) Styrene	100-42-5
(51) 1,1,1,2-Tetrachloroethane	630-20-6
(52) 1,1,2,2-Tetrachloroethane	79-34-5
(53) Tetrachloroethylene; Tetrachloroethene; Perchloroethylene	127-18-4
(54) Toluene	108-88-3
(55) 1,1,1-Trichloroethane; Methylchloroform	71-55-6
(56) 1,1,2-Trichloroethane	79-00-5
(57) Trichloroethylene; Trichloroethene	79-01-6
(58) Trichlorofluoromethane; CFC-11	75-69-4
(59) 1,2,3-Trichloropropane	96-18-4
(60) Vinyl acetate	108-05-4
(61) Vinyl chloride	75-01-4
(62) Xylenes	1330-20-7

[1] This list contains 47 volatile organics for which possible analytical procedures provided in EPA Report SW-846 "Test Methods for Evaluating Solid Waste," third edition, November 1986, as revised December 1987, includes Method 8260 and 15 metals for which SW-846 provides either Method 6010 or a method from the 7000 series of methods.
[2] *Common names are those widely used in government regulations, scientific publications, and commerce; synonyms exist for many chemicals.*
[3] Chemical Abstracts Service registry number. Where "Total" is entered, all species in the ground water that contain this element are included.

5.12.1 When Assessment Monitoring Is Not Required

The owner/operator does not have to proceed to assessment monitoring if: (1) contamination from the site is shown to be from another source; (2) there has been an error in sampling, analysis, or statistical evaluation of data; or (3) there is a natural variation in the ground-water quality at the site. The decision not to proceed to assessment monitoring must be based on certification by a qualified ground-water scientist, as defined in Subtitle D.

5.12.2 Elements of an Assessment Monitoring Program

If a statistically significant increase in an Appendix I parameter over background levels exists, the owner/operator must initiate assessment monitoring. At a minimum, assessment monitoring requires annual sampling for many more parameters, called Appendix II parameters.

Some flexibility in developing an assessment monitoring program is allowed. Sampling a subset of wells, for example, is acceptable if the plume definition and hot spots already have been determined, which in turn determines which wells are the most important to sample. Also, chemical parameters other than those listed in Appendix II could be sampled, or an alternative sampling frequency could be used, with the approval of the state director.

If any Appendix II constituents are detected in assessment monitoring, the landfill owner/operator must notify the state director and continue sampling at least semi-annually for the Appendix II parameters. Also, if any Appendix II constituents are detected, the owner/operator must establish the background concentration, and a ground-water protection standard (GWPS) must be set for each detected parameter. A GWPS is defined in Subtitle D as either the MCL for that parameter, if one exists, or the background concentration level for that constituent. A GWPS is established for each detected contaminant.

If, during subsequent assessment monitoring, the contaminant previously detected is no longer found above background levels, the owner/operator can return to detection monitoring. To return to detection monitoring, however, the owner/operator must have at least two consecutive samples that are at or below background concentrations. If this situation occurs, then the owner/operator must notify the state before returning to detection monitoring.

If, however, the level of a contaminant listed in Appendix II remains at a statistically significant level above the GWPS in subsequent monitoring, the owner/operator has to notify state and local officials and clean up the contamination. The owner/operator must make a best effort to characterize the nature and extent of pollution, particularly the delineation of any plume. Additional monitoring wells might be required, but at least one is required at the facility boundary in the direction of ground-water flow, or, more precisely, contaminant migration (because LNAPLs and DNAPLs can move differently than ground water). If the plume is offsite, Subtitle D requires that the owner/operator notify the downgradient individuals whose land overlies the plume.

Also, if the GWPS is exceeded, it is necessary to evaluate alternative corrective measures and select an appropriate remedy. A description of the selected remedy must be placed in the operating record and the state director must be notified. Remediation might not be necessary if certain conditions are met, as discussed in Chapter 6.

Chapter 6
Release Characterization and Remediation

6.1 Introduction

During operation or post-closure, ground-water monitoring might detect pollutants from leachate entering ground water at concentrations that exceed applicable standards (see Chapters 1 and 5). In this situation, the owner/operator of the facility is required to clean up and control the contamination as required in Subtitle D regulations. Some exceptions to this remediation requirement are allowed if:

- The ground water is contaminated by multiple sources, and cleanup of the MSWLF plume will not reduce risk.
- The ground water is not and will not be used as a drinking water source.
- Remediation is not technically feasible.
- Unacceptable cross-media impact would result from remediation.

If remediation is required, two major steps should be undertaken: (1) release characterization, which encompasses delineating the contaminant plume, describing hydrologic processes pertinent to remediation, and compiling other site information; and (2) cleanup, which includes selecting and implementing remedies.

6.2 Release Characterization

6.2.1 Site Assessment

Site assessment is the basic strategy for evaluating the extent of released leachate contaminants and developing other information pertinent to remediation. Preliminary site assessment includes assembling all historical information on the site, analyzing photographic archives, interviewing operators, reviewing landfill design blueprints, compiling facts from utility company records, checking well logs on nearby wells, and collecting existing geologic and hydrologic information. A detailed site assessment often includes installing sampling wells, collecting water and soil samples, conducting a geophysical investigation, analyzing data, and assessing feasible remediation technologies.

During the site assessment, factors that might affect contaminant migration must be evaluated. Factors that speed up contaminant migration include hydrological transport, facilitated transport, and dispersion. Factors that slow down contaminant movement include soil adsorption, chemical precipitation, biotransformation, and other considerations (see Chapter 5 for descriptions of major transport mechanisms). A mass balance can help to estimate how much contaminant has been released, has been volatilized into the gaseous phase, has gone into the nonaqueous phase, has been adsorbed, or has the potential to migrate in various phases. Even if the overall contaminant mass at a site is unknown, the knowledge of the areal distribution of pollutants and a quantitative understanding of which phases a pollutant resides in and how easily it can change phase are crucial information when selecting a remedial strategy.

A review of the basic physical and chemical properties of known or potential contaminants is a first step in estimating mass distribution at a site. For example, reference values for aqueous solubility can give a first approximation of the amount of leachate that is generated at a site. These estimates can then be refined as more information is added, such as the pH, oxygen content, and dissolved salt content of ground water in the area. Batch tests, column tests, and other laboratory bench-scale experiments can further define the site-specific partitioning coefficients in a simulated landfill environment.

A geological investigation can help define the relationship between geology, hydrology, and site remediation. Site geology delineation is crucial for determining which cleanup options are optimal choices and the effectiveness of the remedial alternatives. Questions that should be answered during the investigation include: what geological factors are significant to remediation, how will geological data be collected, and how will the data be interpreted? Information on stratigraphy, lithology, structure geology, and hydrogeology of the site also must be obtained. Such hydrogeological information gathered during the siting and drilling of monitoring wells can help relate site conditions to remedial efforts.

Stratigraphy is one of the most important factors that must be investigated. Stratigraphic studies can define the structure of the contaminated soil so that proper remediation methods are selected. For example, if a sand layer occurs naturally in the contaminated media, it will act as a conduit for either liquid pollution in the saturated zone or gaseous pollution in the vadose zone. Consider a situation where a pumped air method is used to remove gaseous vadose-zone contamination at a site containing a single sand layer surrounded by a finer, wetter material. Because the sand is naturally drier, circulating air will move preferentially through the sand. The sand layer, as a result, will become drier and an even better conduit for flow. In this situation, air will begin to completely circumvent the finer material. The air, therefore, strips volatile organic compounds (VOCs) out of the sand layer only and has hardly any removal effect on VOCs in the clay layer. Pumping air intermittently so that the moisture can be redistributed from the clay into the sand might solve this problem.

Aerial photography can be used to identify past land-use patterns at a landfill and can help define site geology. Particularly in hard rock systems, surface features such as depressions and lineaments can indicate subsurface fracturing and flow conduits. Because landfill operations involve a tremendous amount of shallow excavation, large areas of near-surface geology are exposed for inspection. These excavations normally provide a good initial picture of the stratigraphy in the shallow, unconsolidated material and reveal the degree of local heterogeneity.

6.2.2 Characterization Methods

Certain field techniques can be used for release characterization, including mapping surface features, collecting and analyzing ground water, surveying soil gas, and analyzing soil cores. Other characterization methods include surface and bore-hole geophysics. More than one geophysical technique typically is used to help define a site. A more complete discussion of site characterization methods is available in EPA guidance documents, such as U.S. EPA (1991c).

6.2.2.1 Surface Geophysics and Other Surface Measurements

Noninvasive surface geophysics can be beneficially employed to help delineate the extent of a contaminant plume. Electrical geophysical methods, particularly resistivity and time-domain reflectometry techniques, can be useful when the salinity of the contaminant plume is different from that of ambient ground water. Leachate plumes from landfills typically have high total dissolved solids (TDS) compared to that of ambient ground water, and shallow leachate plumes often can be identified by surface resistivity measurements. Conversely, in a salty seawater environment, a freshwater leachate release also might be located using electrical methods; these methods might be less useful, however, if generalized freshwater recharge and saltwater/freshwater mixing occurs near the plume. These methods are most successful at sites where the salinity of leachate liquids and ambient ground water is sufficiently different.

Other surface geophysical techniques can be useful for characterizing potential pollutant migration and identifying remedial alternatives at a site. For example, stratigraphy can be well defined through seismic surveys, and there is presently interest in developing 3-dimensional seismic surveys to help define NAPL contamination in the subsurface. Electromagnetic techniques and ground-penetrating radar can provide information on buried waste drums, clay lenses, and water-table depths.

Soil sampling and analysis can be conducted at the surface to estimate the areal extent of contaminated soil. Specific protocols are available for collecting, documenting, showing chain-of-custody for, and analyzing samples of solid material at a site. Screening techniques can assist in selecting the best samples for laboratory analysis. For example, a fairly new technique called an immunological survey, currently used at hazardous waste sites, can be adapted for release characterization of contamination near MSWLFs. In this method, a quick, colorimetric test is conducted on soil or water samples using pollutant-specific, polyclonal antibodies. At certain landfill sites, nearby surface water also might require sampling and analysis. Again, rigorous sampling and analysis protocols are required.

6.2.2.2 Downhole Techniques

Downhole logging can provide important clues to the geologic structure surrounding a landfill. Whereas surface geophysical techniques are considered noninvasive, bore-hole logging requires drilling at a site. Several bore-hole logging techniques are available for site characterization, including self-potential, electrical resistivity, temperature, caliper, neutron, natural gamma, gamma-gamma, flow-meter, and television methods.

Many of these techniques involve the use of a specialized probe called a sonde. Several logging devices can be attached to the sonde, which then can be sent down a drilled hole. Types of logging devices that can be attached to the sonde include caliper loggers, a neutron source and detector, and gamma instruments. A caliper logger measures bore-hole diameter, which is an indicator of the degree of consolidation and cohesiveness of porous material. Neutron techniques measure porosity below the water table and regions of saturation in the vadose zone. A neutron logger emits fast neutrons from a radioactive source. When a neutron hits a water molecule or hydronium ion, it is reflected back as a thermalized neutron or a slow neutron, which can be detected by the instrument. The more moisture in the soil, the more neutrons are reflected back to the instrument. Because gamma radiation is naturally emitted by some geologic materials (shales, some clays), gamma devices can be helpful in identifying stratigraphy.

Self-potential and downhole resistivity are important electrical methods for defining stratigraphy. A flow meter is another device that can be used downhole. This device measures flow rate and direction of ground water at different subsurface elevations. Flow-meter logs and vertical temperature profiles of ground water can be used to identify variations in hydraulic conductivity with depth. In fractured rock media, television logs can establish the location and orientation of some fractures when the drilling process itself has not created numerous secondary fractures.

Hydrologic testing of the site provides estimates of hydraulic conductivity and subsurface flow velocity, which are critical in predicting plume migration. Storage coefficients also can be assessed by some methods, providing an approximation of the water stored in the medium. Such field techniques include rate-of-rise (slug) tests, aquifer (pumping) tests, and laboratory estimates such as permeameter tests on "undisturbed" soil samples collected from the site.

The collection of ground-water and aquifer solids for chemical analysis often forms the basis for an evaluation of a site. As in surface soil sample collection, screening techniques such as soil gas surveys can assist in optimizing placement of monitoring wells and in obtaining deeper soil collection. Ground-water characterization methods are described in Chapter 5.

6.3 Remedy Selection and Implementation

This section discusses requirements that must be met during remedy selection and implementation and briefly presents some of the major remediation technologies that are used to clean up contaminated sites. A more complete discussion can be found in U.S. EPA (1991d).

6.3.1 Regulatory Requirements

Based on the results of the corrective measures assessment required by Subtitle D, the owner/operator must select a remedy that, at a minimum, meets the requirements listed below. Within 14 days of selecting a remedy, the owner/operator must place a report in the operating record describing the selected remedy and how it meets the requirements and notify the director of an approved state program. The regulation states that the remedies must:

- Be protective of human health and the environment.
- Attain the ground-water protection standard as specified pursuant to 40 CFR 258.55 (h) or (i).
- Control the source(s) of releases to reduce or eliminate, to the maximum, further release into the environment of the constituents listed in 40 CFR 258 Appendix II.
- Comply with standards for management of wastes as specified in 40 CFR 258.58 (d).

In selecting a remedy that meets the standards, the owner/operator must consider the following evaluation factors:

- The long- and short-term effectiveness and protectiveness of the potential remedy.
- The effectiveness of the remedy in controlling the source to reduce further releases.
- The ease or difficulty of implementing a potential remedy.
- The practicable capability of the owner/operator, including a consideration of technical and economic capability.
- The degree to which community concerns are addressed by a potential remedy.

Once a remedy is selected and implemented, a corrective action program (including ground-water monitoring) must be established. Any necessary interim measures also must be taken during either the site characterization process or the major remedial effort.

If, during remedy implementation, unexpected difficulties arise and a requirement for the remedy cannot be met, the owner/operator must:

- Obtain certification from a qualified ground-water scientist that remediation is not effective.
- Notify the director of an approved state program.
- Implement an alternative measure.
- Continue the alternative corrective action, once effective remedial actions are implemented, until compliance with the ground-water protection standards are met for 3 years (after which it is assumed that the release has been cleaned up).

6.3.2 Remediation Alternatives

After careful release characterization, remediation of the contaminated site should proceed based on the results of the characterization. Methods to achieve objectives of a remedial action can include several, sometimes concurrent, activities to protect human health and the environment. Preventing direct human or animal contact with contamination can be facilitated by institutional controls such as deed or access restrictions, by physical barriers (e.g., fences), and by covering waste. Migration of large masses of contaminants can be controlled by treating principal threats ("hot spots"), installing barriers to protect surrounding ground water, reducing contaminant leaching (often by capping), and by controlling surface run-off and erosion with grading and revegetation. It may be necessary to collect and treat leachate. In some cases where treatment of the waste source is impractical, hydraulic barriers must be maintained for very long periods of time. Wherever practical, remedial efforts should attempt to return ground water to beneficial use, clean up surface water and sediments, and protect wetlands. Collection and treatment of landfill gas also is a common remedial goal, particularly where there are severe odors, nearby homes, and/or when the final disposition of the landfill property will involve public access.

Remediation procedures can include:

- Focused feasibility study (FS)
- Interim remedial measures
- Bench- and pilot-scale studies
- Formal FS
- Selection and design of final remediation
- Implementation
- Monitoring
- Closure (if appropriate)

The following sections briefly describe several common remediation technologies.

6.3.2.1 Excavation

In remedial excavation, equipment is used to dig up the polluted area and transport the soil to another location for treatment or cleanup. This technique is simple and readily available because most landfills have excavation equipment on site. It is especially effective for pollutants that disperse slowly (i.e., pollutants that linger in the vadose zone) or for removal of specific waste drums or canisters. One of the major concerns associated with this method is the amount of the soil that must be excavated. Removing and transporting a large volume of contaminated soil is very expensive. Thus, excavation might not be feasible at landfills with extensive soil contamination or where the primary concern is a leachate release. Removal of contaminated soil ("hot spots"), however, often is an important factor in reducing the source of leachate generation. Removal of such highly contaminated material by excavation could reduce future leachate production. Although excavation will not clean up the leachate plume, it can be an effective tool in reducing risk. Major concerns of using excavation include proper treatment and disposal of the excavated soil and operational safety. For small spills of low-mobility chemicals, however, excavation is a particularly cost-effective cleanup procedure.

6.3.2.2 Fixation and Stabilization

Fixation is the process of adding reagents or hardening agents that absorb, encapsulate, or chemically bond with contaminants, thereby preventing them from moving into the ground water. This process changes the physical characteristics of the waste (e.g., it becomes less water-soluble and sometimes less toxic) and decreases the surface area of pollutants available for leaching. Waste solidification, one type of fixation process, is rarely cost-effective as a pollution prevention measure at Subtitle D facilities; it can, however, be a practical remedial method for reducing the leaching potential of contaminated material removed from landfills during cleanup efforts. In situ stabilization involves the mixing of solidifying reagents or substances (pozzuolanic material) with contaminated soils, typically using standard earthmoving equipment such as backhoes, large diameter augers, and draglines. Mixtures vary depending on what is locally available; a mixture might contain portland cement, fly ash, kiln dust, and/or hydrated lime. Extraneous materials or impurities can strengthen or weaken the solidified mass; therefore, careful evaluation and occasionally pretreatment should accompany any stabilization effort. To date, stabilization has been rarely used at municipal waste sites.

6.3.2.3 Physical and Hydrologic Barriers

The installation of physical barriers to contain ground-water flow is an effective remedial method used in concert with hydrologic barriers and with ground-water cleanup methods, such as pump-and-treat systems (described below). If shallow, unfractured bedrock underlies a site, a slurry trench, grout curtain, or cutoff wall constructed to the depth of bedrock can functionally seal the unconfined aquifer.

A slurry wall is constructed by trenching to bedrock with the trench filled with a mixture of water and clay (e.g., bentonite slurry). The dried slurry in the trench becomes a low-permeability zone that blocks the movement of leachate into downgradient ground water. In regions of topographic variability, bentonite-cement slurries can be used to prevent flow of trench fill to the low topographic point. Cutoff walls or driven pilings also can be placed to block subsurface water flow.

Physical barriers have several limitations, however. Ensuring that the barrier's level of permeability is sufficiently low to prevent the movement of contaminants is difficult. Although low permeability is achieved with a well-designed wall, the barrier also acts as a ground-water dam, producing buildup of hydraulic head on the upgradient side and lowering hydraulic head on the downgradient side. The increase in hydraulic gradient can lead to loss of containment. Also, underflow can occur where the enclosing wall is not well keyed into bedrock. If these problems are not solved, the barrier will lose its ability to contain contaminants.

Where bedrock is very deep, shallow collection trenches or interception wells can contain a pollutant plume hydraulically. Any contaminated water pumped from such a system must be properly treated and disposed.

6.3.2.4 Soil Flushing

Soil flushing is another method for removing subsurface contaminants. If relatively immobile contaminants are located in the vadose zone or the shallow saturated zone, they can be removed by passing specialized washing liquids through the contaminated soil and collecting those liquids downgradient. Because this method mobilizes previously immobile contaminants, the collection system must be particularly efficient. The use of this method at municipal landfills is infrequent.

6.3.2.5 Pump and Treat

Pump-and-treat systems often are used in landfill remediations. In these operations, contaminated ground water is pumped from a collection well, subsurface drain, or trench to an aboveground treatment facility for cleanup. This method requires that all contaminated water be treated to reduce concentrations of target compounds to an acceptable level. Generally, pump-and-treat remediations are time-consuming. Also, even when ground water flowing to a well is apparently clean, adsorbed contaminants in low-permeability areas or residual NAPLs (see Chapter 5) can bleed off once the pumping wells are shut down. Because high contaminant concentrations in ground water can reappear at significant and unacceptable levels after pumps are turned off, it becomes particularly important to define the nature and distribution of contamination during site characterization.

6.3.2.6 In Situ Heating

Heating of subsurface materials can provide several remediation benefits. Warmer subsurface environments can increase evaporation of volatile contaminants, enhance biodegradation rates, and reduce the viscosity of liquids, thus increasing their ability to flow through a porous medium. The subsurface can be heated by steam injection or radio-frequency energy (see Figure 6-1), but caution must be exercised whenever energy is added to the subsurface near a landfill because significant subsurface methane at a site could create potentially explosive conditions.

6.3.2.7 Vapor Extraction and Air Sparging

In vapor extraction, also known as enhanced volatilization, volatile contaminants are stripped out of contaminated soil using forced subsurface ventilation (see Figure 6-2). As

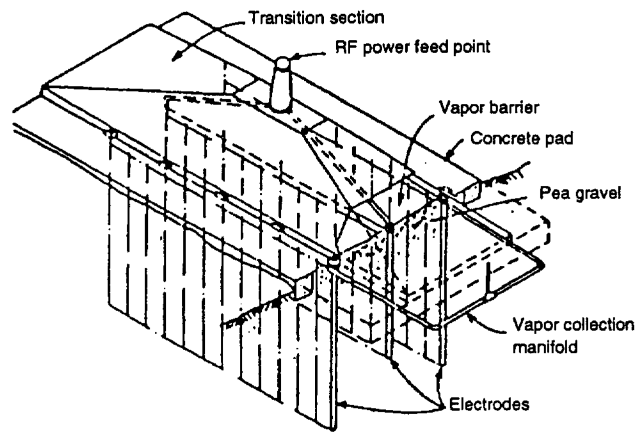


Figure 6-1. In-situ heating device (U.S. EPA, 1992c).

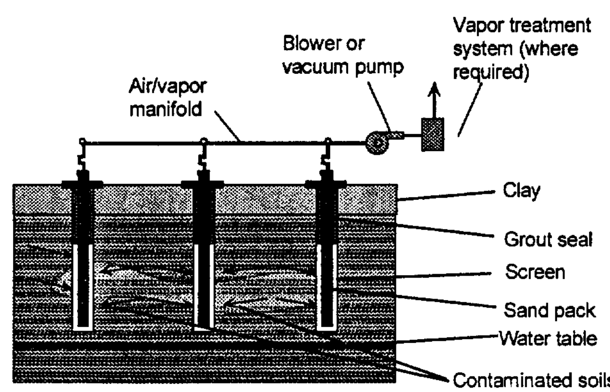


Figure 6-2. Soil vapor extraction (U.S. EPA, 1993b.)

circulating air passes through residual leachate in the vadose zone, it will evaporate the leachate, slowing down leachate movement into the ground water. This method is effective for removal of volatile contaminants when applied to a vadose zone with reasonably high air permeability and moderate- to low-moisture content.

Air sparging techniques, as shown in Figure 6-3, in which air is injected below the water table, can be used to compensate for ineffective aeration of ground water. Unfortunately, rising air in saturated media typically follows certain constrained pathways and does not typically spread out and produce large regions of aeration. In addition, changes in the oxygen content of the subsurface can cause speciation of metals into more mobile fractions. Thus, remedial actions utilizing air sparging techniques should be approached very carefully. These somewhat innovative technologies are acceptable when they represent a low-cost alternative to effectively treat ground water.

6.3.2.8 Bioremediation

Bioremediation is the use of microbial degradation processes in a relatively controlled environment to remove a variety of pollutants from a contaminated site. The

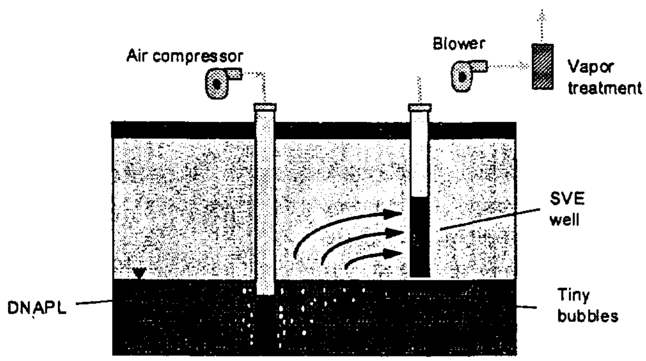


Figure 6-3. Air sparging (U.S. EPA, 1993b).

microbial ecology of the subsurface has the following general characteristics: 1×10^6 to 1×10^3 microbes/g soil (lower in pristine environments); less than 90 percent of the microbes attached to soils; metabolically active, but slow-growing organisms; metabolically versatile organisms; specific microbes that can live in oxic and/or anoxic conditions; and biofilms (polysaccharide exudate) produced by subsurface microbes, which can provide nutrients at later times. These characteristics can be useful in demonstrating the feasibility of bioremediation at a site.

To ensure efficient biodegradation of contaminants, proper microbial growth conditions must be maintained, including the availability of proper amounts and ratios of nutrients (e.g., carbon, nitrogen, phosphorus, and other inorganic substances). A critical factor is the presence of the proper electron acceptor for different types of degradation (e.g., oxygen for aerobic respiration, sulfate and nitrate for reduction, or carbon dioxide and organics for fermentation). Although some research has been conducted to create engineered microbes suitable for degradation, naturally occurring, indigenous microorganisms have been the most successful in contaminant removal.

The designer of a bioremediation system, such as the system shown in Figure 6-4, must demonstrate the feasibility of applying this technology to a specific site. As a part of the feasibility study, the ability of the microorganisms to degrade the contaminants present, as well as limitations in the availability of any nutrients or electron acceptors, should be quantified. The rate of expected degradation relative to the rate of subsurface contaminant migration must be established. This is usually done by the careful measurement of available nutrients and calculation of flow rates. The degradation rate of an analogous compound (e.g., a radioactively tagged compound) that has been added to the site can provide a controlled experiment to delineate degradation rate. A feasibility study also should determine the number of microbes present. Microbial enumeration can be carried out by plating techniques, most-probable-number techniques, staining methods, phospholipid characterization, or other methods.

Claims of biodegradation can be supported by a number of tests that show the biological removal of contaminants. The following characteristics are indicative of microbial degradation:

- Reduction of contaminant concentration in the substrate over time, supported by proper mass balance determinations. Data must show substrate distribution of volatiles in the gaseous phase, adsorbed material on soils, and dissolved-phase contaminants in liquids, so that the consumption of contaminants by microorganisms can be quantified.
- Increase in biomass activity. This information can be obtained through microbial enumeration such as plate methods, staining techniques, phospholipid characterization, or DNA counts.
- Production of daughter products. When microorganisms degrade contaminants, intermediate products (daughters) indicate the first level of biodegradation.
- Adaptation/acclimation phenomenon. In general, microorganisms need some (relatively brief) time to adjust themselves to a new environment before they start to degrade contaminants effectively. When this lag period is demonstrated, the stable and healthy growth of microorganisms is indicated.
- Consumption of terminal electron acceptors.
- Ability to describe the degradation processes mathematically using biodegradation-rate kinetics.
- Abiotic controls. If claims of biodegradation are to be fully supported, data must show that the contaminant transformation occurring is not caused by chemical degradation.

6.3.2.9 Bioventing

Bioventing is a method that combines soil venting and biological degradation for enhanced contaminant removal. The pumped air not only volatilizes the contaminants in the subsurface, but also supplies oxygen to microorganisms for biodegradation of contaminants.

6.3.3 Sources for Further Information on Remediation Techniques

U.S. EPA. 1985. *Handbook of Remedial Action of Waste Disposal Sites (Revised).* U.S. Environmental Protection Agency. EPA/625/6-85/006.

U.S. EPA. 1987. *Technology Briefs, Data Requirements for Selecting Remedial Action Technology.* U.S. Environmental Protection Agency. EPA/600/2-87/001.

U.S. EPA. 1989. *Evaluation of Ground-Water Extraction Remedies. Vol. I, Summary Report.* U.S. Environmental Protection Agency. EPA/540/2-89/054.

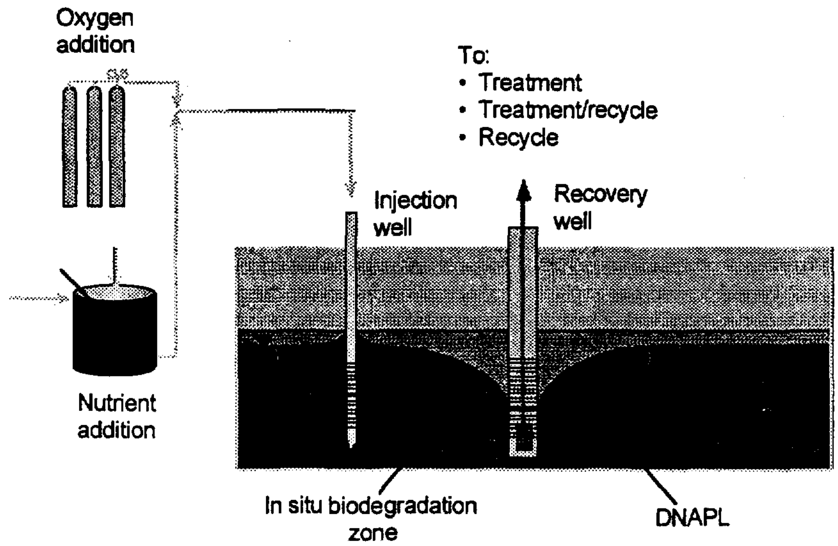


Figure 6-4. Bioremediation system (U.S. EPA, 1993b).

U.S. EPA. 1989. *Stabilization/Solidification of CERCLA and RCRA Wastes.* U.S. Environmental Protection Agency. EPA/625/6-89/022.

U.S. EPA. 1989. *Technology Evaluation Report, Vacuum Extraction System.* Groveland, MA. U.S. Environmental Protection Agency, Office of Research and Development, Risk Reduction Engineering Laboratory. Authored by Michaels, P.A. and M.K. Stinson. EA68-03-3255.

U.S. EPA. 1990. *Basics of Pump and Treat Ground-Water Remediation Technologies.* U.S. Environmental Protection Agency. EPA/600/8-90/003.

Chapter 7
Closure and Post-Closure

7.1 Introduction

Subtitle D requires owners/operators of all MSWLF units to install, at closure, a final cover system designed to minimize infiltration and erosion. The final cover system must be designed and constructed to:

- Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present, or a permeability no greater than 1 x 10^{-5} centimeters per second, whichever is less.
- Minimize infiltration through the closed MSWLF using an infiltration layer that contains a minimum of 18 inches of earthen material.
- Minimize erosion of the final cover using an erosion layer that contains a minimum of 6 inches of earthen material capable of sustaining native plant growth.

The owners/operators of all MSWLFs also must prepare written closure plans that describe the steps necessary to close all MSWLF units at any point during their active life. After the closure of each MSWLF unit, the owner/operator must conduct post-closure care for at least 30 years and at a minimum:

- Maintain the integrity and effectiveness of any final cover.
- Maintain and operate the leachate collection system in accordance with the requirements specified in 40 CFR 258.40.
- Monitor the ground water in accordance with the requirements of Subpart E of 40 CFR 258 and maintain the ground-water monitoring system.
- Maintain and operate the gas monitoring system in accordance with the requirements of 40 CFR 258.23.

More detailed regulatory requirements are presented in Chapter 1.

Subtitle D provides little guidance on the design of final covers and specific elements that might be required in the cover. This section reviews design considerations for both the Subtitle D design objectives and for objectives not directly addressed by Subtitle D. Design considerations discussed include those for the required infiltration and erosion control layer. Also discussed are supplementary layers, which commonly are used in final covers. The supplementary layers reviewed here include a drainage layer used to maintain the stability of the erosion control layer on sideslopes and the gas venting system used to reduce the buildup of gas pressure within the MSWLF.

7.2 Closure Design Considerations

The design components and considerations for MSWLF closure include:

- Profile of the cover
- Infiltration (barrier) layer or an alternative barrier system
- Drainage layer
- Erosion control layer
- Gas venting system
- Landfill cover slope stability
- Subsidence effects
- Weather effects
- Documentation of closure

These components and considerations are discussed below.

7.2.1 Profile of the Cover

The profile of the minimal landfill cover required by Subtitle D is shown in Figure 7-1. Usually, however, the cover also includes supplemental layers to accommodate nonregulatory design criteria. Regulatory and supplemental layers include:

- Initial layer—An interim cover installed above the waste.
- Gas venting layer—A porous, highly permeable system to collect gases produced during waste stabilization.
- Low permeability layer—A soil and/or geomembrane layer with low permeability installed above the gas venting system to limit infiltration of surface waters into the MSWLF.
- Drainage layer—A layer located above the low-permeability layer that maintains the stability of cover slopes by eliminating pore water pressures above the low-permeability layer.

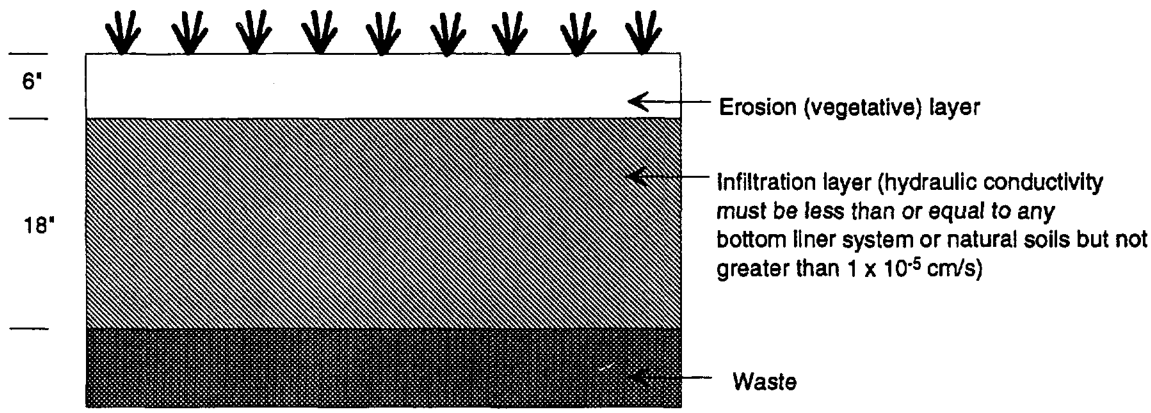


Figure 7-1. Minimum requirement for final cover design (U.S. EPA, 1992d).

- Erosion control layer—The top cover layer consisting of soil covered with vegetation to protect the landfill cover from erosion caused by rain, wind, or animals.

7.2.2 Infiltration (Barrier) Layer

The infiltration (barrier) layer for MSWLFs having only a soil liner consists of a compacted soil layer with a minimum thickness of 18 inches and a maximum permeability of 1 x 10^{-5} centimeters per second. For MSWLFs that use a composite liner system, a geomembrane must be added above the compacted soil layer. Both infiltration layer systems are designed to reduce the rate at which surface waters infiltrate the MSWLF to below the rate at which leachate moves through the liner system. An alternative barrier system with infiltration equivalent to or less than the system described in Subtitle D may be used if approved by the director of an approved state program.

The geomembrane material used for the final cover must be long-lasting and must tolerate anticipated subsidence-induced strains. As an alternative to HDPE, polymers with more suitable biaxial stress-strain capacity should be considered. Typical biaxial stress-strain curves for HDPE and alternative geomembrane polymers are shown in Figure 7-2. Materials with high biaxial strength more easily withstand the differential settling that can occur after closure, thereby resisting failure.

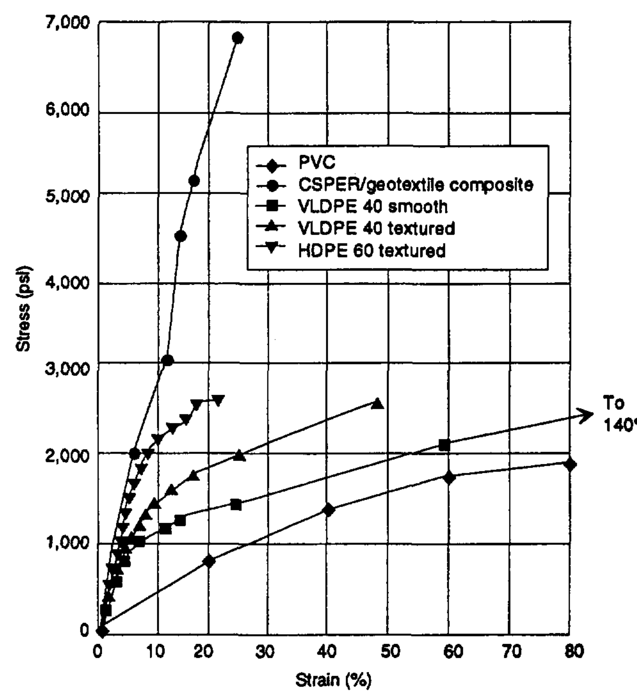


Figure 7-2. Multiaxial stress vs. strain for five geomembrane materials (Frobel, 1991).

7.2.3 Drainage Layer

Subtitle D does not require a drainage layer in landfill cover systems. Many owners/operators of large landfills, however, usually design a drainage layer in portions of the cover system that exceed a 5H:1V slope. The cover drainage layer prevents the moisture that infiltrates the erosion control layer from accumulating above the barrier layer. Such accumulated water can generate excess pore water pressure above the geomembrane and cause the erosion control layer to slide off the cover sideslopes. The sideslope drainage layer commonly is drained to a large capacity toe drain, as shown in Figure 7-3.

7.2.4 Erosion Control Layer

The minimum thickness of the erosion layer required by Subtitle D is 6 inches. Establishing a healthy growth of vegetation in 6 inches of soil can be difficult, however. The minimum practical thickness of the erosion layer should be evaluated using a water-balance analysis,

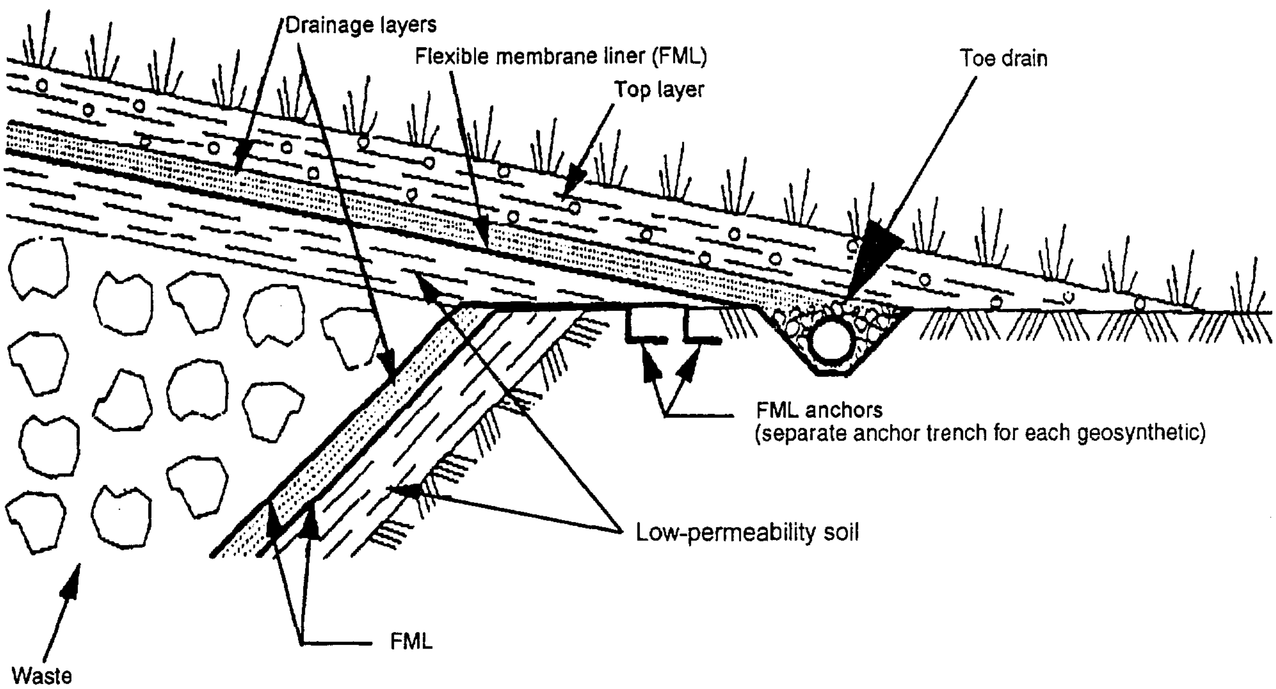


Figure 7-3. Schematic of a sideslope drainage layer (U.S. EPA, 1989c).

such as that performed by EPA's HELP Model (U.S. EPA, 1984). The minimum thickness of the erosion control layer should provide available moisture to plants even during prolonged periods of drought.

Soil loss (erosion) caused by rainfall can be calculated by the universal soil loss equation:

$$X = RKSLCP$$

where:

- X = Soil loss
- R = Rainfall erosion index
- K = Soil erodability factor
- S = Slope gradient factor
- L = Slope length factor
- C = Crop management factor
- P = Erosion control practice

These parameters can be evaluated using data available in soil erosion textbooks and EPA technical resource documents. Erosion-related soil loss should not exceed 2 tons per acre per year to minimize long-term maintenance. Meeting this level of erosion control commonly requires the use of slopes less than 4H:1V and drainage swales placed at 20-foot vertical increments.

Water-related erosion can be controlled not only by vegetation, but also by hardening the cover surface using stones or riprap. Such hardened covers allow more water to infiltrate than vegetative covers because no vegetative evapotranspiration occurs. Hardened covers increase the need for a barrier layer but reduce long-term maintenance.

7.2.5 Gas Collection System

A minimum of one passive gas vent per acre of cover should be installed to prevent the buildup of gas pressure beneath the cover. The gas venting system can use vertical gravel wells, blanket collectors (beneath the barrier layer), or gravel trench drains (also beneath the barrier layer) to collect landfill gases. The collected gases are routed through the cover using vent pipes, as shown in Figure 7-4.

Methane is generated from MSW only when the moisture content of the waste exceeds 40 percent under anaerobic conditions. For example, if a landfill facility contains wastes at 15 percent moisture, the waste will be fossilized; that is, it will not decay and therefore will produce very little methane.

7.2.6 Landfill Cover Slope Stability

The landfill cover slope must be stable enough to sustain infiltration and run-off from a 24-hour, 25-year storm. For slopes steeper than 5H:1V, the designer should ensure that a drainage layer is provided, if needed, and that the interface friction between adjacent layers forming the cover is sufficient to prevent a sliding failure. If sliding occurs, cover integrity can be affected, and other liner systems also might be damaged.

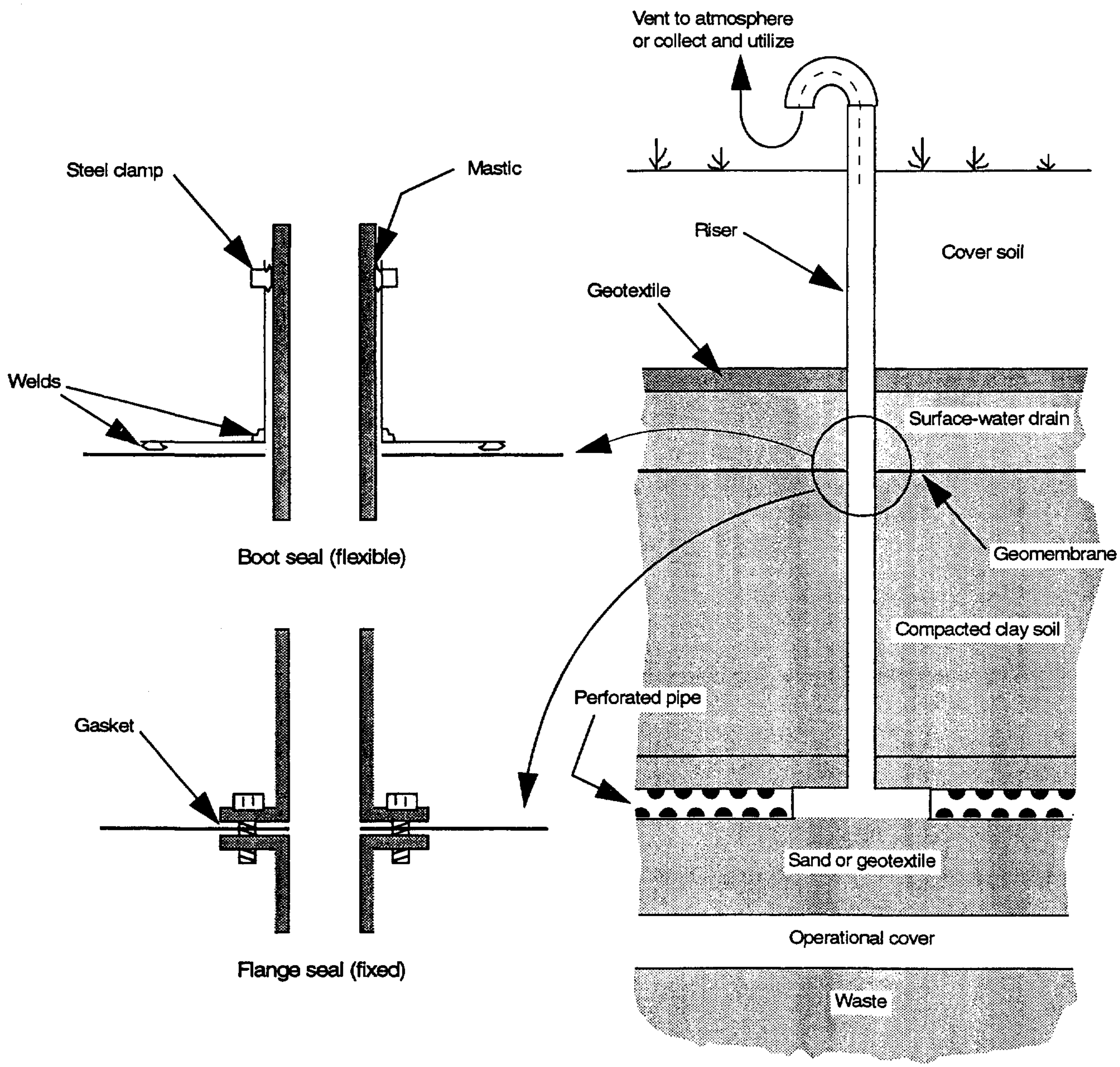


Figure 7-4. Landfill gas vents passing through geomembrane covers (U.S. EPA, 1987c).

Interface friction tests should be conducted to help determine an acceptable maximum slope for a landfill cover. Two types of tests—dry and soaked—should be conducted on interfaces between different cover layers using a direct shear device or a tilt-table. The lowest interface friction slope obtained during the tests then can be designated as the maximum cover slope.

7.2.7 Subsidence Effects

Landfill subsidence can be global (e.g., because of uniform settlement of waste) or localized (e.g., because of the collapse of a large void immediately below a portion of the cover). In general, global subsidence does not result in excessive tensile strains on the cover and improves the stability of the cover by reducing sliding. Therefore, even dramatic global subsidence of the landfill will not harm the final cover.

Localized subsidence, however, can produce small depressions on the cover that can produce excessive tensile strains in cover layers and can lead to ponding of water on the cover. The impact of tensile strains can be minimized using a geomembrane with large ultimate biaxial strain characteristics. These geomembranes are composed of PVC, very low density polyetylene, and polypropylene. Ponding of water must be avoided because it can kill or distress cover vegetation, and the weight of the water can accelerate expansion of a pond on the cover.

7.2.8 Weather Effects

The cover also must be able to withstand extreme weather conditions and remain functional with minimal maintenance. The two extreme weather conditions for which a final cover should be designed are extreme drought conditions and ground freezing. Extreme drought was discussed previously (see Section 7.2.4) and should be considered during the design of the erosion control layer. Freezing of the cover is a concern because of the impact of freezing on clay permeability. Repeated cycles of freezing and thawing can dramatically increase the permeability of compacted clays.

7.2.9 Documentation of Closure

MSWLFs are commonly designed so that new cells are added as contiguous lateral expansions to currently active cells. The final cover for such MSWLF complexes is constructed incrementally, with the final cover being constructed as final cover grades are achieved. Landfill closure is therefore a lengthy process that can extend beyond a single designer's career. For design continuity, as-built drawings and material samples must be maintained for all final cover sections. In this way, the compatibility of abutting geomembranes that have been placed in various years and the continuity of drainage and gas collection systems can be ensured as placement of the final cover progresses.

7.3 Post-Closure Care

After a landfill is closed and the final cover is installed, monitoring and maintenance are necessary to ensure that the landfill remains secured and stable. Subtitle D requires that post-closure care and monitoring be performed for at least 30 years. The owner or operator must prepare a written post-closure care and monitoring plan for review by the director of an approved state program. This plan must include:

- The start and completion dates of the post-closure period
- The monitoring plan description
- The maintenance program description
- The facility's personnel list of contacts for emergencies
- A description of the end-use plan for the site

7.3.1 Required Post-Closure Care

Post-closure care activities must include but are not limited to:

- Maintaining the integrity and effectiveness of erosion controls.
- Maintaining and operating the leachate collection system.
- Maintaining and operating the gas venting system.
- Monitoring ground water for any contamination.

Erosion control maintenance includes routine vegetation management (such as mowing and planting), subsidence repair, and run-on/run-off control. Sedimentation basins and drainage swales must be inspected after every major rainstorm and repaired or cleaned if required.

After a final cover is placed on the MSWLF, the leachate collection system will have a very small leachate load and should be easy to maintain. Leachate generation should drop to less than 1,000 gallons per acre per day, which should not tax a system designed to handle stormwaters. During the post-closure period, leachate production rates should be monitored to identify drops in production rates. If leachate production drops dramatically, then the primary leachate pipes should be inspected for biological clogging. Such inspections can be performed using television cameras commonly used to inspect sewers. The leachate line should be hydro-flushed if clogging is found.

The vent pipes in a passive gas venting system must be inspected frequently for damage that can be caused by mowing or other traffic. A damaged vent pipe can allow surface water to enter the gas venting system and quickly bypass the cover. Damaged vent pipes must be repaired promptly.

Ground-water monitoring has been discussed extensively in Chapter Five. During the post-closure period, ground-water monitoring must continue to be conducted on a routine basis. The owner/operator must be alert to any possible sign of contamination and must take necessary remedial action if contamination occurs. See Chapter 6 for a discussion of remedial action.

Chapter 8
Financial Assurance Criteria

8.1 Introduction

To prove financial assurance, owners/operators of all MSWLFs (except state or federal facilities, which are exempt from the financial assurance requirements) must demonstrate that they have access to sufficient funds to cover the applicable costs of (1) final landfill closure, (2) 30-year post-closure care, and (3) corrective action for known releases of hazardous constituents. The first two requirements are mandatory for all MSWLFs. The third financial assurance requirement is triggered only if a leachate release is detected. Cost estimates must reflect the costs, in current dollars, of hiring a third party to conduct the activity. For closure and post-closure care, cost estimates must be based on the highest costs that could be incurred at the site (e.g., the largest area that might need to have a cover placed on it). For corrective action, cost estimates must reflect the total cost of completing the activity.

For closure, post-closure, or corrective action, the owner/operator can increase or decrease the cost estimates and the amount of financial assurance provided if physical changes in these activities warrant cost modifications. Decreases in cost estimates must be justified and reported to the director of an approved state program. Annual adjustments in cost estimates must be made for inflation. In addition, the owner/operator must provide continuous financial assurance coverage until all Subtitle D requirements for closure, post-closure, and/or corrective action have been met. Completion of required activities must be certified in writing with the approval of either an independent professional engineer or the director of an approved state program.

The Subtitle D financial assurance criteria was due to become effective April 9, 1994. A 12-month extension, however, was given (*Federal Register*, July 28, 1993) to allow EPA to better define a mechanism for local government financial tests (see Section 8.5). The financial assurance requirements for closure, post-closure, and corrective action are described below. Allowable financial mechanisms also are discussed.

8.2 Financial Assurance for Closure

Financial assurance for closure of an MSWLF ensures that the owner or operator will have the necessary funds available to complete construction of the final cover. The owner/operator must provide a detailed cost estimate, in current dollars, for a third party to close the largest open area of the MSWLF. The third-party requirement does not preclude facility personnel from performing the actual work, but it does prevent reliance on such cost-saving measures (e.g., using internal staff rather than contract labor) in cost estimates for financial assurance. For many facilities, financial assurance for closure will change over time because the placement of final cover and the opening of new disposal cells are ongoing processes; closure costs probably will be updated annually to accommodate these adjustments. Subtitle D requires annual adjustment in closure cost estimates to account for inflation and for physical changes during closure that deviate from the closure plan developed before closure (see Chapter 7).

8.2.1 Estimating Final Cover Costs

The cost of constructing a final cover for an MSWLF will depend on the complexity of the cover profile, final slope contours of the cover, and other site-specific factors. This section reviews the costs of individual layers within the final cover and presents current (1993) construction cost guidelines.

8.2.1.1 Infiltration Layer

As discussed in Chapter 7, the infiltration layer can range from an 18-inch layer of soil to a composite barrier composed of a geomembrane overlying a 2-foot layer of soil (in either case, the soil layer must have a permeability equal to or less than 1×10^{-5} centimeters per second). Guidance issued by EPA (*Federal Register*, June 26, 1992) has eliminated the need for compacted clay infiltration layers with permeabilities less than 1×10^{-7} centimeters per second in the cover. This interpretation can provide a cost savings to landfill owners of up to $60,000 per acre.

The cost of the geomembrane component of an infiltration layer ranges from $0.20 to $0.80 per square foot. The less expensive geomembranes can be used on final covers having slopes less than 4H:1V. As the maximum slope of the final cover increases, the geomembrane surface must be roughened to improve the slope stability of the cover system. This roughening is accomplished by either texturizing the surface of the geomembrane or laminating a nonwoven geotextile to both faces of the geomembrane. The cost of such enhanced stability geomembranes is at the upper end of the range.

In many regions of the country, the required soil layer can be constructed using onsite soils. Placing and compacting onsite soils costs $4 to $6 per cubic yard. The recent interpretation of the permeability requirement discussed above is easily achieved with typical soil compaction equipment. If onsite soils are not available, then the cost estimate must include monies for transporting soil to the site. Such transportation costs are typically $0.15 to $0.25 per ton per mile.

MSWLF sites consisting of granular soils might require amendment of available soils to meet the 1×10^{-5} centimeters per second criteria. Amendment might include blending the soils with a local source of soil fines (e.g., quarry fines) or using commercially available bentonite. Soil amendment costs using commercial bentonite are approximately $5 per ton for blending in a pug mill and $2.50 per ton for each percent of bentonite in the mixture. For example, a 3-percent bentonite-amended infiltration layer using onsite soils would cost $12.50 per ton for the bentonite amendment and $6 a ton for placement and compaction.

8.2.1.2 Drainage Layer

A drainage layer in the final cover is required only when the slope of the cover is so steep that water percolating down through the cover will build up excess pore water pressures as it moves down the slopes of the infiltration layer. Such water pressures reduce the stability of the overlying erosion control layer and can lead to cover slope failures. The drainage layer can be constructed using a 6-inch sand layer (at $12 to $20 per ton) or a bonded geonet (at $0.55 to $0.70 per square foot).

8.2.1.3 Erosion Control Layer

Subtitle D requires a minimal erosion control layer consisting of a vegetated 6-inch layer of topsoil. In reality, however, if a geomembrane is incorporated in the final cover, this layer typically must be significantly thicker to maintain vegetation during droughts. The required thickness should be determined by a water-balance analysis. Erosion control layers are commonly 18 to 30 inches thick. Suitable soils to build the erosion control layer typically cost $8 to $14 per ton (including costs of transportation and soil placement). Additional costs for fertilizing, seeding, and hydromulching the erosion control layer range from $1,200 to $1,800 per acre.

Final MSWLF covers also commonly include swales on the sideslopes to control run-off velocities and to convey run-off water off the cover. Swales and associated conveyance devices add approximately $1,100 to $2,000 per acre to the cover cost.

8.2.1.4 Passive Gas Venting Layer

Typically, a minimum of one passive gas vent per acre is incorporated in a final cover. Such vents include a perforated pipe, a gravel collector (both located beneath the infiltration barrier), and a plastic gas vent pipe, which passes through the cover. Gas collectors include both vertical well systems and surface trench drain-type systems. The wells are drilled to the zone of saturation and cost $3,000 to $8,000 to complete. Surface trench collectors are simpler to install and typically cost less than $2,000 each to install.

8.2.2 Annual Updating of Closure Costs

Each year, the estimated cost for constructing a final cover must be updated to account for final cover placement in certain areas of the landfill (resulting in a decrease in the cost estimate) and increased costs of new cell construction during the previous year. Such yearly cost updates also allow changing regulatory requirements or financial assurance mechanisms to be incorporated. Most financial assurance mechanisms (see Section 8.5) will require closure construction costs to be updated annually.

8.3 Financial Assurance for Post-Closure Care

The owner/operator of an MSWLF must demonstrate financial assurance for providing long-term maintenance and monitoring over the 30-year post-closure period. Long-term maintenance can include repair of damaged or stressed vegetation, cleanout of sedimentation basins, maintenance and cleanout of the leachate collection system, and general facility maintenance. Long-term monitoring includes sampling and analysis of ground water, gas emissions testing, and any additional state-required testing.

8.3.1 Estimating Post-Closure Care Costs

Post-closure care costs should be updated annually as a record of actual facility costs is developed. Some costs, such as erosion control and ground-water sampling, might be reduced over time as the cover matures and a meaningful amount of monitoring data is accumulated.

8.3.1.1 Long-Term Maintenance

Erosion-related damage to the final cover increases with increases in the area of the cover and the steepness of its slopes. For typical MSWLF covers with slopes less than 4H:1V, the owner/operator should assume that 5 percent of the final cover will require maintenance (i.e., rebuilding) each year. Such maintenance commonly is performed by facility staff on a monthly basis, but Subtitle D requires that the estimate must be based on hiring a third party to do this work. For this reason, a unit cost ranging from $1,500 to $3,000 per acre should be used.

If swales on the sideslopes are used and a design providing less than 2 tons per acre per year of soil loss is developed, annual erosion control costs can be reduced (perhaps to a maintenance cost of 5 percent of the cover). With good erosion control procedures, maintenance to prevent erosion damage will involve repairing the damage caused by mowing equipment; on wet days, a mower can create ruts and can tear up part of the vegetative erosion control layer.

8.3.1.2 Leachate-Related Costs

The leachate collection system also must be maintained and operated throughout the post-closure period, involving an annual inspection of primary leachate collection lines and possibly hydroflushing to remove sediments and biological growth. Such inspection and cleaning can cost $10,000 to $25,000 annually, depending on the number and length of leachate lines to be cleaned. Operational costs for leachate treatment, repair of lift stations, or hauling leachate to treatment also will be incurred. Costs of maintaining and operating the leachate collection systems during the post-closure period will vary significantly from site to site. A conservative estimate of annual leachate treatment costs can be made by assuming a long-term leachate generation rate of 1,000 gallons per acre per day and a range of leachate treatment costs of $0.15 to $0.25 per gallon.

8.3.1.3 Ground-Water Monitoring

Ground-water monitoring programs will need to be adjusted as a facility increases in size, and such physical changes will need to be incorporated into the cost estimate. Ground-water monitoring wells must be installed in the uppermost aquifer. Typical monitoring well costs can range from $50 to $100 per foot, including ground pad and locking cap. The number of wells required to monitor a given MSWLF is influenced by the site hydrogeology and facility layout. Typically, the number of ground-water monitoring wells is negotiated with the appropriate state regulators and is known before the landfill begins operation. Such negotiations can be long term and can require modification as new MSWLF cells are opened.

Annual ground-water monitoring analysis costs are influenced by the number of wells monitored and the number of contaminants being tested. Full biannual testing for contaminants listed in Appendix I of 40 CFR Part 258 costs from $2,500 to $3,200 per well. Directors of authorized state programs might approve a reduced ground-water monitoring program that focuses on site-specific contaminants.

8.3.1.4 Gas Monitoring System

The gas monitoring system also will need to be maintained and monitored quarterly during the post-closure period. Gas monitoring is relatively inexpensive during post-closure, requiring only a technician to check gas levels in perimeter gas monitoring wells with a handheld explosimeter. Annual gas monitoring costs range from $1,000 to $1,600.

Passive gas venting pipes must be protected from damage by traffic (such as mowing equipment). Damaged vent pipes must be repaired quickly to prevent surface water from entering the gas venting system, and, subsequently, the landfill. Such repairs are inexpensive, costing less than $200 per damaged well. An annual budget of $1,000 for gas vent repair is appropriate.

8.4 Financial Assurance for Corrective Action

The third financial assurance component requires the MSWLF owner/operator to demonstrate that funds are available to complete remediation if corrective action has been deemed necessary at the site (see Chapter 6). The financial assurance requirement for corrective action is not needed unless ground-water contamination is detected in a monitoring well. After the initial detection, the MSWLF owner must develop and implement a corrective action plan that includes identification of actual or potential exposures to the contaminants. The owner/operator of the landfill must notify the director of an approved state program that a corrective action plan exists and also must provide financial assurance for implementing the plan. The amount of money designated for financial assurance can be adjusted annually as remediation progresses. Financial assurance must be provided until the remediation is completed, as certified by a qualified ground-water scientist or the director of an approved state program.

8.5 Financial Assurance Mechanisms

Eleven financial assurance mechanisms are presented as options in Subtitle D, including trust funds, surety bonds, letters of credit, insurance, corporate financial tests, local government financial tests, corporate guarantees, local government guarantees, state-approved mechanisms, state assumption of responsibility, and use of multiple financial mechanisms. These mechanisms are discussed below.

8.5.1 Trust Funds

The owner/operator of a MSWLF may establish a trust fund to demonstrate financial assurance by providing money to a reputable third party, a trustee, who holds the funds until they are needed for closure, post-closure, and/or corrective action. Payments must be made annually into the trust fund. The initial payment must be made before initial receipt of waste or before the effective dates in Subtitle D for closure or post-closure. For corrective action, payments must be made no later than 120 days after a remedy has been selected. The trust fund can be terminated if the owner/operator substitutes another form of financial assurance or is no longer required to demonstrate financial assurance.

8.5.2 Surety Bonds

An MSWLF owner/operator also may demonstrate financial assurance by obtaining a surety bond for closure, post-closure, and/or corrective action. Surety bonds are issued by private firms, which typically require full collateral for the bond. Such collateral usually involves assets independent of the MSWLF. Both payment and performance surety bonds are acceptable to show financial assurance for closure or post-closure. For corrective action, only performance surety bonds are acceptable. The surety company must be listed on an approved U.S. Department of Treasury list referred to in Subtitle D. The bond must be effective before initial receipt of waste or before the effective dates in Subtitle D for closure or post-closure, or for corrective action, no later than 120 days after a remedy has been selected. The owner/operator also must establish a standby trust fund if a surety bond is used as the primary financial assurance mechanism. The owner/operator may cancel the bond if he or she substitutes another form of financial assurance or is no longer required to demonstrate financial assurance.

8.5.3 Letter of Credit

The owner/operator also may use a letter of credit to demonstrate financial assurance. The letter of credit must be irrevocable and issued for at least one year. If the letter of credit is canceled, the owner/operator must obtain another form of financial assurance. The letter of credit must be effective before the initial receipt of waste or before the effective dates in Subtitle D for closure or post-closure. For corrective action, the letter of credit must be effective no later than 120 days after a remedy has been selected. The owner/operator may cancel the letter of credit if he or she substitutes another form of financial assurance or is no longer required to demonstrate financial assurance.

8.5.4 Insurance

The owner/operator may obtain an insurance policy to demonstrate financial assurance. The policy must be issued for a face amount at least equal to the current cost estimate for closure, post-closure, and/or corrective action, whichever is applicable. The face amount refers to the total amount the insurer is obligated to pay; actual payments do not change the face amount (although future liability will be decreased by the amount of the payments). For post-closure care, the insurer must increase the face amount annually, as specified in the Subtitle D regulation.

The insurance policy must include a provision assigning the policy to a succeeding owner/operator. If the insurance policy is canceled, the owner/operator must obtain another form of financial assurance. The insurance policy must be effective before initial receipt of waste or before the effective dates in Subtitle D for closure or post-closure. For corrective action, the policy must be effective no later than 120 days after the remedy is selected. The owner/operator may cancel the insurance policy if he or she substitutes another form of financial assurance or is no longer required to demonstrate financial assurance. At least one insurance company has begun marketing financial assurance as required in Subtitle D.

8.5.5 Corporate and Local Government Financial Tests and Guarantees

Criteria for financial assurance mechanisms for corporate and local government financial tests and for corporate and local government guarantees currently are being developed by EPA. Local financial assurance probably will be an important financial assurance mechanism when EPA determines criteria for local governments. Although local governments probably will not be allowed to use ad valorem (general revenue) taxes as a mechanism for guaranteeing closure, the current bond rating and indebtedness of the local government most likely will be important factors.

8.5.6 State-Approved Mechanisms

The MSWLF owner/operator may use any other financial assurance mechanism that meets the financial assurance requirements of Subtitle D and is approved by the director of an approved state program.

8.5.7 State Assumption of Responsibility

Financial assurance requirements also may be met if the director of an approved state program assumes legal responsibility for an MSWLF's closure, post-closure, and/or corrective action as required in Subtitle D or ensures that state funds will be available to meet these requirements. Subtitle D is the first federal regulation that explicitly treats counties and municipalities as transient, nonpermanent forms of government by requiring financial assurance for landfills. Where populations are decreasing, cities and counties are facing increased financial hardships. In some states, landfills have been abandoned by financially constrained local governments. Financial assurance by states is a vehicle to prevent future abandonment of MSWLFs. State, county, and municipal fiscal responsibility can vary from state to state, depending on government organization. In Tennessee and South Carolina, for example, counties (but not municipalities) are an extension of the state government and therefore covered by state guarantees of financial solvency; this may not be the case in other states.

8.5.8 Use of Multiple Financial Assurance Mechanisms

An owner/operator may use a combination of the financial assurance mechanisms discussed above to demonstrate financial assurance. Subtitle D includes restrictions on using more than one financial mechanism, however, if the mechanisms are not truly independent. For example, the financial test and guarantee provided by a corporate parent may not be combined with the guarantee of a subsidiary if the financial statements of the two firms are consolidated.

Chapter 9
References

When an NTIS numebr is cited in a reference, that document is available from:

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ABB Environmental Services. 1990. As cited in U.S. EPA. 1992, *Seminars: Design, Operation, and Closure of Municipal Solid Waste Landfills.* U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC. EPA/600/K-92/002.

Algermissen, S.T., et al. 1982. *Probabilistic Estimates of Maximum Acceleration and Velocity in Rock in the Contiguous United States.* U.S. Geological Survey, Open-File Report 82-1033.

Algermissen, S.T., et al. 1990. *Probabilistic Earthquake and Velocity Maps for the United States and Puerto Rico.* U.S. Geological Survey, Misc. Field Studies Map MF-2120.

Department of Health and Human Services. (No date.) Publication No. 90-177.

EMCON. 1980. As cited in U.S. EPA. 1992, *Seminars: Design, Operation, and Closure of Municipal Solid Waste Landfills.* U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC. EPA/600/K-92/002.

EMCON. 1981. As cited in U.S. EPA. 1992, *Seminars: Design, Operation, and Closure of Municipal Solid Waste Landfills.* U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC. EPA/600/K-92/002.

Freeze, R. Allan, and John A. Cherry. 1979. *Ground-water.* Englewood Cliffs, NJ: Prentice-Hall.

Frobel, Ron. 1991. *Geosynthetic Material Response to Landfill Cap Settlement and Subsidence.* Proceedings of Geosynthetics 1991 Conference, IFAI, Atlanta, GA.

Government Refuse Collection and Disposal Association. 1985. As cited in U.S. EPA. 1992, *Seminars: Design, Operation, and Closure of Municipal Solid Waste Landfills.* U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC. EPA/600/K-92/002.

Illinois State Water Survey. 1983. *A Guide to the Selection of Materials for Monitoring Well Construction and Ground-Water Sampling.* ISWS Contract Report 327.

Johnson. 1983. As cited in U.S. EPA. 1989, *Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells.* U.S. Environmental Protection Agency. EPA/600/4-89/034.

Jordan, E.C. 1986. As cited in U.S. EPA. 1992, *Seminars: Design, Operation, and Closure of Municipal Solid Waste Landfills.* U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC. EPA/600/K-92/002.

Palmer and Johnson. 1989. As cited in U.S. EPA. 1991, *Handbook: Ground Water, Volume II—Methodology.* U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC. EPA/625/6-90/016b.

SCS. 1980. As cited in U.S. EPA. 1992, *Seminars: Design, Operation, and Closure of Municipal Solid Waste Landfills.* U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC. EPA/600/K-92/002.

U.S. EPA. 1984. *Hydrologic Evaluation of Landfill Performance (HELP) Model.* U.S. Environmental Protection Agency, Washington, DC. EPA/530-SW-84-010.

U.S. EPA. 1985. *Handbook of Remedial Action of Waste Disposal Sites (Revised).* U.S. Environmental Protection Agency. EPA/625/6-85/006.

U.S. EPA. 1986. *Technical Guidance Document: Construction Quality Assurance for Hazardous Waste Land Disposal Facilities.* U.S. Environmental Protection Agency, Washington, DC. EPA/530-SW-86-031.

U.S. EPA. 1987a. *Handbook: Ground Water.* U.S. Environmental Protection Agency, Robert Kerr Environmental Research Laboratory, Ada, OK, and Center for Environmental Research Information, Cincinnati, OH. EPA/625/6-87/016.

U.S. EPA. 1987b. *Technology Briefs, Data Requirements for Selecting Remedial Action Technology.* U.S. Environmental Protection Agency. EPA/600/2-87/001.

U.S. EPA. 1987c. *Geosynthetic Design Guidance for Hazardous Waste Landfill Cells and Surface Impoundments.* U.S. Environmental Protection Agency. EPA/600/52-87/097.

U.S. EPA. 1988. *Loading Point Puncturability Analysis of Geosynthetic Liner Materials.* U.S. Environmental Protection Agency, Cincinnati, OH. NTIS PB88-235544.

U.S. EPA. 1989a. *Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells.* U.S. Environmental Protection Agency. EPA/600/ 4-89/034. U.S. EPA. 1989b. *Technical Guidance Document: The Fabrication of Polyethylene FML Field Seams.* U.S. Environmental Protection Agency, Washington, DC. EPA/530-SW-89-069.

U.S. EPA. 1989c. *Technical Guidance Document: Final Covers on Hazardous Waste Landfills and Surface Impoundments.* U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC. EPA/530-SW-89-047.

U.S. EPA. 1989d. *Technology Evaluation Report: SITE (Superfund Innovative Technology Evaluation) Program Demonstration Test. TERRA-VAC In-Situ Vacuum Extraction System,* Groveland, MA. Vols. I and II. U.S. Environmental Protection Agency, Office of Research and Development, Risk Reduction Engineering Laboratory. Authored by Michaels, P.A. and M.K. Stinson. EPA/540/589/003a and b.

U.S. EPA. 1989e. *Evaluation of Ground-Water Extraction Remedies. Vol. I, Summary Report.* U.S. Environmental Protection Agency. EPA/540/2-89/054.

U.S. EPA. 1989f. *Stabilization/Solidification of CERCLA and RCRA Wastes.* U.S. Environmental Protection Agency. EPA/625/6-89/022.

U.S. EPA. 1990a. *A Subtitle D Landfill Application Manual for the Multimedia Exposure Assessment Model (MULTIMED).* U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, GA. NTIS PB93185-536.

U.S. EPA. 1990b. *Basics of Pump and Treat Ground-Water Remediation Technologies.* U.S. Environmental Protection Agency. EPA/600/8-90/003.

U.S. EPA. 1991a. *Landfill Leachate Clogging of Geotextiles (and Soil) Filters.* U.S. Environmental Protection Agency, Cincinnati, OH. EPA/600/S2-91/025.

U.S. EPA. 1991b. *Technical Guidance Document: Inspection Techniques for the Fabrication of Geomembrane Field Seams.* U.S. Environmental Protection Agency, Cincinnati, OH. EPA/530-SW-91-051.

U.S. EPA. 1991c. *Site Characterization for Subsurface Remediation.* Seminar Publication (November 1991). U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, OH. EPA/625/ 4-91/026.

U.S. EPA. 1991d. *Conducting Remedial Investigations/ Feasibility Studies for CERCLA Municipal Landfill Sites.* U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, DC. EPA/540/P-91/001. U.S. EPA. 1992a. *Characterization of Municipal Solid Waste in the United States: 1992 Update.* U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response. July. EPA/530-R-019.

U.S. EPA. 1992b. *Technical Guidance Document: Quality Assurance and Quality Control for Waste Containment Facilities.* U.S. Environmental Protection Agency, Cincinnati, OH. EPA/600/R-93/182.

U.S. EPA. 1992c. *Seminars: Design, Operation, and Closure of Municipal Solid Waste Landfills.* (April 1992) U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC. EPA/600/K-92/002.

U.S. EPA. 1992d. *A Ground Water Information Tracking System with Statistical Analysis Capability GRITS/ STAT* v4.2. U.S. Environmental Protection Agency, Office of Research and Development, Office of Solid Waste, and Region VII. EPA/625/11-91/002.

U.S. EPA. 1993a. *Solid Waste Disposal Facility Criteria: Technical Manual.* U.S. Environmental Protection Agency, Solid Waste and Emergency Response, Washington, DC. EPA/530/R-93/017.

U.S. EPA. 1993b. *Seminar on Characterizing and Remediating Dense Nonaqueous Phase Liquids at Hazardous Waste Sites: Presentation Outlines and Slide Copy.* (May 1993) U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, OH. EPA/600/K-93/003.

U.S. EPA. 1993c. *Subsurface Characterization and Monitoring Techniques: A Desk Reference Guide.* Volumes I and II. U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC. EPA/625/R-93/003a and b.

U.S. EPA. 1993d. *Behavior and Assimilation of Organic and Inorganic Priority Pollutants Codisposed with Municipal Refuse, Volumes I and II.* U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, Cincinnati, OH. EPA/R-93/137a and b (NTIS PB93-222198 and PB93-222206).

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